J. Plasma Physics (2006), *vol.* 72, *part* 6, *pp.* 1077–1080. © 2006 Cambridge University Press
doi:10.1017/S0022377806005484 Printed in the United Kingdom

Plasma particle simulations using a special-purpose computer system for gravitational N-body problems

HIBINO SHINYA[1], MIZUNO YASUNORI[1], INUZUKA HIROSHI[1], CAO YONGGAO[2], LIU YAN[2] and YAZAWA KENICHI[2]

[1]Faculty of Engineering, Shizuoka University, 3-5-1 Johoku, Hamamatsu 432-8561, Japan
[2]Hamamatsu Metrix Co., Ltd, 1-4-10-8 Shinmiyakoda, Hamamatsu 431-2103, Japan

(Received 11 August 2005 and accepted 19 December 2005)

Abstract. Plasma particle simulations are performed using GRAPE-6, a special-purpose computer for calculating gravitational N-body systems. GRAPE-6 rapidly calculates the gravitational force between particles using specialized pipeline processors. The peak performance of a unit of GRAPE-6 reaches 985 GFLOPS. We investigated speeding up plasma simulations through the use of GRAPE-6 for the calculation of Coulomb interactions, which have the same form of central force as the gravitational force. As an example of plasma particle simulation using GRAPE-6, we simulated the Buneman instability. As another example of plasma particle simulation, we simulated a Coulomb crystal in a dusty plasma. The formation of a Coulomb crystal was observed under typical laboratory conditions. We found that GRAPE-6 can perform the entire operation of the simulation of a Coulomb crystal with 5×10^3 particles up to 210 times faster than a 1.6-GHz Pentium4 CPU.

1. Introduction

Recently, in order to achieve high calculation speeds and lower the cost of the hardware used for simulations, special-purpose computers have been developed. These special-purpose computers are typically massively parallel processing computers that contain numerous custom LSI chips that have been specifically designed to calculate a few expressions. By limiting the versatility of the calculation, the hardware complexity can be reduced drastically. Therefore, a special-purpose computer can incorporate a greater number of processors onto a single chip, compared with a general-purpose computer. GRAPE-6 (G6) is a special-purpose computer for solving gravitational N-body problems [1]. G6 can rapidly calculate the gravitational force between particles using specialized pipeline processors. The peak performance of a G6 unit is upwards of 985 GFLOPS. We have used G6 for the calculation of Coulomb interactions, which have the same form of central force as the gravitational force, in order to accelerate plasma simulation [2]. In the following, we present the basic concept of computation using G6. In addition, we present some examples of simulation results and discuss the actual performance of G6.

https://doi.org/10.1017/S0022377806005484 Published online by Cambridge University Press

2. Calculation by G6

One unit of G6 has 32 custom LSI chips, each containing six pipeline processors for the calculation of gravitational interactions between particles. Since one pipeline processor works logically as eight pipelines, G6 has 1536 pipelines per unit. G6 realizes high-speed calculations by efficiently using these pipelines in parallel. G6 is connected to a general-purpose host computer (Pentium4 personal computer) through a communications interface. G6 calculates only the force due to gravitation between particles, and the host computer performs the other calculations. The user program runs on the host computer and can use G6 only by calling library functions. G6 is comprised of multiple memory units and pipeline processors. Each LSI chip has its own memory unit, and whole particle data are stored distributively in these memory units. Thus, the calculation of the force exerted on a particle is divided among all LSI chips. In addition, G6 calculates the forces on different particles in parallel using pipeline processors on the LSI chip.

