Research on Structure Formation of Plasmas Dominated by Multiple Hierarchical Dynamics

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Based on parallelized codes for the Earth Simulator (ES) tuned during FY2002, we have performed large scale simulations with high resolutions for two major subjects, (1) micro-scale electron temperature gradient (ETG) driven turbulence simulations in tokamak plasma using GT3D, a gyro-kinetic toroidal particle code, (2) discharge/lightning simulations for high pressure neon gas where high voltage electric field is applied, using EPIC3D, a new version of 3-dimensional relativistic particle code EM3D-EB which includes complex atomic and relaxation processes. In the turbulent transport simulation, we found a new prominent turbulent structure due to the ETG turbulence in reversed magnetic shear plasmas, which support the formation of internal transport barrier. In the discharge/lightning simulation, we successfully reproduced streamer and micro-scale sprite formations which reveal a fractal structures and found a new physical process which leads to fast time scale avalanche event.

Keywords: multiple hierarchical phenomena, magnetic confinement fusion plasma, particle simulation, turbulent transport, lightning phenomena

1. Introduction

Various phenomena associated with structure formation in high temperature magnetically and inertially confined fusion plasmas, space and astrophysical plasmas, and also industrial and laser-produced plasmas, are realized through the complicated nonlinear interaction among different scale fluctuations. Those phenomena are dominated by fluctuation dynamics with different time and spatial scales, revealing a character of "*Multiple-hierarchical Complex Plasma* (*MHCP*)". In this FY2003, based on the parallelized codes for the Earth Simulator (ES) tuned during FY2002 [1], we have performed large scale simulations for two major subjects, (1) micro-scale electron temperature gradient (ETG) driven turbulence simulations in tokamak plasma using GT3D, a gyro-kinetic toroidal particle code, (2) discharge/lightning simulations for high pressure neon gas where high voltage electric field is impressed, using EPIC3D, a new version of 3-dimensional relativistic particle code EM3D-EB which includes complex atomic and relaxation processes. As a result of simulations with high resolution, we successfully reproduced the structure formations which lead to key understandings of the complex plasma dynamics.

2. Gyro-kinetic particle simulation of electron temperature gradient driven turbulence using GT3D

GT3D [2] is a global gyrokinetic toroidal particle code, which was developed for studying tokamak anomalous turbulent transport arising from pressure driven micro-instabilities such as the toroidal ion temperature gradient driven (ITG) mode. In this fiscal year, GT3D is extended for an annular wedge torus simulation of the electron temperature gradient driven (ETG) turbulence. In the code, electron scale microscopic fluctuations with n~1000 are straightforwardly calculated using the quasi-ballooning mode expansion, where n is the toroidal mode number. Typical simulation parameters are $N_r \times N_\theta = 304 \times 128$ finite elements, 64 toroidal modes, and 640 M particles. For these parameters, the parallelization efficiency was 99.976%, and a linear scalability with ~20% processing efficiency (the vectorization efficiency: 99.795%) was obtained up to 512 nodes.

The ETG turbulence is considered as one of experimentally relevant electron transport mechanisms in tokamak plasmas. In recent local flux tube toroidal ETG simulations [3], it has been shown that in the moderate positive magnetic shear configuration, an enhanced electron thermal diffusivity χ_e, which is order of magnitude larger than the mixing length estimate, may be caused by radially elongated structures or streamers. On the other hand, in our previous global slab ETG simulations [4], it was found that in the reversed magnetic shear configuration, χ_e may be suppressed by ETG driven zonal flows in weak magnetic shear regions near the minimum q surface, where q is the safety factor. In order to understand these quali-

