Ion Temperature and Hydrodynamic-Energy Measurements in a *Z*-Pinch Plasma at Stagnation

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The time history of the local ion kinetic energy in a stagnating plasma was determined from Doppler-dominated line shapes. Using independent determination of the plasma properties for the same plasma region, the data allowed for inferring the time-dependent ion temperature, and for discriminating the temperature from the total ion kinetic energy. It is found that throughout most of the stagnation period the ion thermal energy constitutes a small fraction of the total ion kinetic energy; the latter is dominated by hydrodynamic motion. Both the ion hydrodynamic and thermal energies are observed to decrease to the electron thermal energy by the end of the stagnation period. It is confirmed that the total ion kinetic energy available at the stagnating plasma and the total radiation emitted are in balance, as obtained in our previous experiment. The dissipation time of the hydrodynamic energy thus appears to determine the duration (and power) of the *K* emission.

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The thermalization of accelerated fluids and the dissipation of hydrodynamic motions are fundamental problems manifested in a variety of fluid phenomena in laboratory plasmas and astrophysics [1–3]. In particular, high-energy-density plasmas are commonly characterized by 3D flows involving shock waves and turbulence. Examples are imploding plasmas (where an accelerated plasma undergoes collisions) or plasmas interacting with high power lasers (where fast plasma heating, ablation, and compression occur). Information on electron and ion temperatures in plasmas is crucial for the analysis of various processes, e.g., for evaluating the fusion rates in fusion plasmas or the rates of heat transfer in nonequilibrium plasmas. Thus, it is of paramount importance to develop experimental methods for the discrimination between the thermal and the hydrodynamic kinetic energies. It is known [4] that in turbulent plasmas it is difficult, if not impossible, to determine the ion temperature from Doppler broadening of ionic spectral lines due to the difficulty in discriminating between the contributions of the thermal and the random hydrodynamic motion to the line shapes. In *Z*-pinch experiments [1,3], the plasma kinetic energy gained from the magnetic-field energy during the implosion is converted, as plasma stagnates on axis, to particle heating, ionization, and radiation emission. It is commonly believed [1] that the ions accelerated in the imploding plasma rapidly thermalize at stagnation (at the ion-ion collision time τ_{ii}), then deliver their thermal energy to the electrons (at a time τ_{ie} of the ion-energy loss to electrons), followed by the loss of the electron heat (through ionizations and excitations) to radiation. However, this process is known to be highly complex [1,3] due to MHD phenomena and the radiation emission involved. In addition, there is the potential of further energy deposition, at the stagnating plasma, due to Ohmic heating or magnetic-energy dissipation through various mechanisms [1,5,6]. Progress in experimental investigations of the plasma thermalization at stagnation is thus highly needed.

The electron temperature and the charge states in the stagnating plasma have been commonly determined from

K and L emission [3]. In this Letter the determination of the ion temperature is addressed. Investigations of ion velocities from Doppler contributions to K lines were reported in a few studies [5,7,8]. Recently [7], Doppler-dominated shapes of optically thin K lines from the stagnating plasma were recorded for a single instant throughout the stagnation period, yielding the total kinetic energy of the ions in the plasma. Together with the determined plasma properties, the data allowed for concluding that the total kinetic energy of the ions ($\mathcal{E}_k^{\rm tot}$) assembling in the plasma is sufficient to provide the entire radiation emitted from the plasma. However, while those results yielded a detailed quantitative energy balance in the plasma, based on the observed $\mathcal{E}_k^{\rm tot}$, they did not give information on the ion temperature.

Here, the ion velocity distribution is determined similarly to the previous work [7]; however, the measurements allow for recording four distributions (integrated over ≈ 1 ns) throughout the stagnation period in a single discharge. The data thus reliably yielded the history of the ion velocity distribution throughout the stagnation. As in the previous experiment [7], in the present experiment with higher current and shorter implosion time, the total kinetic energy per ion in the plasma (denoted by $E_{k,\rm ion}^{\rm tot}$) is seen to drop down to about the electron thermal energy, and $\mathcal{E}_k^{\rm tot}$ is found to account for the total radiation. However, in the present experiment the history of the total kinetic energy per ion, together with an independent study of the local and time-dependent stagnating plasma properties and the assessed energy balance, allow for (i) determining the ion temperature and (ii) concluding that early in time $E_{k,\rm ion}^{\rm tot}$ is significantly dominated by a hydrodynamic motion rather than by heat. This motion dissipates into ion heat during the stagnation period, until $E_{k,\rm ion}^{\rm tot}$ (and the ion temperature) drop down to about the electron temperature.