The gravitational force calculated by a pipeline of the G6 is given by

$$\mathbf{F}_i = Gm_i \sum_j m_j \frac{\mathbf{r}_{ij}}{(r_{ij}^2 + S^2)^{3/2}}, \tag{2.1}$$

where $\mathbf{x}_i$ and $\mathbf{x}_j$ and m_i and m_j are the positions and masses of particles i and j, respectively, $\mathbf{r}_{ij} = \mathbf{x}_i - \mathbf{x}_j$, G is the gravitational constant and S is a softening parameter used to suppress any divergence of the force at $\mathbf{r}_{ij} \to 0$. The value of the softening parameter must be set so as not to influence the simulation results. The Coulomb force between charged particles is expressed by

$$\mathbf{F}_i = \frac{-q_i}{4\pi\epsilon_0} \sum_j q_j \frac{\mathbf{r}_{ij}}{(r_{ij}^2 + S^2)^{3/2}}, \tag{2.2}$$

where q_i and q_j are the respective charges of particles i and j, and ϵ_0 is the dielectric constant. This equation shows that we can accelerate computations using G6 for systems that include Coulomb interaction, by replacing G, m_i and m_j in expression (2.1) with $-1/4\pi\epsilon_0$, q_i and q_j, respectively.

3. Simulation of the Buneman instability using G6

As an example of plasma particle simulation using G6, we have calculated the Buneman instability. For the case in which the number of plasma particles is extremely high, in order to use G6 to calculate the interactions between particles of the entire space, a suitable boundary condition is necessary. The particle does not exist outside the distribution space of the particle. In the case of periodic boundary conditions, in which particles that leave the boundary are injected from the opposite boundary, these particles are accelerated and the total energy in the system increases. The total energy does not increase if the speed of the injected particles is in accordance with the half Maxwell distribution.

We simulate the Buneman instability using this boundary. In the initial conditions of this simulation, we let electrons have relative drift velocity to ions and generate the Buneman instability. Electrons and ions are distributed uniformly within the system, and the velocity distribution is set to the Maxwellian velocity distribution with a plasma temperature of 1 eV. The drift velocity of electrons is six times faster than the electron thermal velocity. The electron to ion mass ratio is 64.

https://doi.org/10.1017/S0022377806005484 Published online by Cambridge University Press

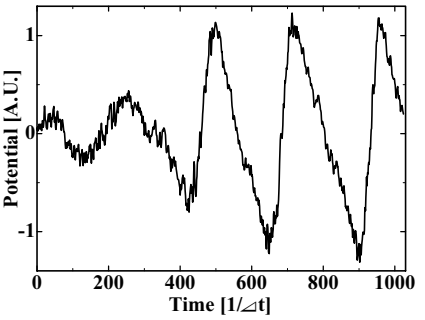


Figure 1. Time evolution of the potential at the center of the system.

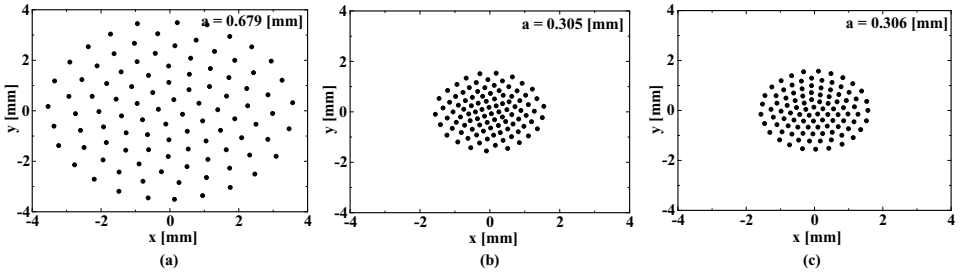


Figure 2. Coulomb crystal structures calculated using (a) the Coulomb potential, (b) the shielding potential and (c) two particles.

As an example of the simulation of the Buneman instability, a temporal variation of the potential in a certain fixed location is shown in Fig. 1.

The wave of the potential in Fig. 1 grows with time. A result of a spectral analysis of time evolution of the potential corresponds approximately to the theoretical value. Therefore, G6 can simulate the Buneman instability if a suitable boundary condition is used.

