Anomalous Ion Heating in Very Low q_a Discharges of the SINP Tokamak

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Impurity ion temperatures and their rate of rise were anomalously high ($T_i > T_e$) in the SINP tokamak having a high current density in a low toroidal magnetic field ($q_a \approx 1.5$). The dynamo effect, which is believed to explain the anomaly in such discharges of reversed-field pinch or ultralow q_a discharges of other tokamaks cannot account for our heating results. Large fluctuations in n_e, the potential and the magnetic field of frequency ($\omega/2\pi \sim 40-50$ kHz) which appeared during the ion heating indicate large amplitude drift-Alfvén waves existed in the plasma and caused the anomalous heating by fast stochastic processes. [S0031-9007(98)07363-3]

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Heating of ions in plasma is of substantial interest from the viewpoint of fusion reactor. In Ohmically heated and high-frequency–high-power rf heated tokamak plasmas, ions are usually heated classically by hot electrons through Coulomb collisions. As the energy confinement time is shorter than the thermal relaxation time between ions and electrons, T_i cannot get higher than T_e. This is commonly observed in all stable normal q_a tokamaks having an edge safety factor $q_a = aB_T/RB_\theta > 3$ (R and a are major and minor radii, B_T and B_θ are toroidal and poloidal magnetic fields).

The present experiment was done in the SINP tokamak by driving a large toroidal current I_P in a low B_T producing very low q_a (VLQ) discharges ($1 < q_a < 2$) where magnetic field lines are strongly twisted—a scenario favorable for the design of a compact fusion reactor because of its high energy density (high beta value) and high current density at a given B_T [1]. In this Letter we report the observation of an anomalously high temperature ($T_i > T_e$) of impurity ions (oxygen, carbon) for the first time in such discharges. We found that the heating rate also is anomalously high, at least about an order of magnitude higher than the classical heating rate. Previously, in the reversed-field pinches (RFP's) ($q_a < 0$) and more recently in the ultralow q_a (ULQ) discharges ($0 < q_a < 1$), where large I_P is driven in low B_T also, similar anomaly in ion temperature was seen [2], but nothing was mentioned about the rate of heating. In the VLQ discharges of REPUTE-1 an anomalous electron heating was seen [3], but no anomaly in T_i was reported. In all these devices MHD fluctuations associated with relaxation processes induce a dynamo electric field which is widely believed to be the cause of the anomalous heating mechanism [4]. In contrast, for the first time we show here that the anomalously high fast ion heating in the high I_P, low B_T discharges of the SINP tokamak is due to stochastic processes by drift-Alfvén waves. These results indicate that ion heating in the VLQ phase shows a unique characteristic and we contend that our results may be crucial to bridge the gap between the two types of magnetically confined toroidal high temperature plasma devices, RFP's and tokamaks, in regard to the understanding of ion heating.

The SINP tokamak [5] is a small iron core tokamak with $R = 30$ cm and $a = 7.5$ cm. It has a conducting shell of 7 mm thickness outside the SS vacuum vessel. Though it is operated in the normal q_a mode [6], it was relatively easy to access stable VLQ and ULQ discharges in this machine [7]. Typical plasma parameters were $I_P \approx 29$ kA, $B_T = 0.45$ T, $p(H_2) \approx 0.2-0.7$ mtorr, $T_e \approx 50$ eV, $n_e \approx 1-3 \times 10^{19}$ m^{-3}, and $(q_a)_{\min} \approx 1.5$. Discharges were highly reproducible and repeatable and a typical one is shown in Fig. 1.

