Anomalous Thermalization of Fast Ions in Magnetized Plasma

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A novel anomalous process causing the perpendicular energy of fast ions to be thermalized and lost on average to bulk ion heating, instead of classical slowing down and bulk electron heating, is investigated with particle-in-cell simulations. More than half of the fast ions are slowed down to the thermal ion level, although some are heated to twice their birth energy. The fast ion density perturbation is large. This process is excited by a new two-gyro-stream instability and may continually occur in a burning plasma. The implications for fusion ignition and fast ion confinement are assessed.

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Fast ions exist in laboratory, fusion [1], space, and astrophysical [2] plasmas. In a fusion plasma, the energy needed to sustain ignition is provided by the isotropic shell-distributed fast ions produced from thermonuclear fusion reactions. Thus, the anomalous behavior of fast ions due to collective instabilities, as well as the implications for their confinement, are critically important issues for the performance of a burning fusion reactor.

In the past, research on fast-ion-driven instabilities has focused on mechanisms based on an imbalanced population (e.g., inverse Landau damping). The time scales of the waves (e.g., the toroidal Alfvén eigenmode [3,4]) are usually longer than the inverse ion cyclotron frequency. Furthermore, the fast ions are assumed to be distributed smoothly in real space and to have a slowing-down distribution in energy, as predicted classically, where the collision time is much longer than the inverse ion cyclotron frequency.

Recently, intense localized harmonic ion cyclotron emission induced by fast ions has become an active area of research, with both theoretical studies [5-9] and experimental observations [10-12]. In particular, the mechanism of the two-gyro-stream instability (also called the two-energy-stream cyclotron instability [5]), which is driven by the fast ions due to a weak relativistic mass effect, has been proposed [6] to explain the experimental observations.

In this Letter, I investigate a novel anomalous process that causes the perpendicular energy of fast ions to be thermalized and lost on average to bulk ion heating, instead of classical slowing down [13] and bulk electron heating [1,13]. My simulations show that the fast ion dynamics is dramatically affected in both real and velocity space, in contrast to other recently proposed mechanisms [7-9], which predict effects that are weaker and occur in narrower regimes of phase space. This process is excited by the two-gyro-stream instability, and persists even when the external confining magnetic field is nonuniform. The investigation was carried out by means of particle-in-cell simulations with a quiet start [14,15]. The simulations imply that the anomalous process may continually occur in a burning plasma. When the weak relativistic mass effect is turned off, the observed anomalous phenomena disappear. The anomalous process has implications for burning conditions and their confinement.

The two-gyro-stream instability arises from the coupling of a fast ion Bernstein branch and its corresponding slow ion Bernstein branch. Because of the relativistic mass dependence, the harmonic cyclotron frequency of the fast ions is slightly smaller than the harmonic cyclotron frequency of the slow ions. It gives rise to a "two-streaming" process in gyrospace (i.e., gyrophase vs perpendicular momentum). The peak growth rate ω_i [5] of the instability for the system considered here is

$$\omega_i/l_s\omega_{cs} = (\sqrt{3}/2)(\gamma-1)^{1/3}(\omega_{pf}^2/\omega_{ps}^2)^{1/3}[\langle J_{l_f}(k\rho_f)\rangle]^{1/3} \times (l_f^2\omega_{cf}^2-\omega_{cs}^2)^{1/3}/(kc)^{2/3},$$

with the real frequency of the wave given by $\omega_r/l_f\omega_{cf} = 1+(1/\sqrt{3})(\omega_i/l_s\omega_{cs})$; here, l is the harmonic number, ω_c is the relativistic cyclotron frequency, γ is the fast ion Lorentz factor, ω_p is the plasma frequency, k is the wave number, c is the speed of light, J_{l_f} is the Bessel function of the first kind of order l_f, $\langle\rangle$ represents the integration over a shell velocity distribution, ρ is the Larmor radius, and the subscripts f and s indicate fast and slow ions, respectively. The fast ions give up energy to the wave, and the wave to the slow ions, which brings their frequencies closer. The wave growth ceases when the difference of ω_r and $l_f\omega_{cf}$ vanishes due to the change in γ. Hence, the rate of fast ion energy loss is estimated [5] to be $\eta = 3^{-1/2}(\omega_i/l_f\omega_{cf})(\gamma-1)^{-1}$. In the simulations, the coupling of the first proton cyclotron harmonic and the second bulk deuteron cyclotron harmonic is dominant.

