Determination of the ion temperature in a high-energy-density plasma using the Stark effect *

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We present experimental determination of the ion temperature in a neon-puff Z-pinch [1]. The diagnostic method is based on the effect of ion coupling on the Stark lineshapes. It was found, in a profoundly explicit way, that at stagnation the ion thermal energy is small compared to the imploding-plasma kinetic energy, where most of the latter is converted to hydromotion. The method here described can be applied to other highly non-uniform and transient high-energy-density (HED) plasmas.

The conversion of the kinetic energy of accelerated plasmas to ion heating, resulting in radiation emission or in nuclear fusion, is of fundamental interest in the field of HED plasmas, and has general implications for laboratory and astrophysical plasma research. Of particular importance is determination of the ion thermal energy, addressed here.

In a stationary plasma, the ion temperature is associated with the spread of the kinetic energy per ion K_i. The latter is manifested in the Doppler broadening of spectral lines emitted or, in the case of fusion plasmas, in a respective spread of the energy spectra of neutrons and other products of the fusion reactions. However, for plasmas formed in the process of implosions, both thermal *and* hydrodynamic motions contribute to K_i. Therefore, the *apparent* ion Doppler pseudo "temperature" $T_i^D = \frac{2}{3}\langle K_i \rangle$ may be a significant overestimation of the *true* ion temperature T_i. In an imploding plasma the electron temperature T_e cannot be assumed to represent T_i, either: the radial kinetic energy is first transferred to T_i and then to T_e. Thus, $T_e < T_i < T_i^D$ until the plasma fully thermalizes.

Here we present direct measurements of T_i in a HED plasma, requiring only localized instantaneous spectroscopic data. The underlying physical phenomenon is the ion-temperature dependence of the Stark profile of certain lines in moderately coupled plasmas.

We demonstrate this approach by measuring T_i at the stagnation phase of a neon-puff Z-pinch, where the $T_e < T_i < T_i^D$ inequality holds. In our Z-pinch system stagnation lasts a few nanoseconds, during which the plasma is characterized by electron density and temperature $\lesssim 10^{21}\text{cm}^{-3}$ and ~ 200 eV, respectively. These parameters are also typical for the measurements described here.

Stark line broadening is widely used for plasma diagnostics. The Stark width depends strongly on the plasma density (typically, between $\propto N_e^{2/3}$ and $\propto N_e$); this is true for broadening due to plasma electrons and ions alike. Contrary to that, the temperature dependence is rather weak and sometimes non-monotonous. Furthermore, the electron and ion contributions may have opposite tendencies resulting in a nearly complete cancellation over a wide temperature range. Consequently, the Stark diagnostics is typically perceived synonymous to the density diagnostics. However, if N_e and T_e are known with a sufficient precision independently of the lineshape measurements, then even the moderate Stark-width sensitivity to T_i can be used to infer the latter; this approach is used in the present study.

The static Stark effect in a hydrogen-like atom is proportional to the electric field F. In a plasma, the charged particles form a microfield distribution around the typical field value that depends on the density N_p and charge q_p of the plasma particles as $\propto |q_p| N_p^{2/3}$. This distribution is sufficient for evaluating the plasma broadening by the plasma ions when their Stark effect can be described in the quasistatic approximation. Furthermore, the electron broadening is usually smaller than that due to the ions, because of the dynamical nature of the electron perturbation and the larger ion charge. Thus, the broadening of these lines is mainly determined by the ion microfield distribution.

In an ideal plasma, the microfield distribution is a universal Holtsmark function that is independent of temperature. However, Coulomb interactions between the particles modify the Holtsmark distribution, due to the Debye screening and the repulsion between the ions and the positively charged radiators, resulting in a decrease of the Stark broadening.

The Debye screening influences the ion fields at large distances ($r \gtrsim \lambda_{D,i}$, where $\lambda_{D,i}$ is the ion Debye length), while the Coulomb repulsion is only important at short distances ($r \lesssim r_{m,i}$, where $r_{m,i} = q_i^2/T_i$ is the classical distance of minimal approach). In a weakly non-ideal plasma the double inequality $r_{m,i} \ll r_i \ll \lambda_{D,i}$ holds, where $r_i = (4\pi N_i/3)^{-1/3}$ is a typical inter-ion distance; since the line width is mostly affected by microfields formed by ions at distances $\sim r_i$, the ion-temperature corrections in such a plasma are minor and the respective effect on the line broadening is small. However, the more non-ideal the plasma is (characterized by the ion–ion coupling parameter $\Gamma_{ii} = q_i^2/(r_i T_i)$), the stronger the corrections become.

As an example, Fig. 1 shows the width of Ne X Ly-δ, calculated using a computer simulation, as a function of Γ_{ii} for a few values of the electron density at a fixed electron temperature. It is seen that for each density, there is a range of Γ_{ii} where the dependence of the Stark width on it and

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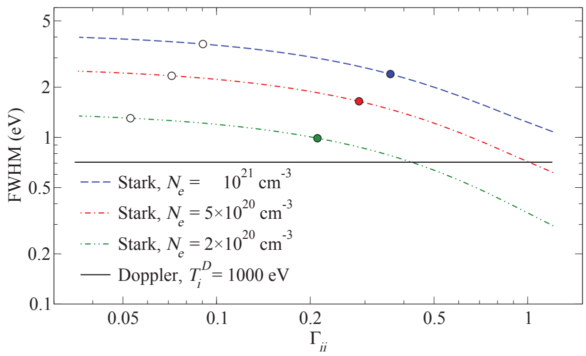

Figure 1: Ne X Ly-δ Stark width as a function of Γ_{ii}, assuming three values of the electron density and a constant $T_e = 250$ eV. The filled and opaque circles correspond to $T_i = T_e = 250$ eV and $T_i = T_i^D = 1000$ eV, respectively. Also shown is the Doppler broadening.

