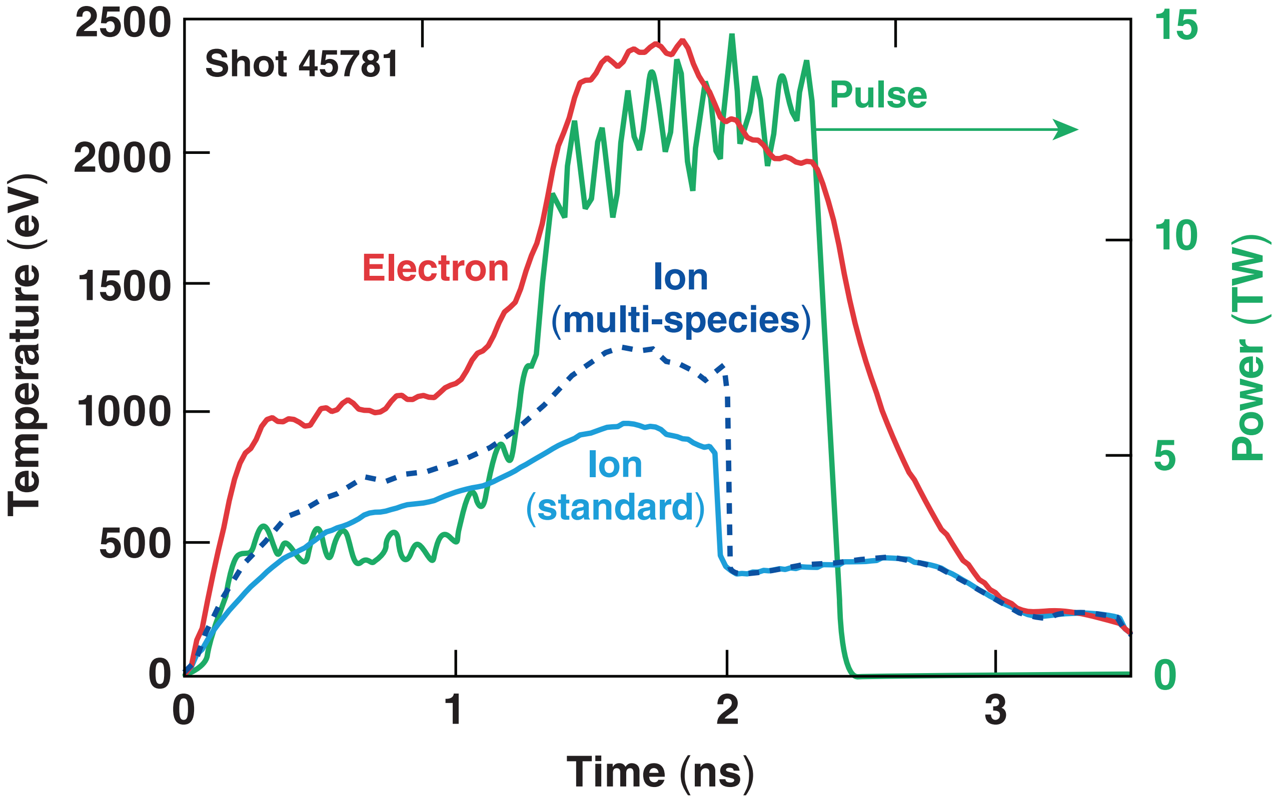
Modeling of Two-Plasmon-Decay Instability Driven by Crossing Laser Beams



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38th Annual Anomalous
Absorption Conference
Williamsburg, VA
1–6 June 2008

Summary

The multi-species composition of plasmas has a strong effect on the laser–plasma interaction including the two-plasmon-decay instability

- The multi-species composition modifies the ion–ion collision properties and, therefore, the ion-heat conductivity and the ion viscosity.
- The changes in the ion-temperature profile are caused by the modification of the coupling between the electron and ion temperatures.
- The presence of a high-Z dopant in the multi-species plasma can decrease ion wave damping and therefore limit the growth of the two-plasmon-decay instability.