A one-space-and-three-momentum-dimensional simulation code is employed. The saturated wave potential is expected to be smaller than the slow ion temperature. Because the wavelength is much larger than the plasma Debye length, the saturated field energy should be very small. Thus, I adopt the quiet start technique for the simulation to have low noise. Also, the model is simplified in order to make the simulation affordable even while the essential physics is retained. Because the modes with vanishing parallel wave number ($k_z=0$) are more unstable than the $k_z\neq 0$ modes [5], the wave vectors may be taken to be transverse to the external magnetic field as

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in previous papers [5-7,10,16]. Also, inclusion of the electromagnetic Alfvén mode should not be important, since its excitation requires the extra condition $kv_A = l\omega_c$, where v_A is the Alfvén velocity, which is not satisfied for the low harmonics for typical tokamak parameters. In addition, almost all the energy of the Alfvén mode is in its magnetic component whereas an electric field is needed to change particle energy. Therefore, only the effects caused by electrostatic ion Bernstein modes are considered. The spatially localized feature as inferred from the experimental observations makes a periodical boundary condition suitable. The electrons are treated with a dielectric, but the kinetic ions can be treated relativistically or classically, which offers an important check on the importance of the weak relativistic mass effect.

The physical parameters for the simulation are as follows: $\omega_{pD}/\omega_{cD} = 19.2$, $n_p/n_D = 5\times10^{-3}$, $E_p/T_D = 147$, and $\gamma = 1.0157$ (which corresponds to 14.7 MeV protons produced from deuterium-helium-3 reactions) with 4% energy spread (full width at half maximum). Here n is the density, E is the energy, T is the temperature, and the subscripts p and D represent the shell-distributed protons and Maxwellian deuterons, respectively. The instability is absolute [17] because the peak growth rate for the first proton harmonic, $8.2\times10^{-3}\omega_{cD}$, is larger than the critical rate for absolute instability, $3.8\times10^{-3}\omega_{cD}$. The system length is 4096 grids, with dx the grid size (normalized to unity). The fast ion gyroradius is $\rho_p = 222dx$. Time is normalized to ω_{cD}^{-1}, and one time step is 0.02. The proton mass is normalized to have unit value. The unit charge is the proton charge. Energy is normalized to the total system energy. The simulations use 177 146 superparticles for the deuterons and 21 600 for the protons. Modes with mode numbers from 1 to 15 are kept; the wave number k is equal to $2\pi/4096$ times the mode number. The initial system noise is about 1×10^{-8}.

The simulations show that the field energy of the wave grows exponentially from 1×10^{-10}, with a growth rate $\omega_i = 0.8\%$ that agrees with the theoretical prediction. It reaches a saturation level of 8×10^{-6} at $t = 1000$, as shown in Fig. 1. The wave potential divided by the slow ion temperature is 0.09, 0.28, and 0.13 at saturation, respectively, for modes 6, 7, and 8 (which are the modes of largest field energy). From the power spectrum, these modes have peaks at the real frequencies 1.980, 1.974, and 1.967, respectively. Because of the collective instability, the fast ions have lost kinetic energy, on average, of about 20% at the saturated peak and 12% at the end of the simulation at $t = 3200$, which losses are consistent with the theoretical estimate of 15%. Figure 1 also shows that almost all the energy loss goes into bulk ion heating. The resultant slow ion distribution becomes non-Maxwellian and has an energetic tail. When I turn off the weak relativistic mass effect by using Newton's equation instead of the Lorentz equation for the particle motion, there is no wave growth, no fast ion energy loss, and no energy gained by the slow ions, as shown in Fig. 1. This

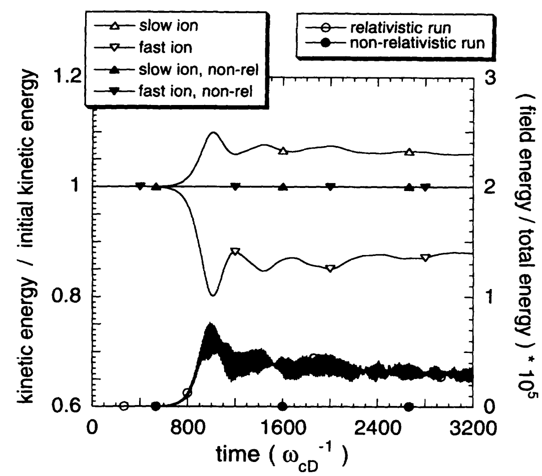

FIG. 1. The history of the field energy and the kinetic energies of the fast ion and the slow ion for the relativistic and nonrelativistic runs, respectively.

verifies that the anomalous process is caused by the weak relativistic mass effect.

