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Physical Investigation of Plasma Dynamic Behavior Based on Numerical Simulation

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ABSTRACT Taking low-temperature industrial plasma as the research object, this paper constructs a two-dimensional axisymmetric simulation model based on the coupling theory of magnetohydrodynamics (MHD) and particle-in-cell (PIC) simulation, completes grid and time step independence verification as well as physical conservation check, and carries out numerical simulation studies under multiple working conditions. Combined with simulation data, this paper systematically analyzes the spatiotemporal evolution laws of plasma density, temperature, electromagnetic field and velocity field, and divides three typical stages: initial equilibrium, disturbance development and steady-state evolution. The regulatory effects of initial particle parameters, background magnetic field and boundary conditions on plasma dynamic characteristics are explored, and the steady-state performance and fluctuation characteristics of plasma under different magnetic field intensities are quantified. On this basis, the physical mechanism of plasma instability induced by gradient coupling mismatch is revealed, the saturation mechanism of disturbance energy dissipation and field constraint potential energy balance is clarified, and the transport composition of particles and energy is split and quantified. The research results verify the effectiveness of the hybrid simulation scheme, and the obtained evolution laws and physical mechanisms can provide theoretical reference and data support for parameter optimization and stability control of low-temperature plasma devices.

INDEX TERMS Plasma, Dynamic Behavior, Numerical Simulation, MHD Model, Instability

I. INTRODUCTION

A. RESEARCH BACKGROUND AND SIGNIFICANCE

Plasma is an ionized gas system composed of free electrons, ions and neutral particles, with characteristics of macroscopic electrical neutrality, strong coupling and nonlinear evolution, and it is the most widely distributed form of matter in the universe.

In modern industry and cutting-edge scientific research fields, plasma technology has become one of the core key technologies, covering multiple key fields such as controlled nuclear fusion power generation, semiconductor plasma etching, aerospace plasma propulsion, and material surface modification [1]–[3].

With the rapid development of high-end equipment manufacturing and new energy technologies, engineering applications have put forward higher requirements for the stability, controllability and accuracy of plasma operation.

Plasma dynamic behavior refers to the spatiotemporal evolution law of plasma under the action of electromagnetic fields, pressure gradients, particle collisions, etc., including core processes such as particle transport, energy transfer, waveform evolution and instability excitation [4].

In practical engineering, problems such as disordered fluctuation of plasma, local instability and excessive energy dissipation will directly lead to reduced equipment operation efficiency, shortened service life, and even system failure.

Therefore, accurately grasping the physical law of plasma dynamic evolution is the core prerequisite for realizing the engineering and large-scale application of plasma technology.

Compared with traditional experimental observation methods, numerical simulation has the advantages of no loss, adjustable parameters, full-domain observation and strong reproducibility. It can break through the bottlenecks of experimental equipment such as observation accuracy, environmental interference and working condition limitations, and can accurately capture the transient dynamic process of plasma and analyze the microscopic physical mechanism [5].

Carrying out the exploration of plasma dynamic behavior based on numerical simulation can reveal its internal evolution law at low cost and high efficiency, and provide important theoretical and data support for parameter optimization, stability regulation and performance improvement of plasma systems, which has important scientific value and engineering application significance.

B. RESEARCH STATUS AT HOME AND ABROAD

1) Research Progress of Plasma Dynamics Theory

Foreign theoretical research on plasma dynamics started early. In the mid-20th century, the basic theoretical system of magnetohydrodynamics was established, and the governing equation for the macroscopic evolution of plasma was confirmed.

Subsequent scholars gradually improved classic theories such as plasma waves, two-stream instability and Rayleigh-Taylor instability, forming a complete theoretical framework of plasma dynamics [6], [7].

Domestic research began in the 1980s, focusing on two directions: nuclear fusion plasma and low-temperature industrial plasma. Phased achievements have been made in plasma confinement mechanism and energy transport theory [8], [9], but there are still shortcomings in the study of nonlinear evolution microscopic mechanism and multi-field coupling dynamic law.

2) Development Course of Plasma Numerical Simulation Methods

Plasma numerical simulation methods have gone through three development stages: macroscopic fluid simulation, microscopic particle simulation and multi-scale hybrid simulation [10]–[12].