Collaborators

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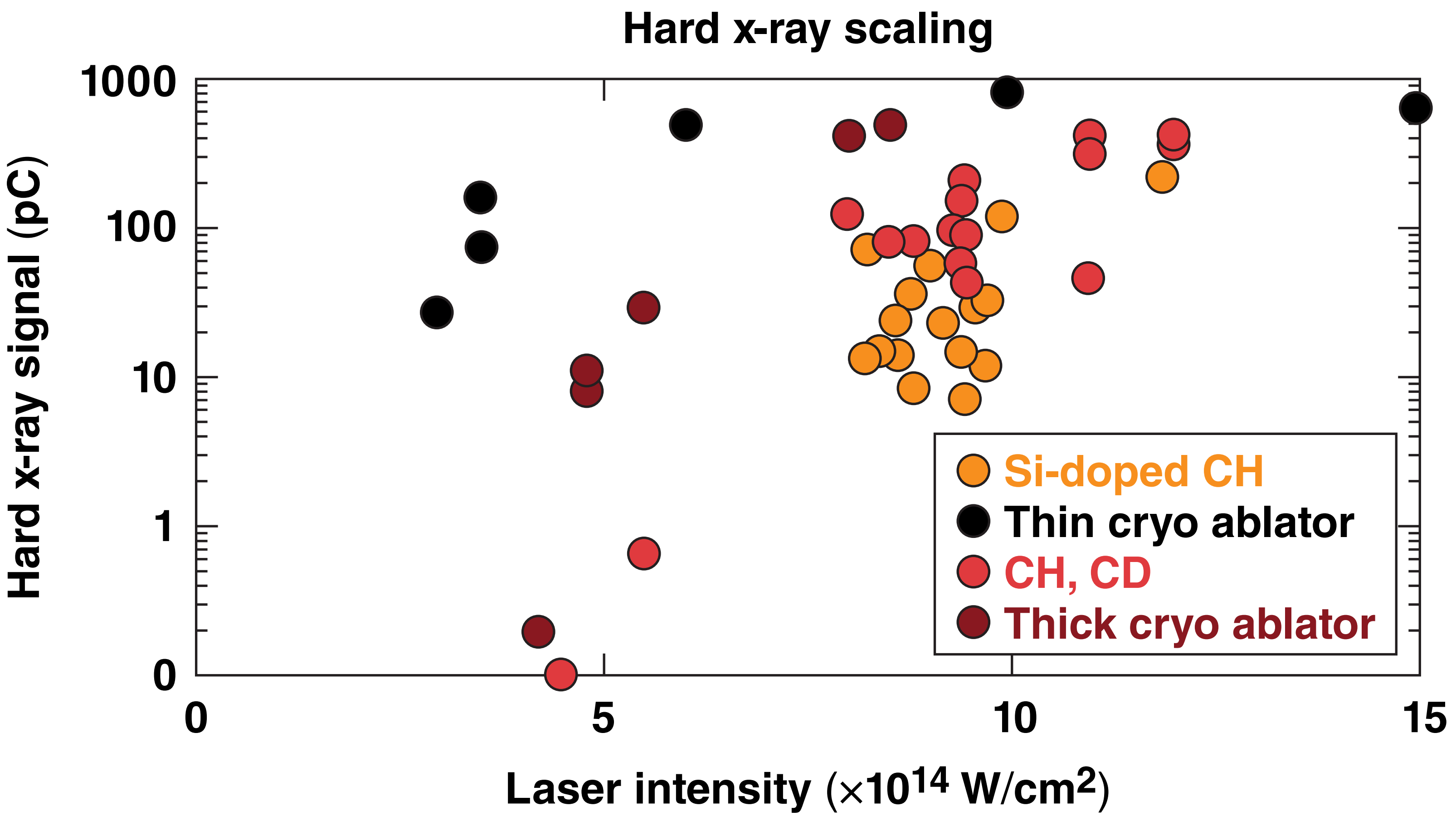
In direct-drive experiments, the target materials consist of multiple-ion species, including high-Z dopants