Temperatures of impurity ions were determined from the Doppler widths obtained with a SPEX 1.26 m monochromator (Czerney-Turner type) having a $f/10$ optics and a photomultiplier tube (RCA C31034) and was set to view radially along a central chord. The entrance slit was focused to the plasma center by a lens yielding a spatial resolution of 5 mm. We measured the intensity profiles of O IV (373.7 nm), O III (376.0 nm),

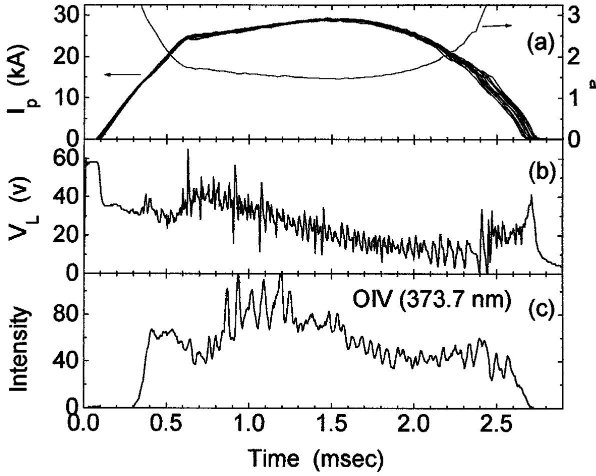

FIG. 1. Time history of typical VLQ discharges. $B_T = 0.45$ T, $p(H_2) \approx 0.2$ mtorr. (a) I_P and q_a (reproducibility is illustrated by overlapping I_P for 12 consecutive shots); (b) loop voltage (V_L); (c) intensity of O IV (λ373.7 nm) line.

O II (374.9 nm), O I (777.2 nm), and C III (464.7 nm) lines. In Fig. 1 the time evolution of O IV line is shown for a typical discharge. Wavelength scans were taken on a shot-to-shot basis taking advantage of the excellent reproducibility of the plasma shots. The reliability of the experimental results was established by repeating the scans at different machine times. (A total of 50 scans were taken.) Figure 2 shows the typical line profiles of the O IV line observed at different instants of time during the current rise phase. The line profiles are very well fitted with Gaussian curves. The instrument profile, also of Gaussian nature having a FWHM of 0.072 nm for 100 μm slits, was taken into account in determining the Doppler widths. Contributions to the line widths from natural and Stark broadenings or Zeeman effect were estimated and found to be negligible.

The temporal behavior of the temperatures of O I to O IV ions and C III ions are shown in Fig. 3, where we see that O IV, O III, and C III temperatures started rising from $t \approx 400$ μs, just after q_a crossed 3. q_a reached 2 around 520 μs. The $T_{\mathrm{O\,IV}}$ rose to a peak value of (240 ± 40) eV around 700 μs, thus yielding a rise rate of ~1 MeV/s. After this it dropped to ~170 eV in about 300 μs. It remained fairly constant until ~2.2 ms, when q_a rose to 2 again, then started dropping. The O III and C III temperatures reached a peak of about (130 ± 35) eV and (110 ± 20) eV, respectively, and showed a similar behavior, but the O I and O II temperatures stayed below 20 and 30 eV, respectively. So, the O IV, O III, and C III ions are evidently heated fast to anomalously high temperatures. The classical heating rate of ions (characteristic energy exchange time ~2 ms) is estimated to be 35 keV/s which is about 25 times lower than the observed heating rate. Energy confinement time is <50 μs.

In all the discharges discussed so far the I_P rose at the rate ≥50 MA/s initially, and then reached its peak gradually to 29 kA where $(q_a)_{\min} \approx 1.45$ was attained. To get a parametric dependence of impurity ion heating on I_P, we lowered the latter to 17 kA by lowering B_T (≈ 0.22 T) and loop voltage, but maintained the same $(q_a)_{\min}$. In the process, the dI_P/dt decreased by a factor of 3, but we still observed a high $T_{\mathrm{O\,IV}}$ though at a lower value ~100 eV. Furthermore, keeping $(q_a)_{\min}$ constant we increased the filling pressure from 0.2 to 0.7 mtorr. This decreased the dI_P/dt; however, $T_{\mathrm{O\,IV}}$ also reduced to (50 ± 30) eV [Fig. 6(b)] indicating much less heating at higher pressures. We also increased B_T to 1.2 T keeping other parameters constant to obtain normal q_a discharges with $(q_a)_{\min} \approx 4.5$. In this case the dI_P/dt dropped by a factor of 2 and the $T_{\mathrm{O\,IV}}$ stayed low, ~(30 ± 50) eV.