In the present experiment a neon puff ($\approx 70\ \mu$g/cm and 9 mm long), similar to that described in [9], with an initial diameter of 38 mm [7], is imploded in 500 ns under a current pulse that rises to 500 kA at the stagnation time. The line emission used to obtain the ion velocity distribution in the stagnating plasma is the singlet Ly$_\alpha$ satellite ($2p^2\ ^1D_2$–$1s2p\ ^1P_1$). This line has a Doppler-dominated shape since it is optically thin (as verified by the kinetic modeling described below), with negligible effects of Stark or Zeeman broadenings. An essential feature of the diagnostic system is the high spectral resolution ($\lambda/\Delta\lambda \approx 6400$) that is required to track the ion kinetic energy down to the level of the electron temperature. The spectrograph used was based on a spherical potassium acid phthalate (KAP) crystal, verified using double-crystal diffractometer measurements to have a Lorentzian spectral response of a 1.8 mÅ width, when focused on the neon Ly$_\alpha$ $n = 2$ satellites. This broadening, together with the autoionization rate ($3.7 \times 10^{14}\ {\rm s}^{-1}$) of the satellite upper level, give for the measurement a Lorentzian spectral response of 5.1 mÅ.

The spectra were viewed in the radial direction, and the spherical shape of the crystal allowed for both obtaining spectra imaged along the z axis and for collecting sufficient number of photons. The imaging of the spectra along the pinch column allowed for a separate data analysis for each Δz segment. Because of the common nonuniformities along the column, this feature, together with targeting all other spectroscopic observations to the same Δz segment, was essential for reaching the conclusions here stated (in this Letter all data given are for the $\Delta z = 4$–6 mm segment). Finally, an image dissector [10] that splits the spectrograph image into four identical images is coupled to a four-gated microchannel plate detector for recording the spectrum at four gated times (≈ 1 ns) in a single discharge.

Images of the Ly$_\alpha$ satellites are shown in Fig. 1(a). It is seen that the spectra at $t \leq -3$ ns (where $t = 0$ ns represents the time of the peak K-emission signal) show the ion motion has a significant radial component demonstrated by Doppler splitting. Assuming ion radial flow, the line shape (interpreted as radial velocity distribution, after deconvolving the negligible contribution of the spectral response) is integrated to yield the total kinetic energy per ion $E_{k,\rm ion}^{\rm tot}$. This is used to define an ion effective temperature $T_i^{\rm eff} = \frac{2}{3}E_{k,\rm ion}^{\rm tot}$ for $t \leq -3$ ns, indicated in Fig. 2 (yielding a mean velocity of 2.3×10^7 cm/s for the ion radial velocity at the earliest stage of the stagnation).

Later in time, the line shape appears to be nearly Gaussian. Thus, these shapes are fitted by convolving a Gaussian shape, that represents a quasi-isotropic hydromotion, with the Lorentzian spectral response of the system. The Gaussian contributions thus obtained are used to define $T_i^{\rm eff}(t)$ (also here $\frac{3}{2}T_i^{\rm eff} = E_{k,\rm ion}^{\rm tot}$, assuming the ion motion is quasi-isotropic at this period), as given in Fig. 2. It is seen that $T_i^{\rm eff}(t)$ drops continuously in time, with an e-folding time of ≈ 3 ns.

The analysis of the energy balance and the ion-electron energy relaxation time requires information on the histories of the mass, electron temperature, and ion composition of the radiating plasmas described in detail in Ref. [7]. In brief, the line shapes are also used to obtain the time-resolved electron density n_e of the H-like plasma, based on the n_e dependence of the triplet-satellite intensity ratio [11]. The absolute, time-dependent value of the total K radiation from the $\Delta z = 4$–6 mm pinch segment (25 ± 8 J) was obtained using an absolutely calibrated photoconductive detector (PCD) [7], and the radius of the K-emitting plasma (of this segment) was obtained from four-frame (1-ns gates with 1.5-ns interframe time) filtered pinhole photography. It was seen to rise from ≈ 0.2 mm at $t \approx -3.5$ ns to a peak value ≈ 0.45 mm at $t \approx 0$.