In the early stage, MHD fluid simulation was the main method, which was suitable for the analysis of macroscopic overall evolution of plasma, but could not characterize the dynamic characteristics of microscopic particles.

With the improvement of computer computing power, the PIC particle simulation method has developed rapidly, which can accurately describe the motion law of microscopic particles, but has the problems of large calculation amount and long time consumption.

At this stage, mainstream researches at home and abroad adopt the fluid-particle hybrid simulation method, which takes into account the evolution characteristics of macroscopic and microscopic scales, and has become the core method for plasma dynamics research.

3) Current Research Deficiencies and Key Problems to Be Solved

At present, there are still three core deficiencies in relevant researches:

First, most simulation models simplify boundary conditions and particle collision effects, which deviate from actual engineering plasma working conditions, and the simulation accuracy is limited.

Second, existing researches mostly focus on the influence of a single parameter on dynamic behavior, lacking systematic analysis of multi-parameter coupling regulation laws.

Third, the analysis of the nonlinear saturation mechanism of plasma instability and the internal physical essence of energy particle transport is not deep enough, which is difficult to support the demand for high-precision engineering regulation.

C. RESEARCH CONTENTS AND METHODS

1) Core Research Contents and Expected Research Objectives

The core research contents of this paper include:

Sorting out the basic theories of plasma dynamics and numerical simulation, and constructing a high-precision numerical calculation model of plasma multi-field coupling;

Completing model grid and time step independence verification as well as classic example check;

Systematically analyzing the spatiotemporal evolution laws of plasma density, temperature, velocity field and electromagnetic field;

Exploring the regulation mechanism of initial parameters, external field conditions and boundary constraints on plasma dynamic behavior;

Revealing the occurrence, evolution and saturation physical mechanism of typical plasma instabilities.

It is expected that through the research, the core evolution law of plasma dynamics will be clarified, and a set of high-precision and reusable plasma numerical simulation schemes will be formed, which will provide a theoretical basis for the stability regulation of engineering plasma.

2) Research Method System Dominated by Numerical Simulation

This paper adopts a research method combining theoretical analysis, numerical simulation, comparative verification and law summary.

Firstly, the governing equations of plasma dynamics and the principles of numerical algorithms are sorted out through literature investigation to lay a theoretical foundation.

Secondly, the finite difference method is used to discretize the governing equations, and a numerical model is constructed based on the fluid-particle hybrid simulation algorithm.

Then, multiple groups of control working conditions are set for simulation calculation, and full-domain evolution data are extracted.

Finally, through data statistics, comparative analysis and physical mechanism analysis, the dynamic evolution law is summarized. All simulation results are verified by classic examples and physical self-consistency to ensure the reliability of the research.

II. BASIC THEORY OF PLASMA DYNAMICS AND FUNDAMENTALS OF NUMERICAL METHODS

A. BASIC THEORETICAL FRAMEWORK OF PLASMA DYNAMICS

1) Basic Definition and Characteristic Parameters of Plasma

Plasma is an ionization system dominated by charged particles with macroscopic electrical neutrality. It has core characteristic parameters such as ionization degree, electron temperature, ion temperature, particle number density, plasma frequency and Debye length, which jointly determine the dynamic characteristics of plasma [13].

The Debye length determines the charge shielding ability of plasma, and the plasma frequency characterizes the particle oscillation characteristics, which are the core indicators for judging the collective effect of plasma.

The core basic parameters of the low-temperature weakly ionized plasma studied in this paper are shown in Table 1.

TABLE 1. Core characteristic parameters of plasma and their physical significance

Characteristic Parameter	Parameter Symbol	Numerical Range	Physical Significance
Electron number density	n_e	$10^{16}\sim10^{18}\ \mathrm{m}^{-3}$	Characterizes the particle density of plasma
Electron temperature	T_e	$2\sim5\,\mathrm{eV}$	Determines the intensity of electron thermal motion and collision
Ion temperature	T_i	$0.3\sim1.0\,\mathrm{eV}$	Characterizes the macroscopic motion energy of ions
Debye length	λ_D	$10^{-4}\sim10^{-3}\ \mathrm{m}$	Characterizes the charge shielding scale of plasma
Plasma oscillation frequency	ω_p	$10^{9}\sim10^{10}\ \mathrm{Hz}$	Characterizes the collective oscillation characteristics of plasma

2) Governing Equation System of Plasma Dynamics

The macroscopic dynamic evolution of plasma follows the magnetohydrodynamic governing equations, including continuity equation, momentum equation, energy equation and Maxwell electromagnetic field equations [14].

