Experimental determination of the ion temperature and hydromotion in an imploding plasma and implications to pressure and energy balance

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Motivation for the $T_{\text{ion}}$ measurement

- The ion temperature plays a crucial role in energy-transfer processes.
- Understanding the dynamics of stagnating and imploding plasmas.
- Relevant for HED plasmas and astrophysics.

Discriminating between the thermal and hydrodynamic motion is very difficult since both contribute to Doppler broadening similarly.

Two methods were developed and implemented:
1. Doppler method
2. Stark method

The Experimental Setup

The WIS Z-pinch
- Gas-puff load (Neon)
- Shell-on-jet configuration
- $\Omega_{\text{out}} = 38$ mm
- A – K Gap = 9 mm

Typical Current and XRD traces for $I_{\text{peak}} = 0.5$ MA

Lyman and satellites analysis - Doppler and $n_e$ measurement


Collaborators

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Z-pinch plasma experiment

An axial current driven through a cylindrical plasma induces an azimuthal magnetic field which compresses the plasma radially, forming a hot and dense core.

Implosion (compression, acceleration, and heating) Stagnation (H-like ions)

Lyman-$\alpha$-satellites

- Spherically-bent KAP
- Ultra-high resolutions:
  - Spectral >6700
  - Temporal –1 ns
  - Spatial –50 µm
- Imaging along z-axis

Knowledge of $n_i$ is essential!

The Stark method

- The Stark method employs Stark-broadened high-$\alpha$ spectral lines.
- Stark is dominated by ionic fields, which are affected by $T_i$.
- Corrections to Stark width are $\propto$ the ion-ion coupling $\Gamma_{ii}=\frac{e^2}{4\pi\varepsilon_0}\frac{Z^2}{r_i}\langle \delta \rangle$.
- Moderate coupling is required (for our plasma $0.1 \leq \Gamma_{ii} \leq 0.5$).
- Stark line-shape calculations are required (including correlation and ion-dynamics effects).

Challenges in measuring $T_{ion}$ from the plasma spectrum

- Lines must be dominated by Stark broadening (high-$\alpha$ or low-Z).
- Optically-thin, high-$\alpha$ lines are weak.
- In addition, one must obtain simultaneously:
  1. The electron density - for the line-shape calculations
  2. The total Doppler broadening - in order to de-convolve the Stark broadening from the line shape.
- The line-shape calculations account for inter-particle correlations, ion dynamics, $\Delta n=0$ level mixing.
- High resolutions in spectrum, time, and space are crucial.

Results

1-ns gated spectra images obtained simultaneously at $t=+5$ ns

For the analysis, all line spectra used are from the same location.

Error-bar analysis of $T_i$ for $t=+6$ ns

$Ly_\alpha$ shape calculated for $n_i=3\times10^{20}$ cm$^{-3}$ and $T_{ion}=200$ eV measured. for different $T_i$, accounting for: Total Doppler- measured simultaneously and Instrumental broadening-experimentally determined.


Considerations

- For fusion we need fast dissipation of \( T_i \) (effective) into heat, and slow ion-electron energy transfer.
- For radiation sources we need fast dissipation of \( T_i \) (effective), and the ion-electron energy transfer rate should not be slower.

Possibilities for application in HED experiments

Ion temperature in W implosions on Z:

The Stark and Doppler widths of \( T_i \) for Ly\(_6\), and Ly\(_6\) at 20% titanium being embedded in a tungsten plasma:

\[
n_i = 10^{23} \, \text{cm}^{-3}, \quad Z = 60, \quad T_{\text{ion}} = T_e
\]

Possibilities for application in HED experiments

Reflected-Shock model

- High \( T_{\text{ion}} \) causes the pressure to remain high and the radiation to be slower.
- This prevents radiative collapse.
- Indeed, both our experiment and the wire-array experiments (on much larger machine >18 MA, and 100-ns implosion), showed that globally the process is in agreement with a reflected-shock model:

\[
\begin{align*}
\frac{n_2}{n_1} &= \frac{c_1}{c_2} \\
n_2 &= \frac{m_1 v_1^2 + T_{\text{eff}} + Z_1 T_{\text{e1}}}{m_2 v_2^2 + T_{\text{eff}} + Z_2 T_{\text{e2}}} \\
\frac{m_2 v_2^2}{2} &= \frac{m_1 v_1^2}{2} + \Delta E_{\text{ion}} + \frac{5}{2} (T_{\text{ion}} + Z_1 T_{\text{e1}})
\end{align*}
\]

Conclusions

- Since for the MHD instabilities to grow, the Alfven time at the stagnating plasma must be short relative to the stagnation duration, the low-B inferred suggests less likelihood for such a growth at stagnation.

- Related papers:
Summary

- Knowledge of $T_{ion}$ is essential for hot-and-dense plasma research.
- Distinguishing thermal and hydrodynamic motions is highly important.
- Two methods were employed to determine $T_{ion}(t)$:
  - The Doppler method: using the measured drop in $T_{ion}$
  - The Stark method: using the Stark line shape
- The dissipation of $T_{ion}$ is determined; affects the radiation-pulse duration.
- $T_{ion}$ contributes to the balance of the imploding-plasma pressure. Allowed for inferring the energy balance between the plasma kinetic-energy and the radiation, and for explaining the appearance of an expanding shock.
- The methods can be useful for other HED plasmas.

**Ly$\alpha$ Satellite-Line Shapes Give the Total $E_{k,ion}$**

(Only the D$2$ satellite is shown)

**Results**

\[
T_{eff}^{\text{ion}} = \frac{2}{3} E_{tot}^{\text{ion}} = T_i + \frac{2}{3} E_{k,ion}^{\text{hydro}}
\]

\[
dT_i^{eff} = \frac{2}{3} \frac{dE_{k,ion}^{\text{hydro}}}{dt} - \frac{2}{3} \frac{dE_{k,ion}^{\text{hydro}}}{dt} 
\]

\[
\frac{dT_i}{dt} = -\frac{T_i - T_c}{\tau_{sc}} - \frac{2}{3} \frac{dE_{k,ion}^{\text{hydro}}}{dt} 
\]

\[
\frac{d}{dt} \left( T_i + \frac{2}{3} E_{k,ion}^{\text{hydro}} \right) = \frac{d}{dt} T_{eff}^{\text{ion}} = -\frac{T_i - T_c}{\tau_{sc}}
\]

$n_e = 8 \times 10^{28}$ cm$^{-3}$, $T_c = 200$ eV

$Z_{eff} = 9$, $\tau_{sc} = 5 \times 10^{-11}$ s