The properties of the stagnating plasma are obtained from the measurements described above with the aid of

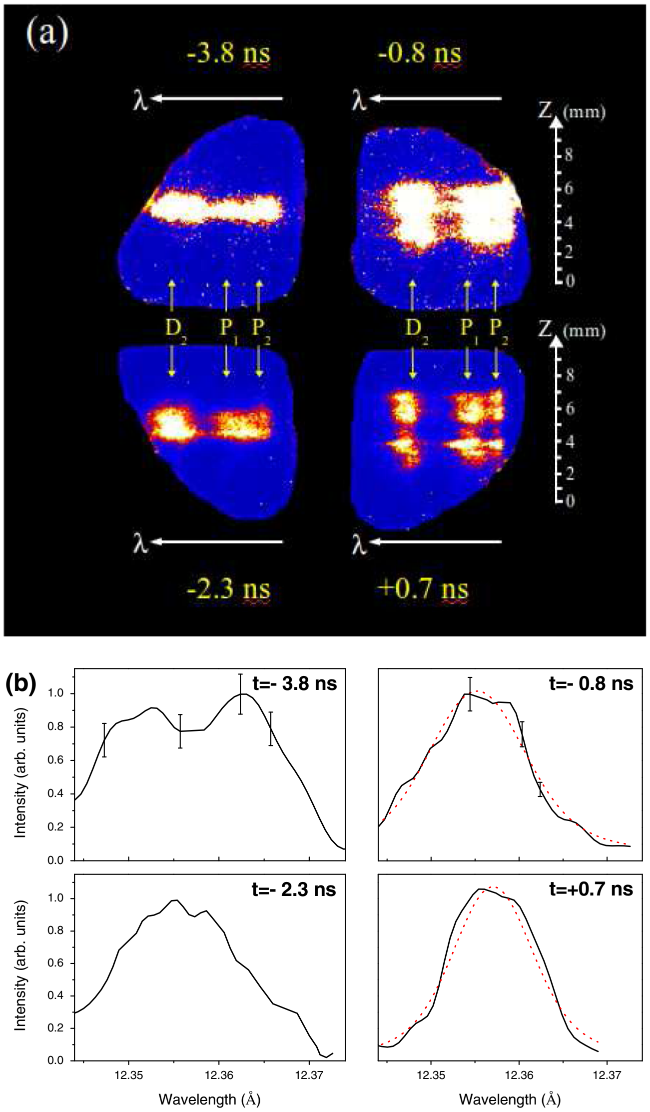

FIG. 1 (color online). (a) A CCD image of the Ly$_\alpha$ $2p^2$ singlet (^1D) and the triplet ($2p^2\ ^3P$ and $2s2p\ ^3P$) satellites (marked by the arrows D_2, P_1, P_2, respectively) imaged in the z direction, recorded in a single discharge at four gated times relative to the peak K-emission signal. The cathode and anode surfaces are located at $z = 0$ and $z = 9$ mm, respectively. (b) Spectra of the Ly$_\alpha$ D_2 satellite integrated over $\Delta z = 4.8$–5.2 mm at the four gated times shown in (a). A best fit of a Gaussian convolved with the Lorentzian instrumental response is given for $t = -0.8$ ns and for $t = +0.7$ ns.

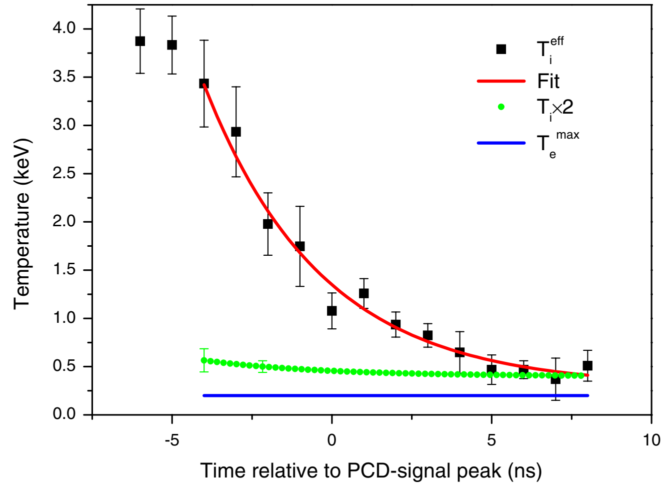

FIG. 2 (color online). The measured ion effective temperature, obtained from the measured line shapes, where each data point is an average of 2–5 identical discharges, together with the true ion temperature, calculated using Eq. (2).

