Experimental Discrimination between Thermal and Hydrodynamic Motions in High-Energy-Density Plasmas

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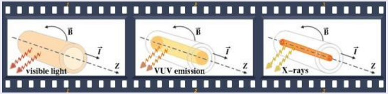
Imploding plasmas

Imploding plasmas are promising candidates for fusion (NIF, MagLIF) and unique sources of intense x-ray radiation (z-pinches).

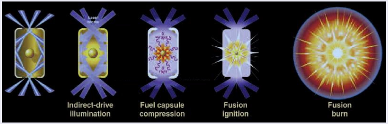
Z-pinch

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



NIF

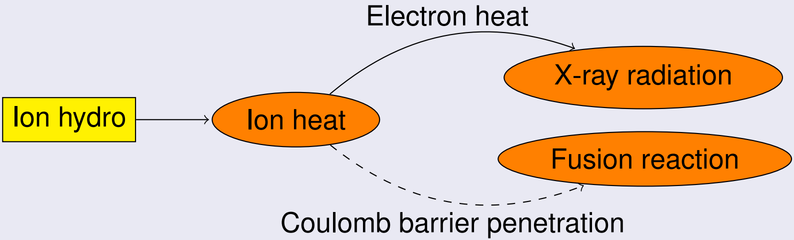
X-rays from the laser-driven hohlraum create a rocket-like blowoff of the capsule surface and the fuel plasma implodes, resulting in thermonuclear ignition and burn.



Conversion of hydrodynamic ion motion

In implosion schemes, accelerated ions dissipate their energy to ion heat. The hydro energy itself is useful neither for radiation sources nor for fusion.

"Good uses" of ion hydro energy



Thus, one needs to measure T_{ion}. It is also helpful to measure the (available) hydro energy.

Challenges in measuring T_{ion}

Principal difficulty:

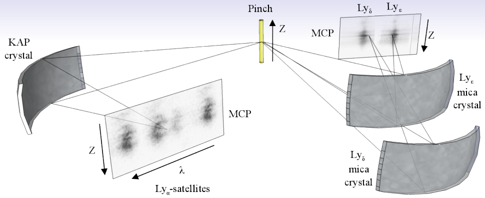
Both Doppler broadening [Kroupp et al., 2007a] and neutron spectrum [Murphy, 2014, Munro, 2016] give information only on the total ion velocity distribution.

To the best of our knowledge, the ion temperature and distinguishing it from the hydromotion in HED plasmas had never been determined experimentally prior to the studies described here.

Two methods have been used:

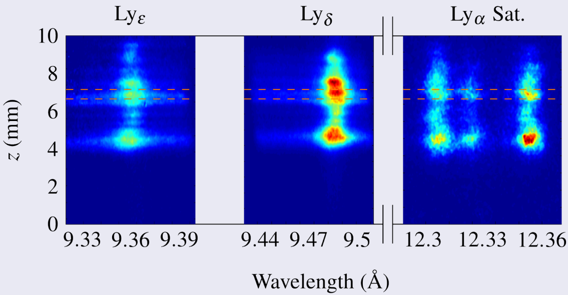
- Based on the detailed energy balance considerations (PRLs [Kroupp et al., 2007a] and [Kroupp et al., 2011]);
- Based on the effect of the ion-ion coupling on the Stark line shapes [Stambulchik and Maron, 2006, Alumot et al., 2012]; more in preparation.

The Stark method

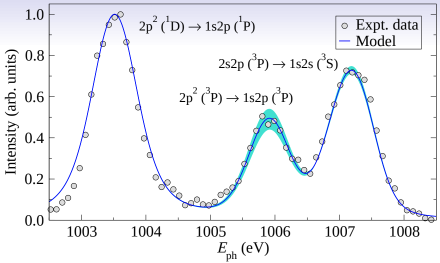


The method is based on lineshape analysis of high-*n* transitions (Stark-effect dominated) and Ly-α satellites (Doppler dominated), measured *simultaneously*.