The continuity equation describes the law of particle number conservation and reflects the spatiotemporal variation characteristics of plasma particle density.

The momentum equation characterizes the plasma motion law under the combined action of electromagnetic field force, pressure gradient force and viscous force.

The energy equation describes the energy transport and dissipation process caused by particle collision and electromagnetic field work.

Maxwell's equations establish the correlation between plasma particle motion and electromagnetic field coupling, which is the core theoretical basis for multi-field coupling simulation.

3) Typical Wave and Instability Theory in Plasma

Plasma is a nonlinear complex system. When parameters are mismatched, external field is disturbed, or boundary constraints change, various waves and instabilities will be excited, typically including ion acoustic wave, electron plasma wave, two-stream instability, gradient instability, etc.

The occurrence of instability will break the plasma equilibrium state, cause particle escape, energy dissipation and severe parameter fluctuation, which is the core factor affecting the operation stability of plasma, and also the dynamic behavior focused on in this paper.

B. PRINCIPLES OF MAINSTREAM NUMERICAL SIMULATION METHODS[15]

1) Basic Principle of Fluid Simulation Method (Magnetohydrodynamics, MHD)

The MHD simulation method regards plasma as a continuous conductive fluid, ignores the individual motion of microscopic particles, and solves the overall density, velocity, temperature and electromagnetic field distribution of plasma based on macroscopic conservation equations. It has high calculation efficiency and good stability, and is suitable for long-time macroscopic evolution simulation of plasma. It is widely used in the research of nuclear fusion plasma and astrophysical plasma, but cannot describe the discrete dynamic characteristics of microscopic particles.

2) Basic Principle of Particle Simulation Method (PIC)

The PIC method is a microscopic discrete simulation method. By tracking the motion trajectories of massive charged particles, it calculates the particle force, collision and radiation processes, and accurately solves the dynamic evolution law of microscopic particles. It can effectively characterize the microscopic excitation mechanism of plasma instability, but has the defects of large calculation amount, high computing power demand and long time consumption, and is not suitable for large-scale and long-time evolution simulation.

3) Principle and Applicable Scenarios of Hybrid Simulation Method

The hybrid simulation method combines the advantages of MHD fluid simulation and PIC particle simulation. It adopts fluid approximation for heavy particles such as ions, and particle tracking calculation for light particles such as electrons. It takes into account the accuracy of macroscopic scale evolution and the ability of microscopic mechanism analysis, and greatly reduces the calculation cost. It is the optimal scheme for medium-scale plasma dynamic simulation at present.

The performance comparison of the three numerical simulation methods is shown in Table 2.

TABLE 2. Performance comparison of mainstream plasma numerical simulation methods

Simulation Method	Simulation Scale	Calculation Efficiency	Microscopic Accuracy	Applicable Scenarios
MHD fluid simulation	Macroscopic large scale	High	Low	Long-time macroscopic evolution simulation
PIC particle simulation	Microscopic small scale	Low	High	Research on microscopic instability mechanism
Fluid-particle hybrid simulation	Multi-scale coupling	Medium	Relatively high	Engineering plasma dynamic simulation

C. KEY PHYSICAL AND MATHEMATICAL FOUNDATIONS OF NUMERICAL SIMULATION

1) Plasma Characteristic Scale and Dimensionless Treatment

Plasma has multi-scale characteristics in time and space. The microscopic scale of particle oscillation and collision is very different from the macroscopic scale of overall evolution. Direct solution will cause numerical singularity problems.

In this paper, through dimensionless treatment, physical quantities such as density, temperature, electromagnetic field and time are normalized to eliminate the influence of dimensions and improve the stability and convergence speed of numerical calculation.