the following modeling [12]: the stagnating plasma is assumed to be a uniform cylinder with a radius $R(t)$, an electron density $n_e(t)$, and an electron temperature $T_e(t)$. Our time-dependent collisional-radiative calculations account for the radiation transport self-consistently. They are used for the determination of the time-dependent level populations, optical coefficients, and radiation flux onto each of the detectors. For the emissivity and opacity we use spectral line shapes based on the observed Doppler broadening. For $R(t)$ in the modeling we use the pinhole photography data, and for $n_e(t)$ we use the value determined from the Ly$_\alpha$ satellite-intensity ratios, found to be nearly constant (as in the previous experiment [7]), $(6 \pm 3) \times 10^{20}$ cm^{-3}, for $t \geq -2$ ns. For $T_e(t)$, as an input parameter, we use a smooth function that rises and drops during the stagnation period, as confirmed in the previous experiment, based on the analysis of the time-dependent K-radiation and free-bound continuum [7]. The peak value of $T_e(t)$ is further confirmed by comparing the time-integrated continuum slope obtained from the modeling to the measured one. Also in the modeling, n_e and $R(t)$ are repeatedly varied within the measurement uncertainties, in order to obtain best fits to absolute time-dependent K-emission and continuum signals, as well as to the absolute time-resolved satellite intensities. The modeling yields that $T_e(t)$ in the H-like plasma rises from a value of ≈ 110 eV at $t = -4$ ns, peaks at ≈ 200 eV ($T_e^{\max}$) at $t \approx 0$ ns, and then drops to 70–120 eV at $\approx +6$ ns. As given by the modeling, the K-emitting-plasma mass rises up to $t \simeq 0$, reaching 8 ± 2 μg/cm. The time dependence of T_e and of the charge-state distribution obtained by the modeling are also used to estimate the change in the ionization energy and the electron thermal energy. This yields a drop in these energies of 0.6 ± 0.7 keV/ion during the K emission, plausibly assumed to be converted to the K radiation. These inferred quantities allow us to assess the energy balance, similarly to the procedure described in [7]. In brief, using the measured ion-energy drop (Fig. 2), and estimating the change in the internal energy in the stagnating plasma, yields that the total energy available for radiation is 4.4 ± 1 keV/ion. Multiplying this value by the number of ions in the K-radiating plasma in the $z = 4$–6 mm segment of the pinch, gives 29 ± 6 J, which is in agreement with the total K and soft emission, 34 ± 10 J, from this plasma section, obtained from the

PCD measurements and the kinetics modeling (as in Ref. [7]). Thus, based on the modeling above it is found, as in the previous experiment [7], that $\mathcal{E}_k^{\rm tot}$ available at stagnation accounts for the total radiation output. Also from the modeling above, in most of the stagnation period, the K-emitting plasma is dominated by H-like ions, so that the average quantities obtained from the H-like ion transitions and from the free-bound emission above the H-like edge accurately reflect the stagnating plasma dynamics.

In the following we assume that the ions in the stagnating plasma lose their kinetic energy only to electrons (this assumption is shown below to have no effect on the conclusion to be drawn). Using n_e in the plasma the Spitzer ion-ion collisional-thermalization time $\tau_{\rm ii}$ in our nearly ideal plasma is ≈ 2 ps (the ion mean free path is ≤ 1 μm), and that of the ion-thermal-energy loss to electrons, using $T_e^{\rm max}$, is $\tau_{\rm ie} \approx 0.1$ ns. Thus, the time of the ion-kinetic-energy loss to electrons is observed to be much longer (≈ 3 ns) than the expected time (≈ 0.1 ns). In principle, the apparent slow drop of the ion kinetic energy could be explained by the continuous flow of the accelerated ions into the stagnating plasma, consistent with the rise of the plasma mass. However, modeling the continuous flux of the imploding plasma into the stagnation region as observed in the experiment, assuming the entire ion kinetic energy is thermal, and thus is lost to the electrons in $\tau_{\rm ie} \approx 0.1$ ns, contradicts the data. Such a short $\tau_{\rm ie}$ results in a kinetic energy that, averaged over the plasma, is much smaller than the observed one during most of the stagnation duration. This is rather expected, since if $E_{k,\rm ion}^{\rm tot}$ were thermal, then at each instant t, only the ions assembling at the time interval between $t - \tau_{\rm ie}$ and t are energetic (where the rest have already lost their energy). Since the ion energy loss to electrons is determined by the temperature difference between the two fluids, we suggest that the slow drop of $E_{k,\rm ion}^{\rm tot}$ results from the domination of the ion kinetic energy by hydrodynamic motion $E_{k,\rm ion}^{\rm hydro}$ rather than by an ion temperature T_i. Under this picture, the energy of hydrodynamic motion continuously dissipates (with a relatively slow time scale ≈ 3 ns) into ion heat (followed by ion-heat dissipation into electron heat in $\tau_{\rm ie} \approx 0.1$ ns), namely,