Shot #1715

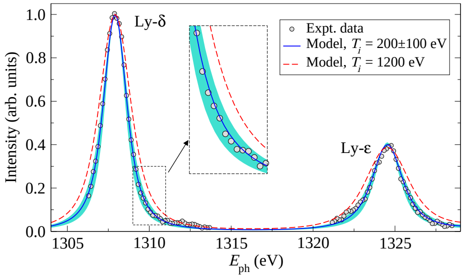


The Stark method

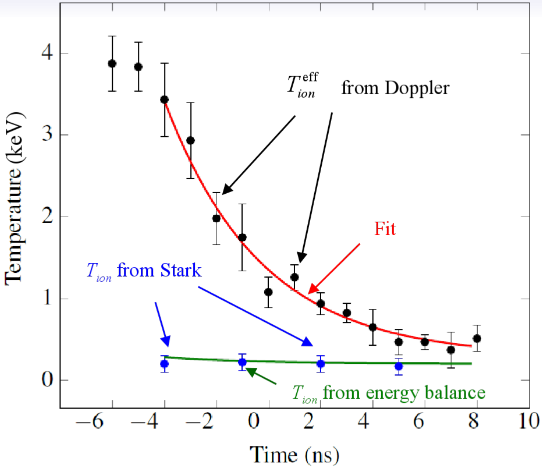


Widths and intensities of the Ly-α satellites allow for determining T_i^{eff} and n_e, respectively. Here, $T_i^{\text{eff}} = 1200\,\text{eV}$ and $n_e = (4 \pm 1) \times 10^{20}\,\text{cm}^{-3}$. T_e is inferred independently.

The broadening of high-n lines is Stark-effect dominated, sensitive to $\Gamma_{ii} \propto Z_i^{5/3} n_e^{1/3} / T_i$. Hence, provided n_e is known, one can infer T_i. (The Doppler contribution $\propto \sqrt{T_i^{\text{eff}}}$ is also accounted for.)



T_i: comparing results of two methods



Hydro energy dissipation is measured ≈ 2 ns.

The energy-balance method

The method is based on determining the rate of heat transfer from ions to electrons by measuring the total ion kinetic energy, its dissipation rate, the total radiation from the plasma, and the electron density and temperature
[Kroupp et al., 2007a, Kroupp et al., 2011].

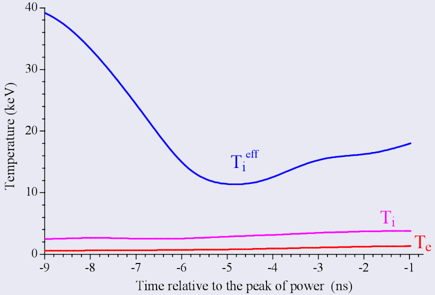
$$\frac{T_i - T_e}{\tau_{ie}} = \frac{dT_i^{\mathrm{eff}}}{dt}$$

Typical parameters at different facilities

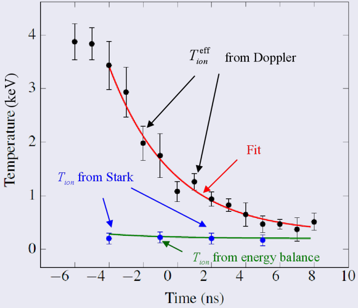
Experiment	T_e (eV)	τ_{ie} (ns)	$T_i - T_e$ (eV)	T_i / T_i^{eff}
WIS, Ne	200	0.1	100	0.1 – 0.2
Sandia Z, Al	900	0.2	2000	0.2 – 0.3
Sandia Z, Ni	3000	1	20000	0.3 – 0.5

Low-Z implosions

Sandia Al wire-array (on-axis data)