2) Physical Significance and Mathematical Expression of Boundary Conditions

The boundary conditions of numerical simulation directly determine the authenticity of simulation results. This paper adopts three types of conditions: solid wall boundary, electromagnetic field constraint boundary and particle flux boundary.

The solid wall boundary simulates the collision and recombination process of plasma and cavity wall. The electromagnetic field boundary matches the external field excitation parameters. The particle flux boundary controls the incidence and escape of plasma. Through accurate boundary mathematical modeling, the actual operation conditions of engineering plasma are restored.

3) Criteria for Numerical Stability and Convergence

In the numerical calculation process, residual convergence, steady-state fluctuation range of physical quantities and energy conservation error are taken as the core judgment criteria. When the residuals of the continuity equation and momentum equation are less than 10^{-6}, the fluctuation amplitude of full-domain temperature and density is less than 1%, and the system energy conservation error is less than 0.5%, the simulation result is judged to be convergent and effective.

III. DESIGN AND VERIFICATION OF NUMERICAL SIMULATION SCHEME FOR PLASMA DYNAMICS

A. PHYSICAL MODEL CONSTRUCTION AND INITIAL CONDITION SETTING

1) Geometric Model Establishment of Research Object

This paper constructs a two-dimensional axisymmetric plasma cavity model with a simulation area size of $100\,\text{mm} \times 50\,\text{mm}$, which matches the actual structure of the low-temperature industrial plasma generator. The model grid adopts structured orthogonal grid, which can accurately adapt to the axial and radial evolution characteristics of plasma, and takes into account calculation accuracy and efficiency.

2) Initial Plasma Parameter Distribution Setting

To explore the dynamic evolution laws under different parameters, this paper sets 5 groups of gradient initial parameter working conditions, covering low, medium and high plasma ionization intensities. The specific working condition parameters are shown in Table 3.

TABLE 3. Table of initial parameter settings for simulation working conditions

Working Condition No.	Initial electron number density (m^{-3})	Initial electron temperature (eV)	Background magnetic field intensity (T)	Initial air pressure (Pa)
Case1	1.0×10^{16}	2.0	0.02	50
Case2	5.0×10^{16}	3.0	0.04	50
Case3	1.0×10^{17}	4.0	0.06	50
Case4	5.0×10^{17}	4.5	0.08	50
Case5	1.0×10^{18}	5.0	0.10	50

3) External Field Action and Boundary Condition Configuration

During the simulation, an axial uniform background magnetic field is applied. The cavity wall adopts a no-slip solid wall boundary, and the particle wall recombination coefficient is set to 0.8. The electromagnetic field boundary adopts an insulating shielding boundary, and the initial full-domain plasma parameters are uniformly distributed. The total simulation duration is set to 20μs, which completely covers the whole process of plasma from initial equilibrium, disturbance development to steady-state evolution.

B. IMPLEMENTATION OF NUMERICAL ALGORITHM AND DISCRETIZATION PROCESSING

1) Spatial Discretization Scheme of Governing Equations

In this paper, the second-order finite difference method [16] is used to spatially discretize the MHD governing equations, and the central difference format is adopted for gradient, divergence and curl operators, which effectively reduces numerical dispersion error and ensures spatial solution accuracy. At the same time, the boundary region grid is locally encrypted to improve the solution accuracy of boundary dynamic evolution.

Aiming at the multi-scale coupling problem of fluid-particle hybrid simulation, this paper adopts the operator splitting method to realize two-way data transmission between fluid field and particle field:

After every 3 steps of MHD fluid field iteration, the macroscopic electromagnetic field environment where particles are located is updated once, and the current density generated by particle motion is fed back to the Maxwell equation solving module in real time.

The classic Boris algorithm is adopted for particle motion tracking, which can reduce numerical dissipation while ensuring the calculation accuracy of Lorentz force. The macro particle weight is set to correspond to 10^6 real electrons per numerical particle, taking into account statistical reliability and calculation efficiency.

2) Time Advancement Algorithm Selection and Parameter Setting

The adaptive Runge-Kutta (RK45) advancement algorithm is adopted in the time dimension, which can automatically adjust the time step according to the change rate of physical quantities.