$$\frac{d}{dt}T_i = -\frac{T_i - T_e}{\tau_{\rm ie}} - \frac{2}{3}\frac{dE_{k,\rm ion}^{\rm hydro}}{dt}. \quad (1)$$

Using $T_i^{\rm eff} = \frac{2}{3}E_{k,\rm ion}^{\rm tot} = T_i + \frac{2}{3}E_{k,\rm ion}^{\rm hydro}$ we obtain

$$\frac{d}{dt}T_i^{\rm eff} = -\frac{T_i - T_e}{\tau_{\rm ie}}. \quad (2)$$

Equation (2) can thus be used to obtain the true T_i from the measured $T_i^{\rm eff}$ and $\tau_{\rm ie}$ obtained from the determined T_e and n_e. Evidently, the slow dissipation of $T_i^{\rm eff}$, and the faster ion-heat loss to electrons, results in T_i that is much lower than $T_i^{\rm eff}$. $T_i(t)$ obtained from Eq. (2) [using $T_e^{\rm max}$, which gives an upper limit for $T_i(t)$] is shown in Fig. 2. It is seen that early in the stagnation (at $t \leq -2$ ns), $T_i \approx \frac{1}{10}T_i^{\rm eff}$, where both $T_i^{\rm eff}$ and T_i decay to about T_e at the end of the stagnation (as found in [7]). Thus, our measurements of $T_i^{\rm eff}(t)$ allow for discriminating between the thermal and the hydrodynamic ion kinetic energies.

We note that Eq. (2) assumes that the entire loss of $T_i^{\rm eff}$ is to electrons (i.e., to radiation), which is justified based on the finding (see above) that the total radiation output can be explained by the loss of $\mathcal{E}_k^{\rm tot}$ in the plasma. It should be emphasized, however, that the conclusion that T_i is significantly smaller than $T_i^{\rm eff}$ appears to be independent of this assumption and valid under various plausible scenarios. For example, it has been often considered [6] that energy can be deposited in the stagnating plasma due to Ohmic heating or due to dissipation of magnetic-field energy. If this additional energy is deposited into the electron fluid (and thus to radiation), it means that the ions must lose only a fraction of their energy to electrons (where the rest of the energy must be lost through other mechanisms), otherwise the radiation output would exceed the observed value. An ion-kinetic-energy loss to electrons over the stagnation period that is less than $E_{k,\rm ion}^{\rm tot}$ means that the ion temperature is even lower than in Fig. 2, based on Eq. (2). On the other hand, if this additional energy is deposited into the ion fluid, then ions should lose this additional energy through other channels rather than to electrons, otherwise, again, the radiation output would exceed the observed value. Thus, the low value of T_i inferred here must still be valid, in order for the ion-energy delivered to radiation to agree with the radiation output. We also note that in assuming a quasi-isotropized ion motion for $t \geq -3$ ns, we obtained the maximum value for $E_{k,\rm ion}^{\rm tot}$, thus inferring the maximum value for T_i.

Evidently, the nature of the hydrodynamic motion that dominates the ion kinetic energy at stagnation is not clear as yet. The 3D flow involved in the transition of the radial-implosion motion into hydromotion at stagnation and then to ion heating requires detailed modeling. Also, to examine the generality of the findings here described, future measurements would be useful in wire-array implosions or other gas-puff configurations.

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