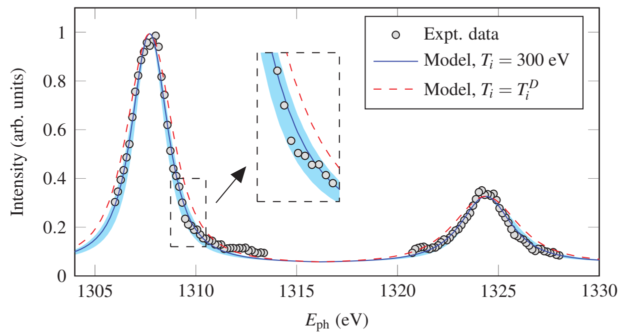

Figure 2: The experimental high-n spectra are compared to lineshape modeling for two values of T_i assumed: $T_i = 300$ eV and T_i^D. $T_i^D = 900$ eV, $N_e = 6 \times 10^{20}$ cm^{-3}, and $T_e = 200$ eV are assumed in both cases. The shaded area designates a spread of modeled spectra for T_i varying between 150 eV and 450 eV.

hence, on the ion temperature can be used for determination of T_i: for too high T_i (weakly coupled plasma) the Stark broadening is not sensitive to T_i, and for low T_i the Stark contribution becomes comparable or even smaller than the Doppler width, especially for lower plasma densities.

The x-ray output from the stagnating plasma is recorded by a $\gtrsim$ 700-eV-filtered photoconductive detector (PCD). The $t = 0$ time is defined as the time of the peak PCD output. The spectroscopic system includes three spherical crystals, recording the Ly-α satellites and the high-n Ly-δ and Ly-ϵ. Each spectrometer allows for imaging the spectra along the Z-pinch axis with a resolution of $\lesssim 50\ \mu m$. The Ly-α satellite spectra are recorded with a 2nd-order spherical KAP crystal. Combined with collisional-radiative (CR) modeling, the spectra provide the time-resolved electron density and the total (thermal and hydro) ion velocities at any z position. Ly-δ and Ly-ϵ are recorded independently using two spherical 4th-order mica crystals. In the analyses below, we show the z-averaged spectra from an axial slice of $\Delta z = 0.5$ mm around the vertical center of the pinch.

Two singly-gated ($\sim$ 1 ns) multi-channel plate (MCP) detectors are used, one for the Ly-α satellite spectra and the other for Ly-δ and Ly-ϵ. Correcting for photon propagation, this enables simultaneously recording all three spectra. We note that even though a single high-n line is sufficient for application of the method, two such lines (Ly-δ and Ly-ϵ) were recorded to decrease the uncertainties.

We present detailed analysis of the Ly-α and high-n lineshapes recorded simultaneously at $t = 0$. The spectral analysis of the Ly-α-satellite lines yielded values of $T_i^D = 900 \pm 200$ eV and $N_e = (6 \pm 1) \times 10^{20}$ cm^{-3}. We refer the interested reader to the full publication [1] for complete details. These values are used in order to calculate T_i from the high-n lineshapes, which were recorded simultaneously from the same plasma region.

The spectra of Ly-δ and Ly-ϵ were modeled by convolving the Doppler and instrumental broadenings with the calculated Stark lineshapes, for a range of T_i values. Results of the high-n lineshape analysis are presented in Fig. 2, demonstrating that the best fit is obtained for $T_i = 300 \pm 150$ eV, while assuming $T_i = T_i^D$ results in lineshapes that are far from fitting the data.

Table 1: The measured plasma parameters for various times throughout stagnation.

t (ns)	$N_e (10^{20}$ cm$^3)$	T_i^D (eV)	T_i (eV)
-2.5	5.0 ± 1.0	1900 ± 400	400 ± 150
-1.5	3.0 ± 0.5	1100 ± 300	300 ± 150
-1.0	3.5 ± 0.5	1300 ± 300	350 ± 150
0.0	6.0 ± 1.0	900 ± 200	300 ± 150
2.0	2.5 ± 0.5	1000 ± 250	550 ± 250
2.5	5.5 ± 1.0	600 ± 200	400 ± 150
4.0	2.5 ± 0.5	600 ± 200	550 ± 200

The spectral analysis was performed on multiple shots at various times throughout stagnation. The results are summarized in Table 1. We observe that most of the kinetic energy of the ions is stored not in the thermal motion, but rather in a form of the hydrodynamic macro-motion, while the true ion temperature is, as a rule, close to the electron temperature.

We emphasize that this is the first study where the ion temperature of a HED plasma is directly obtained from instantaneous localized measurements, without the necessity to obtain an entire history of the plasma parameters, and without relying on complex energy-balance argumentations. Thus, the approach described here may be considered for measurements in highly non-uniform and transient HED plasmas.

References

[1] D. Alumot *et al.*, “Determination of the ion temperature in a high-energy-density plasma using the Stark effect”, Phys. Rev. Lett. **122**, 095001 (2019).