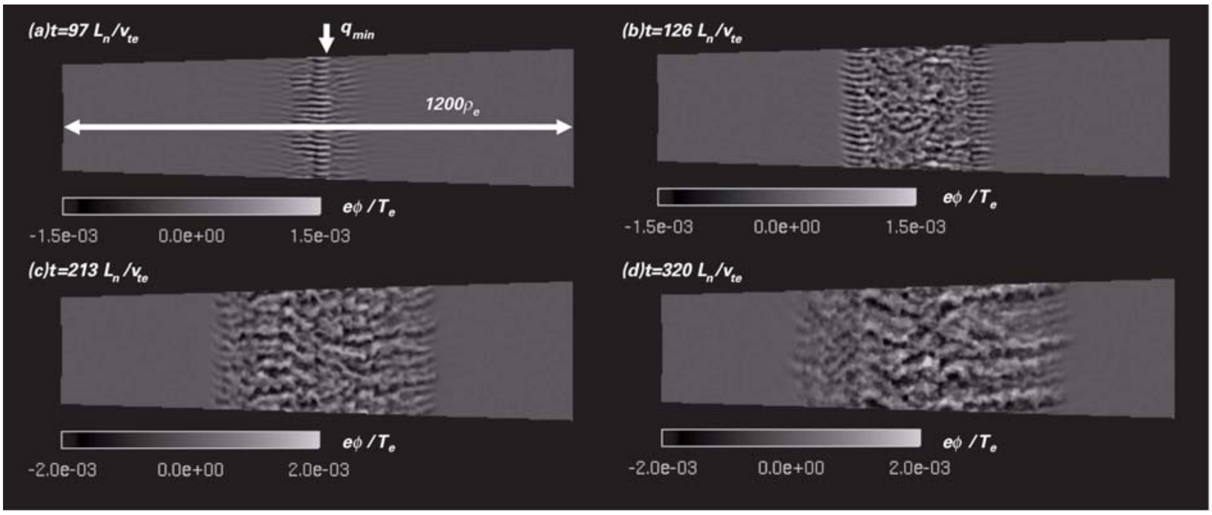

Fig. 1 Contour plots of the electrostatic potential at θ~0. In (a), the linear eigenfunction is dominated by the slab-like ETG mode with n~1600. In (b), a turbulent region spreads in both sides of the qmin surface through avalanche processes of the ETG mode. In (c), secondary instabilities with n~900 are strongly excited inside the qmin surface. In (d), large radially elongated structures are observed in a positive shear region, while in the negative shear region, a radial correlation length is limited by zonal flows.

Table 1 Nx = 1024, Ny = 3840, Nz = 2, N = 24/mesh*11species, 1000step (1.5GB/PE)

PE	Real Time	Vec. Rate	MFLOPS/PE	Vectorization	Parallelization	Available node
480	570.738	96.547 %	372.032 %			
960	300.391	96.641 %	365.668 %	99.9884 %	90.01 %	1080

tatively different turbulent structures, the toroidal ETG turbulence under realistic parameter regimes is first studied in reversed shear tokamaks. From the simulation results, it is found that turbulent structures in the positive and negative shear regions show qualitatively different features. In Fig. 1, in the negative shear region, the ETG driven zonal flows are generated and the radial correlation length of the ETG turbulence is suppressed. On the other hand, the positive shear region is characterized by radially elongated structures or streamers. The results suggest a correlation between streamers and (linear) toroidal driving effects which depends on the sign of the magnetic shear through the magnetic drift frequency. According to the simulation results, at least for the ETG turbulence, transport suppression by zonal flows could be expected in the reversed shear configuration.

3. Lightning simulation using 30dimensional relativistic particle code EPIC3D

We have developed a fully relativistic 3-dimensional particle-in cell code (EPIC3D), an extend version of EM3D-EB [1,5], which self-consistently includes various atomic processes like ionization and recombination and also relaxation process among plasma particles. We performed vectorization and parallelization of the EPIC3D on the Earth Simulator. Based on the developed code, we performed simulations of discharge/lightning dynamics where complex atomic and relaxation processes play an important role.

3.1. Vectorization and parallelization of EPIC3D and tuning on the Earth Simulator

In order to progress the simulation research using the EPIC3D, we improved the vectorization and MPI parallelization efficiencies. As the result, we realized a simulation using 120 nodes (90PE) on the ES. Table 1 shows the vectorization and parallelization efficiency using 480PE (60 nodes) and 960PE (120 nodes), respectively, for neon (Z = 10) discharge simulation. A high parallelization efficiency is obtained, so that a simulation using full ES 640 nodes is available. A relatively low value of the vectorization rate results from the large fraction of the Monte-Carlo calculation. Other computational method for evaluating the atomic and relaxation process, e.g. using the verage ion model and Langivan type of collision operator, may be desirable.

3.2. Research on structure formation in discharge/lightning process

Recently, discharge and lightning phenomena which are sometimes observed in the earth atmosphere and also in the ionosphere have attracted considerable attention [6]. For example, high energy relativistic electrons and even γ-rays were observed during the lightning event. Here, we perform a discharge simulation for high pressure neon gas with the density of 4.6×10^{20} cm^{-3} (17 times the ideal gas), where high voltage electric field, $E = 10^7$ V/cm, is uniformly