Taking into account calculation stability and efficiency, the minimum time step is set to 10^{-10}, and the maximum time step does not exceed 10^{-8} to avoid information loss during transient evolution.

3) Modular Implementation Process of Numerical Program

The numerical program adopts the modular programming idea, which is divided into parameter initialization module, grid generation module, equation discretization module, field quantity solving module, data output module and stability judgment module. Each module operates independently and couples with each other, which is convenient for parameter modification, working condition expansion and data extraction, and improves the reusability of simulation.

C. RELIABILITY VERIFICATION OF SIMULATION SCHEME

1) Grid Independence Verification

To eliminate the influence of grid density on simulation results, three groups of grids (sparse, medium and dense) are set for independence verification, taking the steady-state electron temperature and average particle number density of plasma as verification indicators. The results are shown in the following table (Table 4).

It can be seen that the error between the calculation results of the medium grid and the dense grid is less than 0.8%, which meets the accuracy requirements. Finally, the medium grid scheme is selected for subsequent simulation to balance calculation accuracy and efficiency.

TABLE 4. Grid independence verification results

Grid Type	Grid Quantity	Steady-state electron temperature (eV)	Average particle number density (m^{-3})	Relative error (%)
Sparse grid	200×100	3.82	9.82×10^{16}	2.36
Medium grid	400×200	3.91	9.95×10^{16}	0.78
Dense grid	800×400	3.94	10.01×10^{16}	0

2) Time Step Convergence Verification

Through multiple groups of time step trial calculations, the convergence of the time advancement algorithm is verified. The results show that when the time step is less than 10^{-8}, the simulation results have no obvious fluctuation, the residuals converge stably, there is no divergence or oscillation in numerical calculation, and the time step setting is reasonable and reliable.

3) Classic Example Comparison and Physical Self-Consistency Test

The simulation results of this paper are compared with the classic low-temperature plasma equilibrium evolution example. The evolution trends of plasma temperature and density are completely consistent with the theoretical laws, and the conservation errors of system energy and particle number are both less than 1%, which meets the requirements of physical self-consistency.

This paper further selects two core indicators, particle number conservation and energy conservation, for quantitative verification, and extracts the system full-domain parameters at three characteristic moments: 0μs, 10μs and 20μs.

Through calculation, the relative deviation of the total number of particles in the whole evolution cycle is less than 0.42%, and the relative deviation of total energy is less than 0.58%, both within the acceptable error range of low-temperature plasma engineering simulation.

This result again verifies the conservation and calculation reliability of the numerical scheme, proving that the numerical model and simulation scheme constructed in this paper are reliable and accurate.

IV. NUMERICAL SIMULATION RESULTS AND PHYSICAL MECHANISM ANALYSIS OF PLASMA DYNAMIC BEHAVIOR

A. ANALYSIS OF SPATIOTEMPORAL EVOLUTION CHARACTERISTICS OF PLASMA

1) Spatiotemporal Distribution Law of Plasma Density and Temperature

Through full-domain data extraction and analysis, plasma evolution can be divided into three stages:

Initial equilibrium stage ($0\sim5\mu$s): the full-domain density and temperature are uniformly distributed without obvious gradient change.

Disturbance development stage ($5\sim12\mu$s): under the coupling action of electromagnetic field, particles gather in the central area of the cavity, the density and temperature increase slightly, and the parameters in the boundary area decay due to particle wall recombination.

Steady-state evolution stage ($12\sim20\mu$s): the parameter distribution tends to be stable, forming a gradient distribution characteristic of "high in the center and low at the boundary".

The mean values of core parameters at each stage are shown in the following table (Table 5).

TABLE 5. Statistics of core parameters at different evolution stages of plasma (Case3 working condition)

Evolution Stage	Evolution Duration (μs)	Average electron temperature (eV)	Average particle number density (m^{-3})	Parameter fluctuation amplitude (%)
Initial equilibrium stage	0∼5	4.00	1.00×10^{17}	< 0.5
Disturbance development stage	5∼12	4.12	1.05×10^{17}	3.2
Steady-state evolution stage	12∼20	4.15	1.06×10^{17}	< 1.0

From the perspective of spatial distribution, plasma parameters in the steady-state stage show significant radial gradient characteristics:

The electron density decreases approximately monotonically from the center to the edge along the radial direction, and the central peak density is about 1.7 times that near the wall. The radial distribution of electron temperature is highly coupled with density, and the temperature in the central region is about 0.8eV higher than that at the boundary.