While the fast ions lose energy on average, due to the collective cyclotron instability, some of them gain energy from the waves and some of them lose energy, depending on their gyrophases. The fast ion energy distribution at various times is shown in Fig. 2. The energy spread quickly increases and reaches about 100% at the time of saturation. After that, the energy spread remains about the same, while some of the overshot fast ions gain energy back and others lose (or gain) more energy. At the end of the simulation, more than half of the fast ions are slowed down up to the thermal ion level, although some of them are heated up to twice their birth energy. A similar phenomenon is observed during neutral-beam-injection experiments in tokamaks [18,19]. The two-gyro-stream instability occurs in the perpendicular direction and has no effect on the parallel momentum. Figure 3 shows that, due to the collective instability, the perpen-

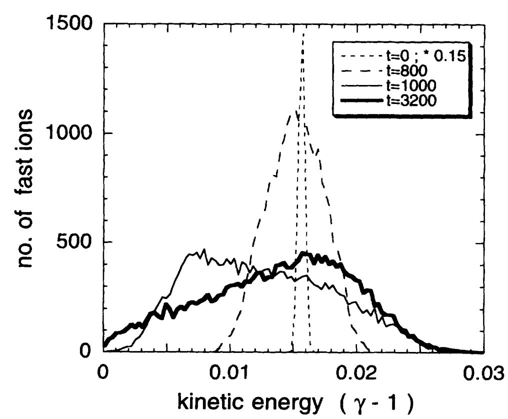

FIG. 2. The kinetic energy distribution of the fast ion at $t = 0$, 800, 1000, and 3200, respectively. The curve for the $t = 0$ case has been multiplied by 0.15.

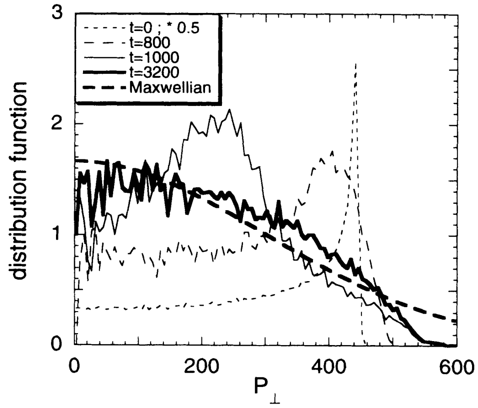

FIG. 3. The perpendicular momentum distribution of the fast ion at $t=0$, 800, 1000, and 3200, respectively. The thermal momentum of the Maxwellian distribution, for comparison, is 300. The curve for the $t=0$ case has been multiplied by 0.5.

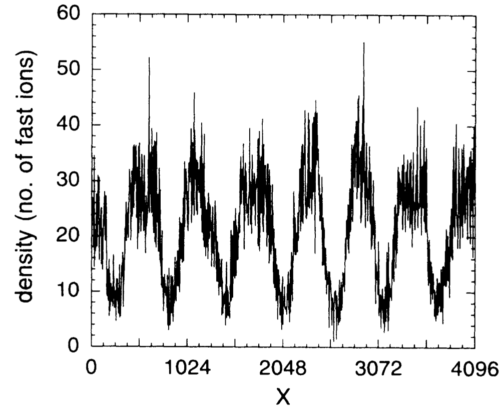

FIG. 4. The fast ion density vs position, x, at $t=1000$. The density is summed over every 4 grids. The average density is about 21.

dicular momentum distribution function of the fast ions changes from a shell distribution toward a Maxwellian distribution. It is also observed that the particles bunch in their gyrophase. An electrostatic wave results from the real space perturbation of the charged particles and vice versa. Figure 4 shows that the fast ion density, which was initially uniform, develops a sizable perturbation. The density perturbation reaches 100% at wave saturation and remains at the 50% level at the end of the simulation.

This anomalous process is strong. As it creates a large spread in the fast ion energy and thermalizes their perpendicular momentum, it removes fast ion kinetic energy and, at the same time, heats the bulk ions. Bulk ion heating favors the occurrence of the hot ion mode [20] and sustained ignition in a fusion reactor. The thermalization dramatically changes the pitch angle and banana width of the fast ions and thus may affect their confinement. On the other hand, it also produces a large perturbation in the fast ion density across the confining magnetic field. In a realistic device, the unperturbed density is usually higher at the plasma center. Thus, a ponderomotive force may be produced that may induce anomalous transport across the confining magnetic field. Although this may provide a means for ash removal and for the weakening of instabilities driven by a real-space gradient, it may also cause serious problems for a burning plasma, such as loss of the fast ions for sustaining ignition.

The basic mechanism for the cubic two-gyro-stream instability is due to the difference of the fast ion cyclotron harmonic frequency and its corresponding slow ion cyclotron harmonic frequency. A nonuniform magnetic field does not change this relationship, although it may localize the waves. Two simulations were also carried out with a perturbed magnetic field that had a 1.6% and 5% peak-to-peak sinusoidal nonuniformity, respectively, with other parameters the same. The ratio of the fast ion gyroradius to the nonuniformity scale length in the 5% case is comparable to that in typical tokamaks.