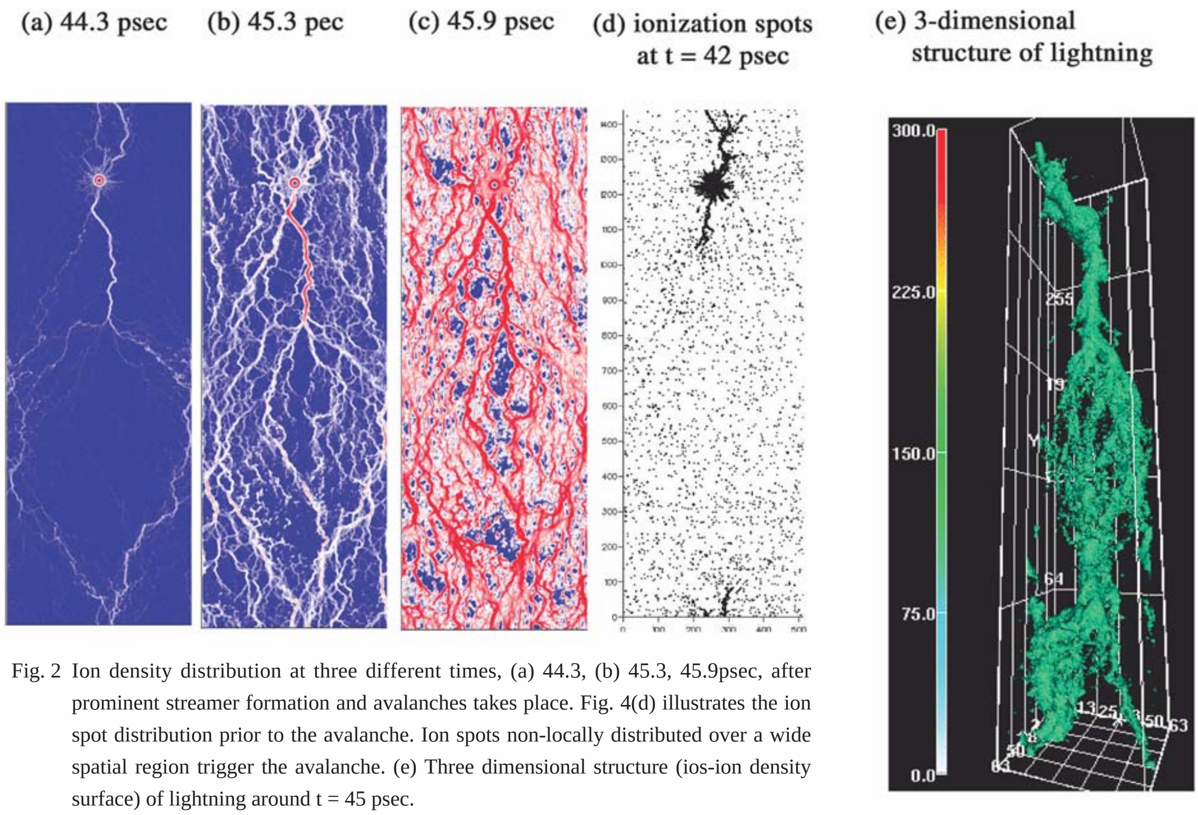

Fig. 2 Ion density distribution at three different times, (a) 44.3, (b) 45.3, 45.9psec, after prominent streamer formation and avalanches takes place. Fig. 4(d) illustrates the ion spot distribution prior to the avalanche. Ion spots non-locally distributed over a wide spatial region trigger the avalanche. (e) Three dimensional structure (ios-ion density surface) of lightning around t = 45 psec.

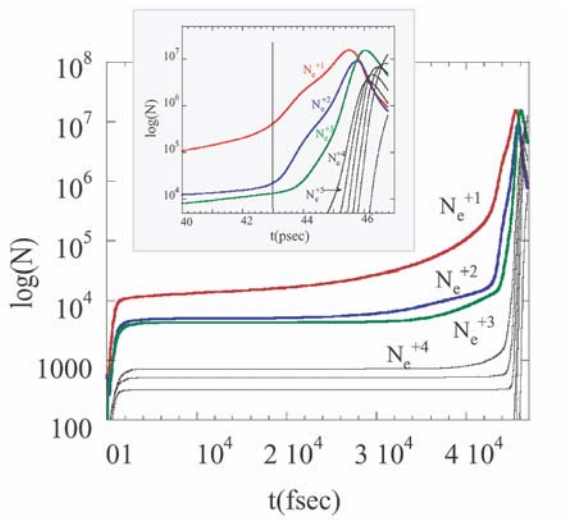

Fig. 3 Time history of ion density for different charge state. Avalanche of N_e^{+1} ion is triggered around t = 43 psec. The region of t = 40–47 psec is shown in order to see the details of avalanches.