- The ion-species parameters determine the properties of the ion-acoustic modes, which are involved in
  - the cross-beam energy transfer and, therefore, in the laser-energy coupling
  - the detuning of the two-plasmon-decay instability

In OMEGA experiments, the hard x-ray production depends on the overlapped intensity of multiple incoherent laser beams



The multi-species composition of plasmas influences the hydrodynamic equations

$$\partial_t \rho + \vec{\nabla}(\rho \vec{V}) = 0$$

ion density $n_\Sigma = \sum_i n_i$

mass density $\rho = \sum_i n_i m_i$

$$\rho\left[\partial_t V_j + (\vec{V}\cdot\vec{\nabla})V_j\right] = -\nabla_j\left(n_e T_e + n_\Sigma T_i\right) - \nabla_k \sigma^{\Sigma}_{jk} - \frac{e^2}{4m\omega_0^2}\left\{n_e \nabla_j |E|^2 - \nabla_k\left[n_e\left(E_k E_j^* + E_j E_k^*\right)\right]\right\}$$

Ion

Electron

$$\partial_t T_e + (\vec{V}\cdot\vec{\nabla})T_e + \frac{2T_e}{3}\vec{\nabla}\cdot\vec{V} + \frac{2}{3n_e}\vec{\nabla}\cdot\vec{q}^{\,e} = \frac{e^2|E|^2\,\nu_{e\Sigma}}{3m\,\omega_0^2} - \sum_i \frac{2m\,\nu_{ei}}{m_i}\left(T_e - T_i\right)$$

Electron–Ion

$$\partial_t T_i + (\vec{V}\cdot\vec{\nabla})T_i + \frac{2T_i}{3}\vec{\nabla}\cdot\vec{V} + \frac{2}{3n_\Sigma}\vec{\nabla}\cdot\vec{q}^{\,\Sigma} = \sum_i \frac{2m\,\nu_{ei}}{m_i}\left(T_e - T_i\right)$$

- The ion temperatures of different species are assumed to be the same.

The Landau–Fokker–Planck collision integral is used to calculate the ion heat conductivity and the ion viscosity

$$J_{\alpha\beta}\left[f^{\alpha},f^{\beta}\right]=\frac{\pi}{2}e_{\alpha}^{2}e_{\beta}^{2}(\ln\Lambda)\frac{\partial}{\partial p_{j}^{\alpha}}\int d\vec{p}^{\beta}\,\frac{\left(U_{j}U_{k}-U^{2}\delta_{jk}\right)}{U^{3}}\left(\frac{\partial}{\partial p_{k}^{\alpha}}-\frac{\partial}{\partial p_{k}^{\beta}}\right)f^{\alpha}f^{\beta}$$

$\vec{U}=\vec{V}^{\alpha}-\vec{V}^{\beta}$ Relative velocity, m_{eff} – effective mass

- For a perturbation

$$f^{\alpha}=f_{m}^{\alpha}+\delta f^{\alpha}$$

$$\boxed{\delta J_{\alpha\beta}\sim\frac{e_{\alpha}^{2}e_{\beta}^{2}}{T_{\alpha}^{3/2}\;m_{\text{eff}}^{1/2}}}$$

- For electrons $\delta J_{e\Sigma}=\sum_{i}\delta J_{ei}$ and $\nu_{e\Sigma}=\frac{4\ln\Lambda}{3\sqrt{2\pi}}\,\frac{e^{2}}{T_{e}^{3/2}\;m^{1/2}}\,\sum_{i}n_{i}e_{i}^{2}$

[Kinetic coefficients follow (Braginskii, 1965)].