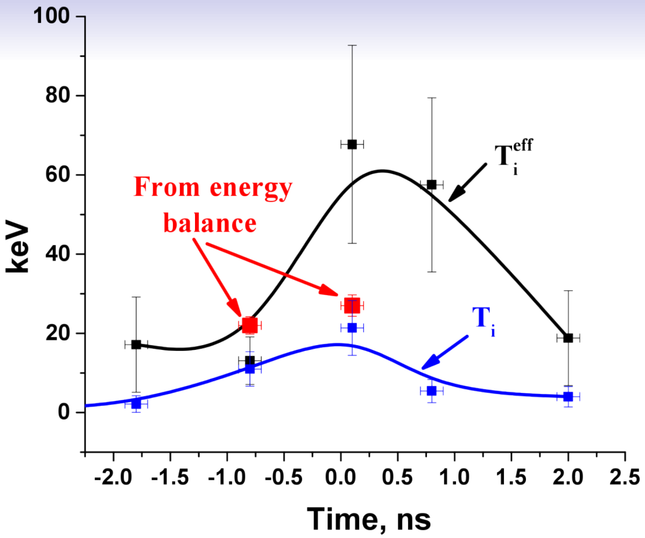


WIS Ne gas-puff



Implosions are complex. For example, $T_i^{\rm eff}$ may rise after the drop due to a specific flux(t) of the imploding plasma.

Stainless steel implosion on Sandia *Z*



Optically-thin Fe lines are used to determine T_i^{eff} and T_i.

T_i in dense plasmas (NIF)

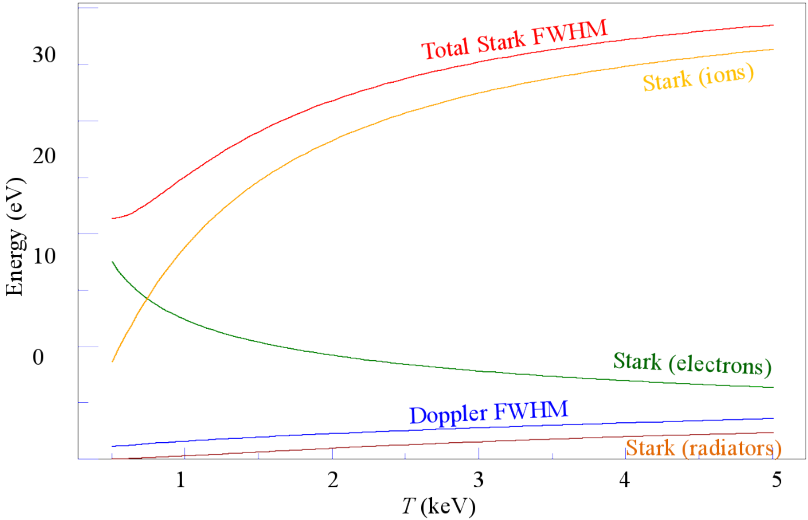
$$\frac{T_i - T_e}{\tau_{ie}} \approx \text{rates of} \begin{cases} \text{radiation (emission and absorption)}, \\ \text{expansion}, \\ \text{conduction}, \\ \text{compression}, \\ \alpha\text{–heating}, \\ \ldots \end{cases}$$

For a DT plasma with $n_e \sim 10^{25}\,\text{cm}^{-3}$ and $T_e \sim 3\,\text{keV}$, $\tau_{ie} \ll 10\,\text{ps}$. Hence, the expectation is that $T_i - T_e$ is small, $\sim 100\,\text{eV}$.

Work in progress with Mark Herrmann (LLNL).

T_i in dense plasmas (Z capsule)

Stark and Doppler widths for Ar Ly-δ, embedded in C ($n_e = 10^{23}\ \text{cm}^{-3}$, $\bar{Z} = 6$, $T_i = T_e$):

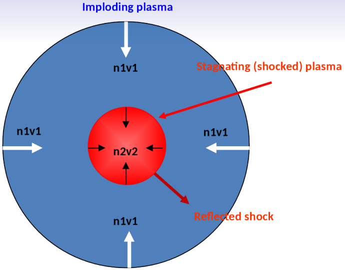


Pressure due to $T_i^{\rm eff}$: Reflected-shock model

High $T_i^{\rm eff}$ causes the pressure to remain high and the radiation to be slower, preventing radiative collapse.