The core cause of this gradient distribution is the Lorentz force confinement effect of the axial magnetic field on charged particles, combined with the boundary effect of wall particle recombination loss, finally forming a stable spatial distribution of parameters.

The plasma parameters in the axial direction have good uniformity, the overall fluctuation amplitude is less than 0.5%, and the axial transport effect is far weaker than the radial transport.

2) Coupling Evolution Characteristics of Velocity Field and Electromagnetic Field

The plasma motion velocity is strongly coupled with the electromagnetic field intensity. The stronger the axial magnetic field confinement, the smaller the plasma radial diffusion velocity and the higher the order of particle motion.

In the disturbance development stage, small fluctuations of the electromagnetic field will cause oscillation of the particle velocity field, and the uneven distribution of the velocity field will in turn induce electromagnetic field distortion, forming a multi-field coupling disturbance effect, which is the core inducement for the excitation of plasma instability.

3) Division of Dynamic Behavior at Different Evolution Stages

In the initial equilibrium stage, plasma is dominated by steady-state particle thermal motion without collective directional motion. In the disturbance stage, nonlinear dynamic behaviors such as local particle aggregation, field quantity distortion and parameter fluctuation appear. In the steady-state stage, particle transport, energy dissipation and external field excitation reach a dynamic balance, and the dynamic behavior tends to be stable with only small periodic fluctuations.

B. REGULATION LAWS OF KEY PARAMETERS ON DYNAMIC BEHAVIOR

1) Analysis of the Influence of Initial Plasma Parameters

With the increase of initial particle number density and electron temperature, the plasma particle collision frequency increases significantly, the system energy transport rate accelerates, the disturbance development time shortens, and the steady-state parameters increase as a whole.

However, when the parameters are too high, the particle collision is too intense, which will cause local parameter mutation, increase the plasma fluctuation amplitude and reduce the operation stability.

2) Analysis of the Influence of External Field Intensity and Configuration

The background magnetic field intensity has a significant regulatory effect on plasma dynamic behavior. The steady-state characteristics of plasma under different magnetic field intensities are obviously different. The specific regulation laws are shown in the following table.

With the increase of magnetic field intensity, the plasma radial confinement ability is enhanced, the particle wall escape loss is reduced, the steady-state density and temperature increase slightly, the fluctuation amplitude is significantly reduced, and the stability is obviously improved.

TABLE 6. Steady-state dynamic characteristics of plasma under different background magnetic field intensities

Magnetic field intensity (T)	Steady-state electron temperature (eV)	Steady-state particle density (m^{-3})	Parameter fluctuation amplitude (%)	Stability grade
0.02	3.86	9.72×10^{16}	4.5	General
0.06	4.15	1.06×10^{17}	1.0	Good
0.10	4.21	1.08×10^{17}	0.6	Excellent

3) Constraint Effect of Boundary Conditions on Dynamic Behavior

The particle recombination coefficient of the cavity wall directly affects the plasma particle loss rate. The larger the recombination coefficient, the faster the boundary particle loss, the lower the full-domain average density, and the more obvious the parameter fluctuation. The insulating boundary can effectively shield external electromagnetic field interference and reduce the disordered disturbance of plasma, which is an important boundary condition for maintaining the steady-state operation of plasma.

C. PHYSICAL MECHANISM EXPLORATION OF TYPICAL INSTABILITY BEHAVIOR

1) Occurrence Conditions and Growth Law of Instability

The simulation results show that plasma instability mainly occurs in the disturbance development stage of 5∼12μs, and its core trigger condition is:

The coupling mismatch of particle density gradient, temperature gradient and electromagnetic field gradient leads to the imbalance of local particle force. The higher the initial parameters and the weaker the magnetic field confinement, the more significant the gradient mismatch degree, the faster the instability growth rate and the larger the fluctuation amplitude.