In plasmas with multi-species ions, the ion-collision frequency includes collisions with all ion species

- For ions $\delta J_{i\Sigma} = \sum_A \delta J_{iA}$ and $\nu_{i\Sigma} = \frac{4 \ln \Lambda}{3\sqrt{\pi}} \frac{e_i^2}{T_i^{3/2}} \sum_A \left(n_A e_A^2 \big/ m_{\text{eff}}^{1/2} \right)$

The ion-heat flux $\vec{q}^{\,\Sigma} = \sum_i \vec{q}^{\,i} = -\kappa_\Sigma \frac{\partial T_i}{\partial \vec{r}}$

Ion-heat conductivity $\boxed{\kappa_\Sigma = \sum_i 3.9 \frac{n_i T_i}{m_i \nu_{i\Sigma}} = 3.9 \frac{3\sqrt{\pi}}{4 \ln \Lambda} \frac{\sum_i \left(n_i \big/ e_i^2 m_i \right)}{\sum_i \left(n_i e_i^2 \big/ m_{\text{eff}}^{1/2} \right)} T_i^{5/2}}$

- The heat conductivity does not depend on density if all ion densitites are proportional (due to collisions).

The electron–ion coupling and ion viscosity are modified in the multi-species plasmas

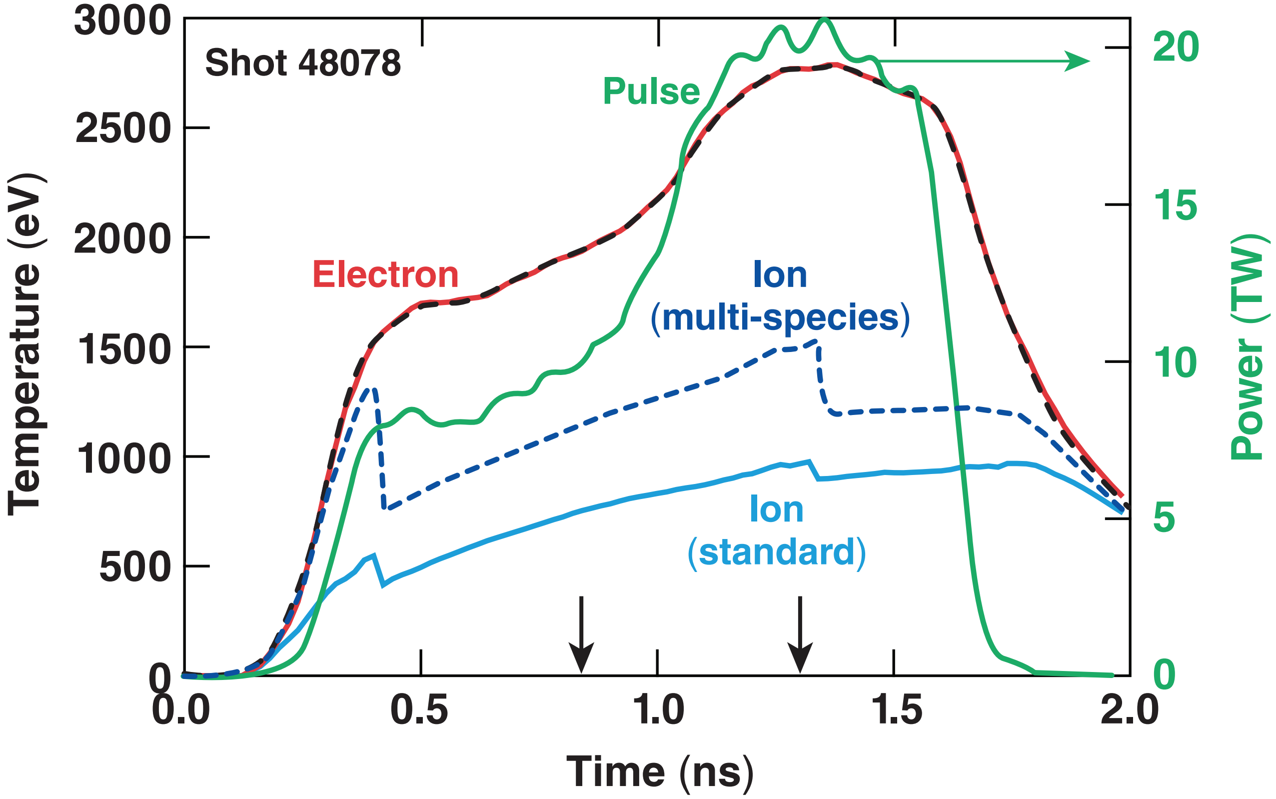
- The ion stress tensor $$\sigma_{kj}^{\Sigma} = \sum_i \sigma_{kj}^{i} = -\eta^{\Sigma}\left(\frac{\partial V_j}{\partial r_k} + \frac{\partial V_j}{\partial r_k} - \frac{2}{3}\delta_{kj}\,\mathrm{div}\,\vec{V}\right)$$