$$\frac{n_2}{n_1} = \frac{v_1}{v_2}$$

$$\frac{n_2}{n_1} = \frac{mv_1^2 + T_{i,1}^{\rm eff} + Z_1 T_{e,1}}{mv_2^2 + T_{i,2}^{\rm eff} + Z_2 T_{e,2}}$$

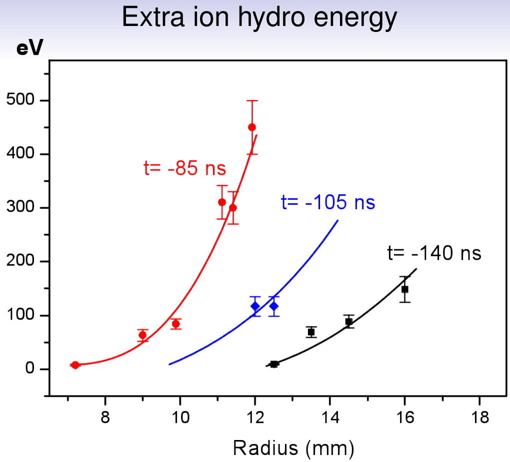


A rejected-schock model was found to describe well the stagnation of both WIS (0.5 MA gas-puff) and Sandia (25 MA wire-array) experiments.

- All equations are balanced to within ±25%;
- WIS – *all* terms in these equations were measured;
- Sandia – v_1 is assumed, based on computations.

PRL [Maron et al., 2013].

T_i during implosion



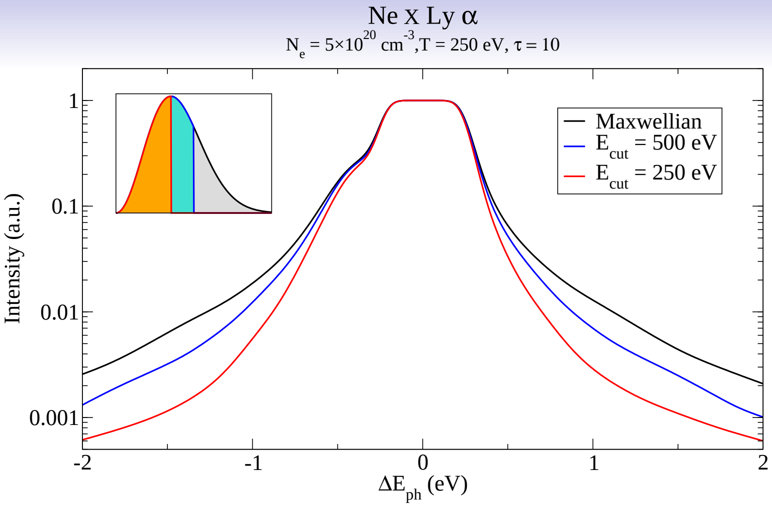
Surprisingly, a significant excess of the ion kinetic energy over T_i was observed much before stagnation—already at $t = -140\,\mathrm{ns}$ and at large radii.

$T_e \approx 13\,\mathrm{eV}$,
$13\,\mathrm{eV} \lesssim T_i \lesssim 25\,\mathrm{eV}$,
$T_i - T_e \sim 10\,\mathrm{eV}$.

[Kroupp et al., 2007b], more to be published.

These results are referred to in [Davidovits and Fisch, 2016].

Thermalization details



Accurate measurements may be able to probe for high-energy tail of ion energy distribution (work in progress, with Nat Fisch).

Conclusions

- Knowledge of T_i is essential for hot-and-dense plasma research.
- Distinguishing between thermal and hydrodynamic motions is highly important for understanding fusion and radiating plasmas.
- Two methods were employed to determine $T_i(t)$:
  - The energy-balance method: using the measured drop in T_i^{eff};
  - The Stark method: using the Stark lineshapes.
- The dissipation of T_i^{eff} is determined. It affects the radiation-pulse duration.
- T_i^{eff} also contributes to the plasma pressure; explains the appearance of expanding shocks.
- The methods can be useful for other HED plasmas.

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