Since classical mechanisms could not explain the anomalous heating of the ions, we looked for some other processes that can directly heat the ions. So we deployed small electric and magnetic probes in the edge region ($r \approx 4$–7.5 cm) without disturbing the plasma current much in the rising phase. The profile of B_θ was measured with the magnetic probe (Fig. 4) from which the current density $j(r)$ was determined assuming a cylindrical geometry. The $j(r)$ profile was found to follow the $(1 - r^2/a^2)^n$ relation, where n was a fitting parameter (Fig. 4). The n jumped from 0.7 to 1.4 within 100 μs near $t = 400$ μs when T_i started rising. Current density estimated at this time was ≈100–150 A/cm^2. Electron density profile $n_e(r)$, measured using a triple Langmuir probe in this region, showed a steep rise at about the same time and the density scale length (L_n) changed from 1.5 to 1 cm (Fig. 5). Taking $n_e \approx 2 \times 10^{19}$ m^{-3} and $j \approx 100$ A/cm^2, the electron drift velocity $V_{De} = j/en_e \approx 3 \times 10^7$ cm/s, whereas electron thermal velocity $v_{\mathrm{th}e} \approx 2 \times 10^8$ cm/s using the measured $T_e \approx 10$ eV at $r/a \approx 0.8$. The Alfvén speed is 2.2×10^8 cm/s. Three well-known instabilities that are driven by the electron current under such conditions are the magnetosonic instability, the ion-acoustic instability, and the electrostatic ion-cyclotron instability. Magnetosonic instability cannot be excited in our case since the electron drift speed is much smaller than the Alfvén speed [8]. Ion acoustic instability is also not possible as $T_e/T_i < 1$ and this would lead to ion Landau damping of ion-sound waves. However, the electrostatic ion cyclotron instability can be excited even when $T_i > T_e$. But this requires [8,9] $V_{De} > V_{\mathrm{cr}} = 15(\frac{T_i}{T_e})v_{\mathrm{th}i}$. Taking

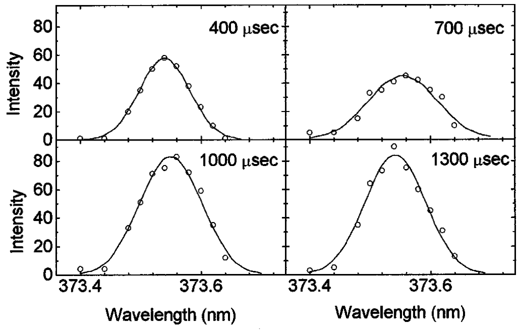

FIG. 2. Typical line profiles of the O IV (λ373.7 nm) line at different times of the VLQ discharge. Open circle: experimental points; solid line: fitted Gaussian curves.

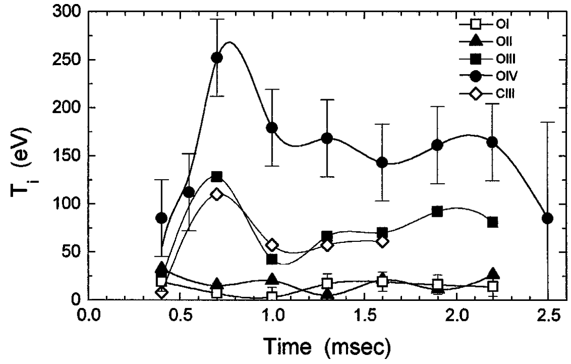

FIG. 3. Temporal behavior of the temperatures for different ions, $p(H_2) \approx 0.2$ mtorr. (Discharge condition same as in Fig. 1.)