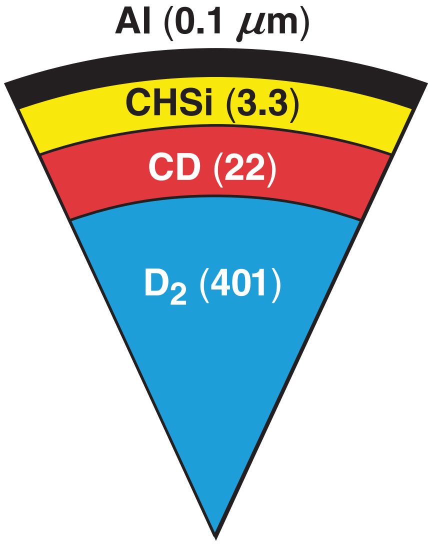
- Ion viscosity $$\boxed{\eta^{\Sigma} = \sum_i 0.96\,\frac{n_i T_i}{\nu_{i\Sigma}} = 0.96\,\frac{3\sqrt{\pi}}{4\ln\Lambda}\,\frac{\sum_i \left(n_i / e_i^2\right)}{\sum_i \left(n_i e_i^2 / m_{\mathrm{eff}}^{1/2}\right)}\,T_i^{5/2}}$$

- The rate of energy transfer between electrons and ions $$\nu_T^{\Sigma} = \sum_i 2\frac{m}{m_i}\nu_{\mathrm{ei}}$$ (~10 to 20% of Ohmic heating for D_2)

The influence of multi-species effects on the plasma parameters has been studied with *LILAC*

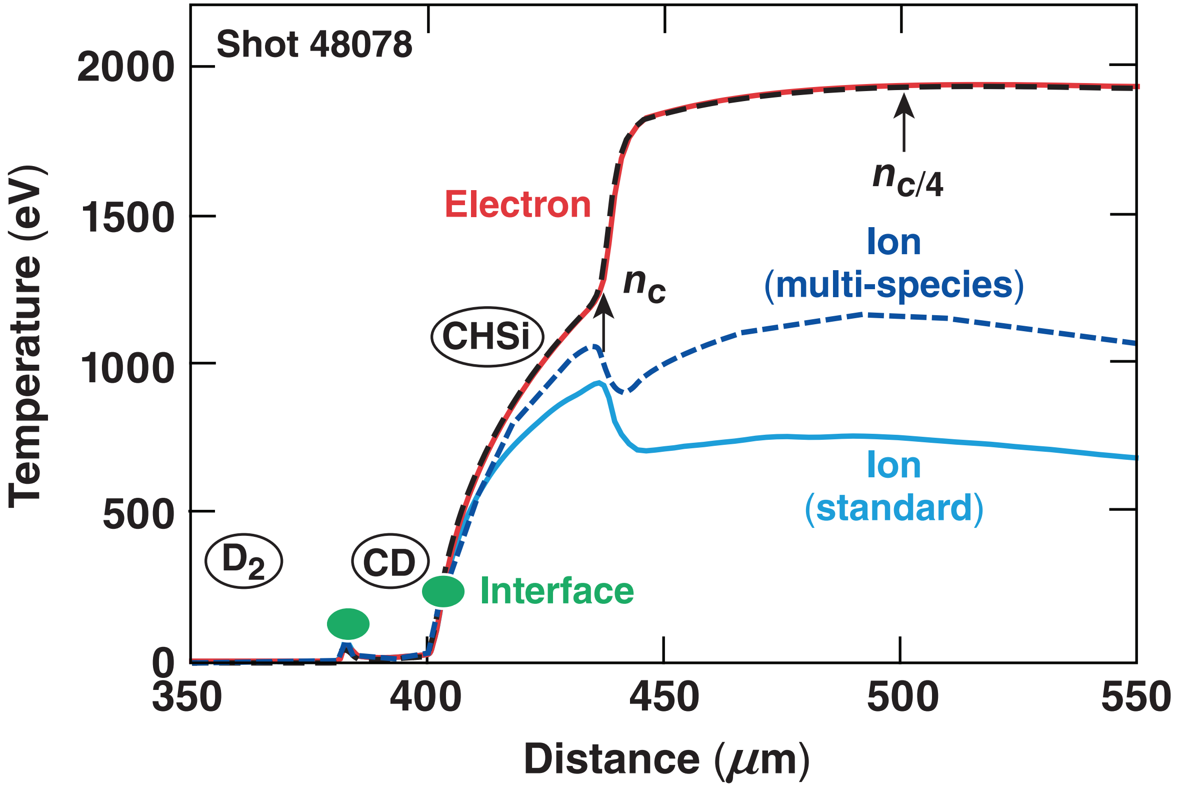
- Temperatures at quarter-critical density