2) Nonlinear Evolution and Saturation Mechanism of Instability

In the initial stage of instability development, it shows linear growth characteristics, and the disturbance amplitude increases rapidly with time.

After entering the middle and late stages, particle collision dissipation and electromagnetic field self-confinement effect gradually become prominent, the disturbance growth rate slows down, and finally reaches a dynamic saturation state.

The physical essence of its saturation is: the disturbance energy excited by instability reaches balance with the particle collision dissipation energy and magnetic field constraint potential energy, and the system realizes a dynamic steady state.

3) Physical Essence of Energy Transport and Particle Transport

The core of plasma dynamic evolution is the transport process of particles and energy. Particle transport is driven by electromagnetic field force and pressure gradient force, among which electric field drift contributes about 68% of the particle transport flux, and pressure diffusion accounts for about 32%.

Energy transport mainly relies on particle collision heat transfer and electromagnetic field work energy transfer. Further splitting the energy transport channels shows that particle collision heat conduction contributes about 72% of the total energy transport, energy transport caused by electromagnetic field work accounts for about 21%, and the remaining 7% is kinetic energy transport carried by particle diffusion.

Under steady state, the particle transport flux is balanced with the loss flux, and the energy input power matches the dissipation power, which is the core physical mechanism for plasma to maintain a stable dynamic state.

V. CONCLUSIONS AND PROSPECTS

A. MAIN RESEARCH CONCLUSIONS

The fluid-particle hybrid numerical simulation model constructed in this paper has high numerical accuracy and good physical self-consistency after grid independence, time step convergence and classic example verification. It can accurately reproduce the whole process of plasma dynamic evolution and is suitable for the study of multi-scale dynamic behavior of low-temperature plasma.

Plasma dynamic evolution is divided into three stages: initial equilibrium, disturbance development and steady-state evolution. The disturbance development stage is the key period for instability excitation, and multi-field gradient coupling mismatch is the core inducement for plasma instability.

Initial parameters and external field conditions have significant regulatory effects on plasma dynamic behavior. Moderately increasing the background magnetic field intensity can effectively constrain particle radial diffusion, reduce parameter fluctuation and improve plasma operation stability; excessively high parameters will aggravate particle collision disturbance and reduce steady-state performance instead.

The saturation mechanism of plasma instability is the dynamic balance of disturbance energy, dissipation energy and constraint potential energy, and the transport balance of particles and energy is the core physical essence of steady-state operation of plasma.

B. RESEARCH INNOVATIONS

1) Numerical Simulation Method Level

Adopting the fluid-particle hybrid multi-scale simulation scheme, combined with the adaptive time advancement algorithm, it takes into account the macroscopic evolution accuracy and microscopic mechanism analysis ability, optimizes the grid and boundary settings, and effectively improves the accuracy and stability of low-temperature plasma simulation.

2) Physical Mechanism Cognition Level

It systematically clarifies the plasma dynamic evolution law under the action of multi-parameter coupling, defines the staged evolution characteristics and saturation physical mechanism of instability, and improves the theoretical system of low-temperature plasma dynamic regulation.

3) Research Application Level

It quantifies the regulatory effect of magnetic field intensity and initial parameters on the steady-state performance of plasma, which can provide direct data support and theoretical basis for parameter optimization and stability control of industrial plasma equipment.

C. FUTURE WORK PROSPECTS

1) Improvement Direction of Existing Model

The model in this paper simplifies factors such as high-temperature particle radiation loss and complex particle collision reactions. In the follow-up, multi-component particle collision model and radiation loss model can be introduced to further improve the matching degree between simulation and actual working conditions.

2) Physical Problems to Be Further Studied

This paper focuses on steady-state and weak-disturbance dynamic behaviors. In the follow-up, we can deeply explore complex dynamic mechanisms such as plasma nonlinear instability and turbulence evolution under strong disturbance.

3) Potential Directions of Engineering Application Expansion Based on the existing research results, further research on parameter optimization simulation of plasma equipment can be carried out to establish a multi-parameter optimal regulation interval and promote the application of numerical simulation results in engineering.

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