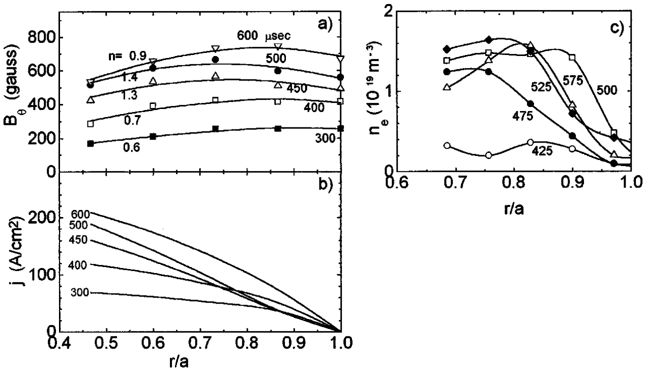

FIG. 4. $B_\theta(r)$, $j(r)$, and $n_e(r)$ vs r in the outer region at different times. (a) B_θ—symbols: experimental data points; solid lines: fitted lines assuming $j(r) = j_0(1 - r^2/a^2)^n$; (b) $j(r)$; (c) n_e—symbols: experimental data points, solid lines: interpolated.

$T_{\mathrm{O\,IV}} \approx 200$ eV, $V_{\mathrm{cr}} \approx 3 \times 10^8$ cm/s. So none of the above instabilities can contribute to the ion heating.

In LT-1 tokamak [10] rapid ion heating coincident with strong current inhibition was observed at disruptive instabilities (marked by large negative spikes in loop voltage) and was attributed to the excitation of ion cyclotron drift waves [11] by the high electric field seen at the instabilities. In our experiment neither such voltage spikes nor any strong increase in resistivity during ion heating was observed.

In RFP and ULQ plasmas, dynamo action is believed to play an important role for the anomalous behavior of plasma resistance, transport, and ion temperature [4]. It has been shown that a dynamo electric field is induced by current driven instabilities associated with magnetic field reconnections during MHD relaxation. Generally an ion viscous dissipation that results from the magnetic pumping induced by the dynamo field is considered. In Ref. [4] for a collisionless plasma the transit time damping is shown to yield a large parallel ion viscosity and an estimate is given for the dissipation power density directly going to ions. Experimentally from our internal magnetic probe data we found the peak $(\tilde{B}_\parallel/B_T) \approx (0.2\text{–}1)\%$, where $\tilde{B}_\parallel$ is the parallel component of the fluctuating magnetic field. Putting $T_{\mathrm{O\,IV}} \approx 200$ eV, $k_\parallel^{-1} \sim qR \approx 0.6$ m, $n_{\mathrm{O\,IV}} \sim 10^{18}$ m^{-3}, we get this power density $\sim 10^{-4}$ MW/m^3 which is much less than the power density of 2 MW/m^3 required to maintain such high O IV temperature in SINP tokamak.

Floating potential fluctuation $\tilde{\phi}_f$ was measured using a radial Langmuir probe array. An enhanced level at a frequency of ~40–50 kHz was seen in all the probes in the region $r \approx 5$ to 7 cm. A typical signal is shown in Fig. 5(a), where we extracted the frequency component in the band of 35–60 kHz from the observed signal by using an ideal filter method based on the fast Fourier transform [12]. It is interesting to note that the fluctuation amplitude increased substantially at about the same time when we observed strong ion heating. Similar behavior was seen in the fluctuation signals $\tilde{n}_e$ [Fig. 5(b)] and $\tilde{T}_e$ of the Triple probe. As stated earlier, a steep gradient developed on the n_e profile at about the same time. All these observations pointed to a pressure gradient driven drift-wave propagating in the poloidal direction which may be strongly excited in the VLQ discharges of the SINP tokamak. During the ion heating phase the amplitude of the fluctuation in the plasma potential, ϕ_o was 12–22 V correcting for the temperature fluctuations, whereas the peak $\tilde{n}_e/n_e$ was ~35%. The measured value of $k_\perp$ is ≈3–3.5 cm^{-1} as reported earlier in this tokamak [5] in the edge region. This also agrees to the estimated value of ~3 cm^{-1} from a saturation turbulence level at $\tilde{n}/n_e \approx 1/(k_\perp L_n)$ as predicted by several drift-wave theories [13]. In addition to the $\tilde{n}$ and $\tilde{\phi}_f$ we observed fluctuations in the B_θ signals inside the plasma and their characteristics were similar [Fig. 5(c)].