The ion temperature is higher when the multi-species effects are taken into account

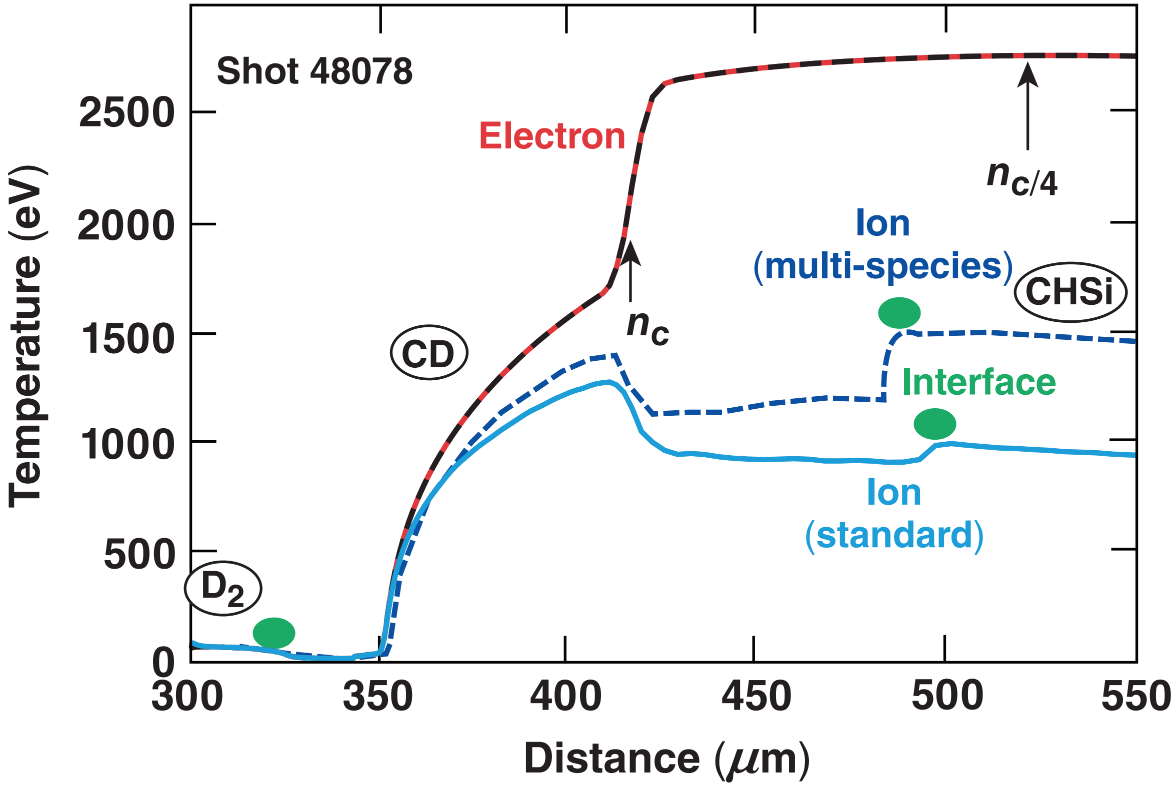
- Temperature profiles at $t = 0.84$ ns



Laser–plasma interaction takes place in the plastic with Si.