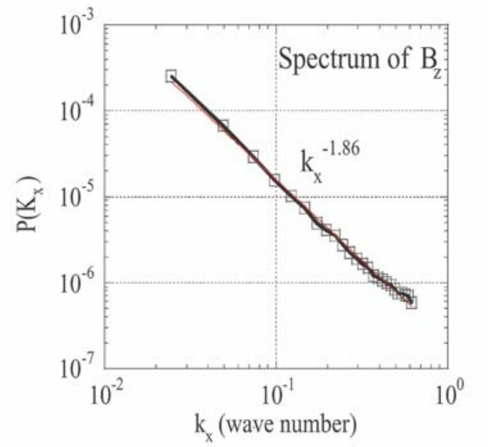

Fig. 4 Wave number spectrum of self- induced Bz field during the avalanche process at t = 45.3 psec. The power law dependence with $kx^{-1.86}$ is obtained.

applied in the system. A tiny ionization spot with Ne^{+2} is initially set to trigger the discharge.

Figure 2 (a)–(c) shows the dynamics of ion charge density and Fig. 3 shows the time history of ion density with different charge state. Fig. 2 (e) illustrates a 3-dimensional iso-surface ion density distribution. The density of N_e^{+1} ion is found to slowly increase, but suddenly exhibits an exponential growth with the fast time scale around t = 43 psec. After the explosive increase of N_e^{+1}, the ion density with higher charge state, i.e. $N_e^{+\sigma}$ with $\sigma \geq 2$, also explosively increases with the growth rate larger than that of N_e^{+1} ion (Fig. 3). A branch-like structure referred as "streamer" develops from the initial ionization spot [Fig. 2 (a)]. However, after the exponential growth, neighboring streamers connect each other (b) and develop to a complex net-like structure (c), which has enormous branches with different spatial scales. This structure may correspond to the so-called "sprite".

Figure 2 (d) illustrates the spatial distribution of ion charge state in early time before the explosive event takes place (t = 42psec). Many tiny ionization spots are found to emerge in the entire system. When the number of spots (or equivalently "packing fraction" of the spot) exceeds a certain value, micro-scale discharges are triggered between neighboring ionizations spots. Such a local event simultaneously propagates over the wide spatial region, leading to an explosive "sprite" phenomenon. This process is similar to that of the "forest burning" and also "percolation" dynamics. Furthermore, since the electron current is driven along ionization branches constituting the streamer and/or sprite, electromagnetic radiations are emitted from the system. Figure 4 illustrates the wave number spectrum of induced magnetic fields obtained from the sprite structure at t = 45.9psec. A clear power low spectrum is found to be observed, suggesting that the sprite shows a fractal nature that has no special scales. It should be noted that a similar spectrum was observed in low frequency electromagnetic signals during lightning events in the atmosphere [7].

Refernece

[1] Y. Kishimoto, *Research on Structure Formation of Plasmas Dominated by Multiple Hierarchical Dynamics*, Annual Report of the Earth Simulator Center, April 2002-Marcg 2003 (ISSN 1348-5822), Chapter 4 Epoch-Making Simulation, pp.201–205.

[2] Y. Idomura, S. Tokuda, and Y. Kishimoto, *Global gyrokinetic simulation of ion temperature gradient driven turbulence in plasma using a canonical Maxwellian distribution*, Nucl. Fusion 43, pp.234–243, 2003.

[3] F. Jenko and W. Dorland, *Prediction of Significant Tokamak Turbulence at Electron Gyroradius Scales*, Phys. Rev. Lett. 89, pp.225001–4, November, 2002.

[4] Y. Idomura, M. Wakatani, and S. Tokuda, *Stability of ExB zonal flow in electron temperature gradient driven turbulence*, Phys. Plasmas 7, pp.3551–3566, September, 2000.

[5] Y. Kishimoto, T. Masaki, and T. Tajima, *High energy ions and nuclear fusion in laser-clauster interaction*, Phys. Plasmas 9, pp.589–601, February, 2002.

[6] V. P. Pasko, M. A. Stanley, J. D. Mathews, U. S. Inan, and T. W. Wood, *Electrical discharge from a thundercloud top to the lower ionosphere*, Nature 416, pp.152-154, March, 2002, H. T. Su, R. R. Hsu, A. BB. Chen et al., Gigantic jets between a thundercloud and the ionosphere, Nature 423, pp.974–976, June, 2003.

[7] M. A. Uman, *The lightning discharge*, Academic, San Diego, 1987.