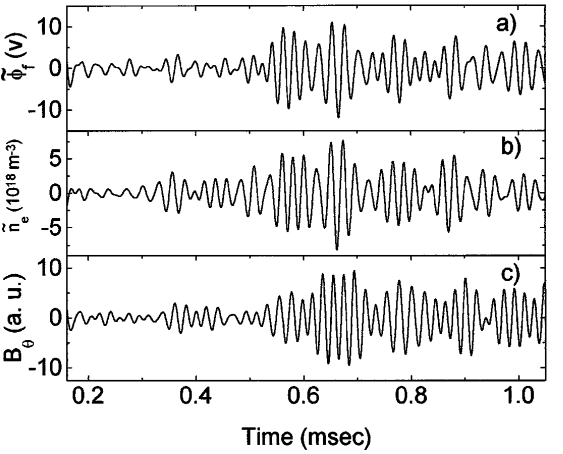

FIG. 5. $\tilde{\phi}_f, \tilde{n}_e$ ($r = 6.7$ cm) and $\dot{B}_\theta$ ($r = 7.0\text{–}7.5$ cm) in the VLQ discharge condition when the anomalous ion heating was observed (35 kHz $< \omega/2\pi <$ 60 kHz). Trace (c) was obtained from a different, though similar, discharge from traces (a) and (b).

Drift waves commonly observed in tokamaks, propagate at electron diamagnetic drift velocities, perpendicular to the magnetic field and the pressure gradient. However, they also propagate parallel to the magnetic field (with $k_\parallel \ll k_\perp$), having substantial magnetic fluctuations, when parallel drift wave velocity becomes comparable to the Alfvén velocity [14], i.e., $\omega/k_\parallel \sim v_A$. In our case $\omega/k_\parallel$ turns out to be $\sim 0.2 \times 10^8$ cm/s, not too far from $v_A \sim 2 \times 10^8$ cm/s. So drift-Alfvén oscillations is possibly excited in the SINP tokamak that gave rise to the above fluctuations in B_θ. The measure of coupling of drift waves to the Alfvén waves may be given by [15] the ratio of the inductive and the electrostatic components of the parallel electric field, i.e., $\omega\tilde{A}/(ck_\parallel\phi_0)$, where $\tilde{A}$ is the amplitude of parallel vector potential of $\tilde{B}_\theta$. Equivalently, the strength of coupling $f = \omega\tilde{B}_\theta/k_\parallel\frac{\partial\phi_o}{\partial r}$. $f = 0$ corresponds to the pure electrostatic drift mode. Observed $\tilde{B}_\theta/B_\theta \geq 1\%$ and $\frac{\partial\phi_o}{\partial r} \approx 5$ V/cm gives $f > 0.2$. So, the coupling is reasonably strong. The $\tilde{\phi}$ was seen to lead the $\tilde{n}$ by a phase difference of about 90° [Fig. 5]. This, according to linear theory, can destabilize drift waves, and from the growth rates [14], we could deduce that these waves were strongly current driven rather than by electron Landau damping. This is supported by the observation that as I_P was lowered the fluctuation amplitudes also decreased. The frequency of the waves is given by [14]

$$\omega = -\frac{1}{1 + k_\perp^2 \rho_s^2} \frac{k_\perp T_e}{m_e \omega_{ce}} \frac{dlnn_e}{dx},$$

where $\rho_s = c_s/\omega_{ci}$ and c_s is the ion sound speed. Taking $T_e \approx 10$ eV, $B_T = 0.45$ T, $(dlnn_e/dr) \approx (1 \text{ cm})^{-1}$ we get $\omega/2\pi \approx 100$ kHz which agrees reasonably well with the observed frequency ~40–50 kHz in potential, density, and the magnetics considering the uncertainties in the values of $k_\perp$ and T_e.