The ion temperature changes in the region near the interface between the plastic with Si and the plastic

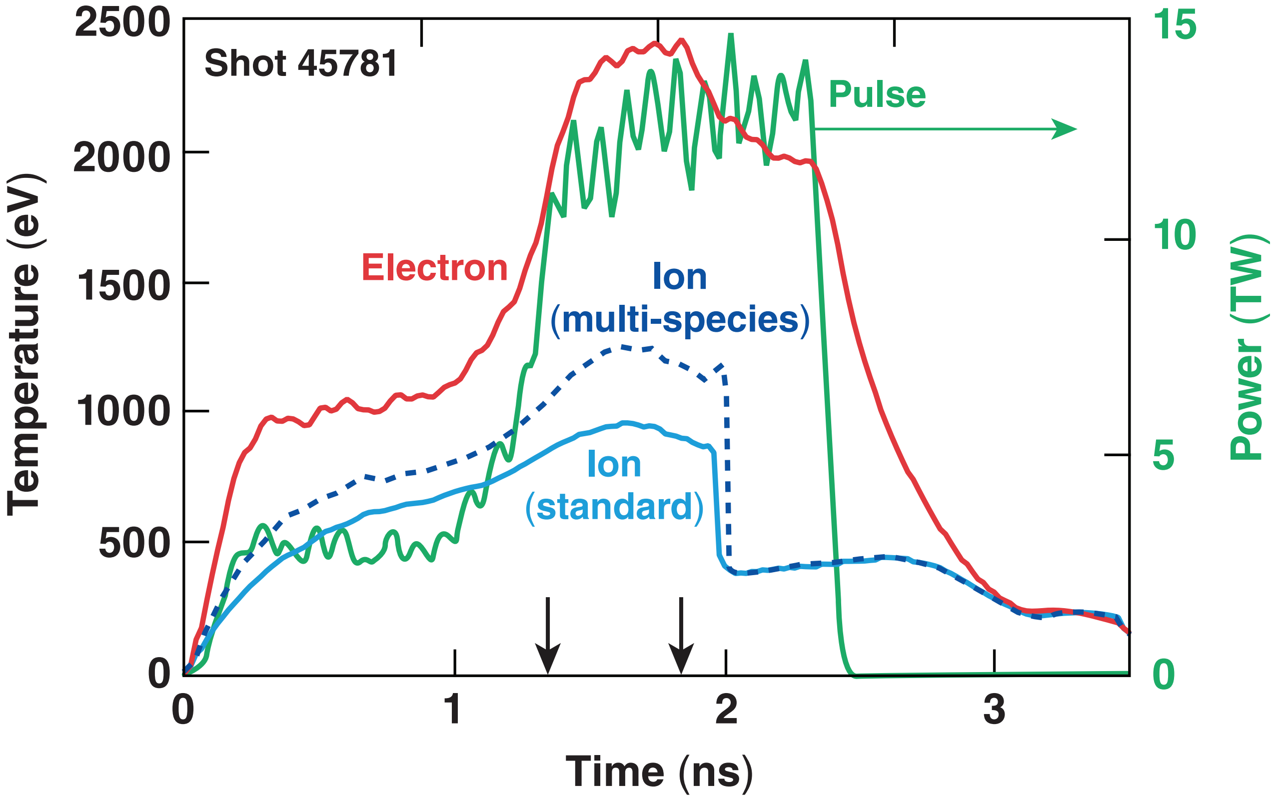
- Temperature profiles at t = 1.3 ns

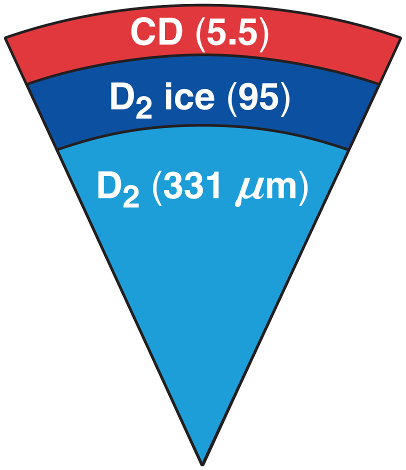


Laser–plasma interaction takes place in the plastic with Si and in the plastic.