4. Simulation of Coulomb crystallizations in plasmas

In this section, we examine the simulation of Coulomb crystallization in plasmas using G6 [3]. In the molecular dynamics simulations of Coulomb crystallization, the Yukawa system is often employed to represent dusty plasmas [4].

The Coulomb potential is computed in G6, but the Debye shielding is not considered. Therefore, we approximate the Debye shielding using two particles. Using this method, G6 can take into account the shielding potential.

In this example, we used a neutral gas pressure of 0.3 torr and a plasma density of 1.5×10^{15} m^{-3}. The electron and ion temperatures were 1 and 0.026 eV, respectively. As the initial conditions of the simulation, dust particles are distributed uniformly within the system using random numbers, and the velocity distribution is set to the Maxwellian velocity distribution for a temperature of 0.026 eV. The movement of dust particles is obtained by calculating the equation of motion using the leap-frog method. The crystal structure is shown in Fig. 2 for both of the cases in which the shielding potential was and was not taken into account.

The crystal structures calculated using the Coulomb potential, the shielding potential and the potential of the two particles are shown in Figs 2(a), (b) and

https://doi.org/10.1017/S0022377806005484 Published online by Cambridge University Press

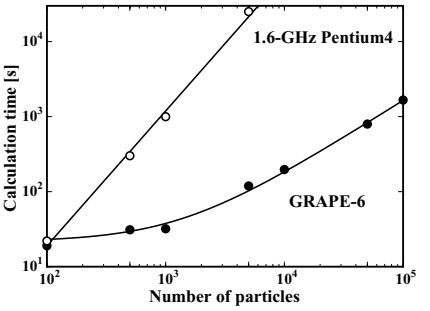


Figure 3. Comparison of the calculation time using G6 with the time required by a 1.6-GHz Pentium4 CPU.

(c), respectively. The averaged distance between particles is given as 'a' at the top right corner of each figure. Using the potential of the two particles, G6 can be used to compute the shielding potential.

5. Evaluation of the calculation speed of G6

Finally, in order to evaluate the actual calculation speed of G6 during the simulation, we compare the calculation speed of G6 with that of a Pentium4 processor. Figure 3 shows the computation time required to perform the entire operation of a simulation using either G6 or only the 1.6-GHz Pentium4 CPU host computer. The simulation of the Coulomb crystal calculated using the Coulomb potential presented above was used for this comparison. In the case of the potential of two particles, the calculation time becomes twice that of the Coulomb potential. The Pentium4 required seven hours to perform the simulation with 5×10^3 particles, whereas G6 required only two minutes. This advantage becomes even more striking in the case of simulations containing more than 10^3 particles.

6. Conclusion

We have performed plasma particle simulations using G6, a special-purpose computer system for solving gravitational N-body problems. As an example of plasma particle simulations using G6, a simulation of the Buneman instability was presented. It was confirmed that the G6 can compute plasma particle simulations. In addition, we have calculated the Coulomb crystal in a dusty plasma using G6. The crystalline structure of the dust particles was observed in the plasma–sheath boundary under typical laboratory conditions. By approximating the shielding potential using two particles, high-speed calculation using G6 became possible. Simulation of a Coulomb crystal in a dusty plasma with 5×10^3 particles was confirmed to be performed 210 times faster using the G6, as compared with 1.6-GHz Pentium4 CPU.

References

[1] Makino, J. and Funato, Y. 1993 *Astron. Soc. Japan* **45**, 279.

[2] Yamamoto, K., Mizuno, Y. and Inuzuka, H. 2004 In: *Technical Session Proceedings of the International COE Forum on Plasma Science and Technology*, Nagoya, Japan, p. 147.

[3] Hayashi, Y. and Tachibana, K. 1994 *Japan. J. Appl. Phys.* **33**, L804–L806.

[4] Asano, K., Nunomura, S., Misawa, T., Ohno, N. and Takamura, S. 1998 *Czech. J. Phys.* **48**, 239.

https://doi.org/10.1017/S0022377806005484 Published online by Cambridge University Press