So it seems in our plasma current driven drift-Alfvén waves exist with large amplitude. It is well known that motion of ions in a strong magnetic field may become stochastic [16] in the field of electrostatic waves whose amplitudes are so large that the ion displacements caused by polarization drift become comparable to the wavelength of the mode. In that case the particles traverse a large region of phase space resulting in broadening of the particle distribution. Experimentally, stochastic particle motion has been reported in few low temperature, low current plasmas [17,18], and computer simulations demonstrated such heating [19]. The condition on wave amplitude is given by [16] $\alpha = m_i \phi_0 k_\perp^2 / q B_0^2 \sim 1$, where q $(= Ze)$ is charge of the ion. Putting in the relevant values of the discharge condition of Fig. 6(a) where we have plotted $\tilde{\phi}_f$ and $T_{\mathrm{O\,IV}}$ in a low pressure discharge we get $\alpha \sim 0.3$–0.5 for O IV ions, ~ 0.4–0.8 for O III ions, and ~ 0.3–0.6 for C III ions. So the anomalous heating of the ions may be due to stochastic heating. As seen in the figure $T_{\mathrm{O\,IV}}$ rose to 200 eV here. There seems to be a threshold value of α above which such heating occurs. This is demonstrated in Fig. 6(b) where we plotted $\tilde{\phi}_f$ and $T_{\mathrm{O\,IV}}$ for a high pressure discharge. For this case $\phi_o < 5$ V, so $\alpha < 0.1$ and observed $T_{\mathrm{O\,IV}}$ was also very low.

In the presence of low frequency waves ($\omega < \omega_{ci}$) an estimate of the ion temperature due to stochastic heating is given as [17]

$$T_i = m_i[(k_\perp \phi_o / B_T)^2 + (\omega_{ci}/k_\perp)^2].$$

Using the parameters of VLQ discharges in Fig. 6(a) we get $T_{\mathrm{O\,IV}} \sim 135$–$160$ eV and $T_{\mathrm{O\,III}} \sim 65$–$90$ eV which are in reasonable agreement with the experimental values. Observation of lower temperature for lower ionization stage is explained from the above equation where Z dependence is clearly seen in the ion cyclotron frequency term. Time scale of this heating method is of the order of the wave period which is few tens of μsec. So the heating rate is quite fast and agreed to the results of the experiment.

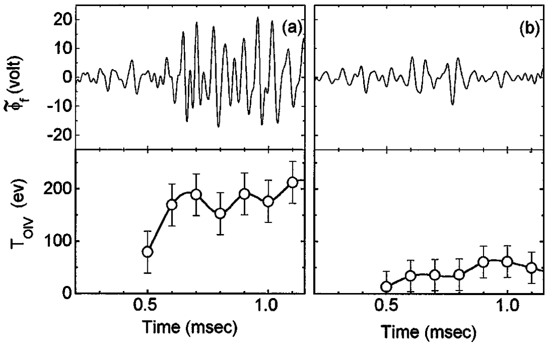

FIG. 6. $\tilde{\phi}_f$ and $T_{\mathrm{O\,IV}}$ for two discharge conditions are shown: (a) $p(H_2) \approx 0.5$ mtorr, $\alpha \approx 0.3$–0.5; (b) $p(H_2) \approx 0.7$ mtorr, $\alpha < 0.1$. Here α dependency on ion heating is clearly demonstrated.

The present experiment poses an important question: whether a drift-Alfvén wave in VLQ discharges becomes dynamo fluctuations when q_a is lowered as in RFP and ULQ or it converts into drift waves in normal q_a discharges, and, if it is, then how.

In conclusion, we have observed for the first time an anomalously high impurity ion heating in VLQ discharges where a large plasma current is driven in low toroidal magnetic field. The heating rate was also found to be anomalously high. The experimental results are explained by the stochastic heating of ions by the observed large amplitude drift-Alfvén waves driven by the high current.

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