Figure 5 shows the fast ion energy distribution at the end of simulations for cases with different amplitudes of the magnetic field nonuniformity. The large energy spreads attained are essentially the same in all the cases. At the end of the simulations, the fast ions lose 9% and 7% of their energy in the 1.6% and 5% nonuniformity cases, respectively. Again, almost all of the lost energy goes into bulk ion heating. The simulations also show the thermalization of the fast ion perpendicular momentum, the large fast ion density perturbation, and other phenomena observed in the uniform simulations. More wave Fourier components are observed to become unstable in the nonuniform magnetic field, but their peak growth rates are smaller than those for the uniform magnetic field case. The power spectrum for the 5% nonuniformity case shows that each wave Fourier mode from 1 to 12 (note that the Fourier modes from 13 to 15 were not retained in order to reduce the numerical noise level) has peaks at the frequency 2.02 or 1.93 or both. Within the numerical resolution, the wave field perturbations are lo-

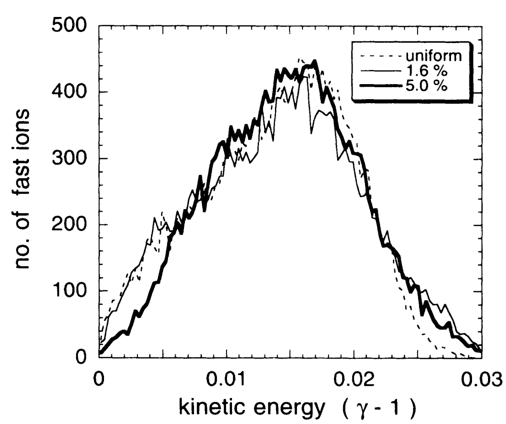

FIG. 5. The kinetic energy distribution of the fast ion at $t=3200$ for the cases with uniform, 1.6% nonuniform, and 5.0% nonuniform magnetic fields, respectively.

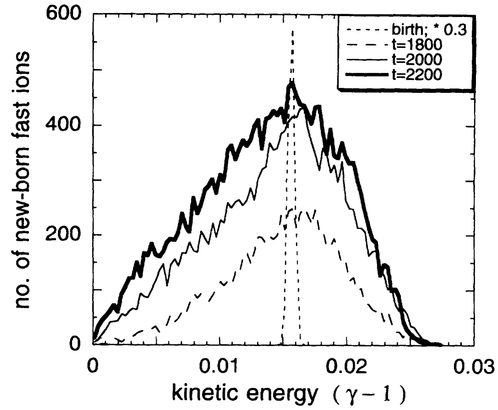

FIG. 6. The kinetic energy distribution of the newborn fast ions at birth, $t = 1800$, 2000, and 2200, respectively. They are added in right after $t = 1600$, 1700, 1800, 1900, and 2000, respectively, each time with a density of $1\times10^{-4}n_D$ and a shell distribution of $\gamma-1 = 0.0157$. The curve for the birth cases has been multiplied by 0.3.

calized and absolutely unstable. This feature indicates the existence of cyclotron eigenmodes and is being studied further. As far as the anomalous process, the simulation results are insensitive to the magnetic field nonuniformity.

The initial distribution used for the fast ions is valid for a burning plasma at its initial stage or for the plasma in the edge region [6–12] where fast ions are pushed out by MHD activity. Further numerical experiments were performed in order to determine whether this process may continually occur in a burning plasma. After the waves have saturated and the fast ions are thermalized, I add newborn fast ions into the system. In the first case, I add in newborn fast ions with density of $5\times10^{-4}n_D$ right after $t = 1600$. The simulation shows that all the previously observed anomalous phenomena occur for the newborn fast ions, within a shorter time scale of $200\omega_{cD}^{-1}$. In the second case, I gradually add in newborn fast ions at times right after 1600, 1700, 1800, 1900, and 2000, respectively, each time with the density of $1\times10^{-4}n_D$. Figure 6 shows the energy distribution of the newborn fast ions at different times. Again, all the previously observed anomalous phenomena—such as the large energy spread, the thermalized perpendicular momentum distribution, and the large density perturbation—occur for the newborn fast ions, in a shorter time. These simulation results imply that this process may continually occur in a burning plasma. Note that the rates of fusion reaction, ash removal, and collisions, as well as nonideal effects, should be taken into account in simulating a realistic device.

In summary, I have investigated the novel anomalous process that causes the perpendicular energy of fast ions to be thermalized and lost to bulk ion heating, which is highly favorable in a fusion device for the operation of the hot ion mode and for sustained ignition. There could be some additional favorable effects such as ash removal and the weakening of other instabilities, but also an unfavorable effect (the loss of some accelerated fast ions). More experiments that measure the fast ion energy distribution and correlate it with the cyclotron emission spectrum could confirm this anomalous process. Not only is this anomalous process important for fusion research, it may also serve in space and astrophysical plasmas as a means of thermalizing fast ions while accelerating some of them to even higher energy and as a mechanism for ion cyclotron emission.

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