The influence of the multi-species effects has been studied for a cryo implosion

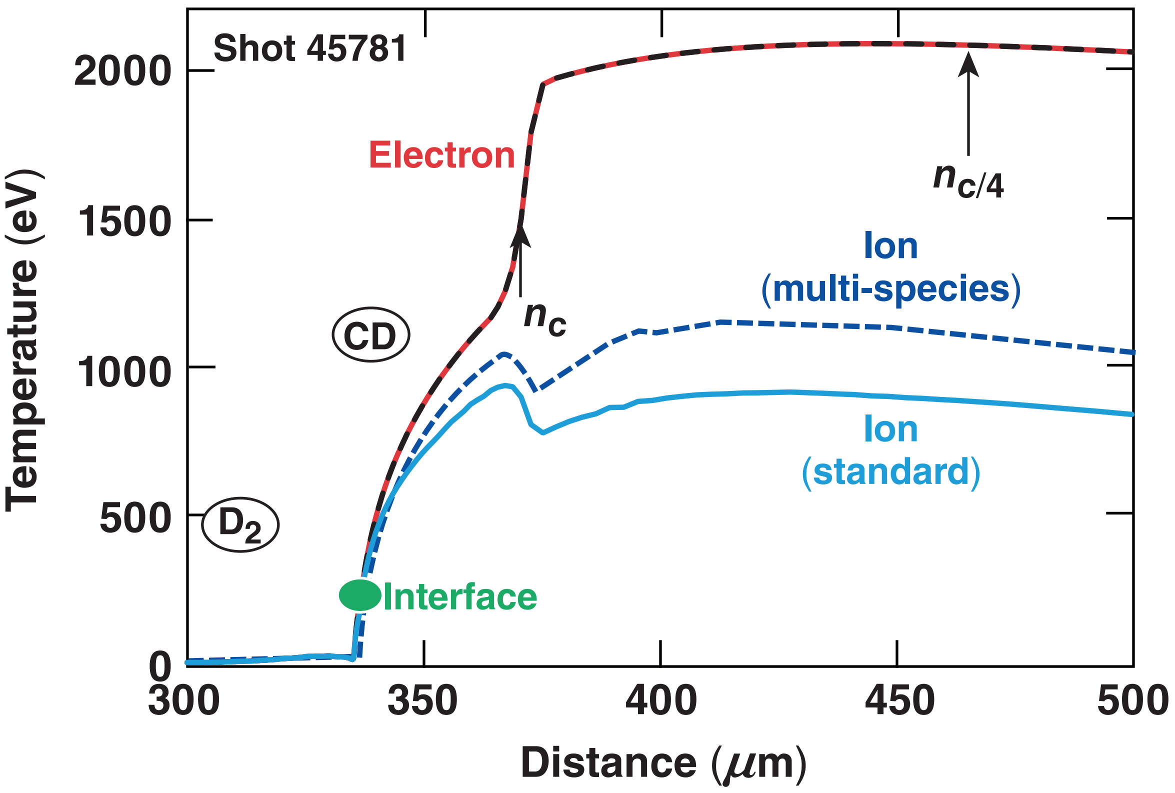
- **Temperature at quarter-critical density**





In the cryo implosion, the electron-temperature profile is not modified, when the interface is inside the critical density

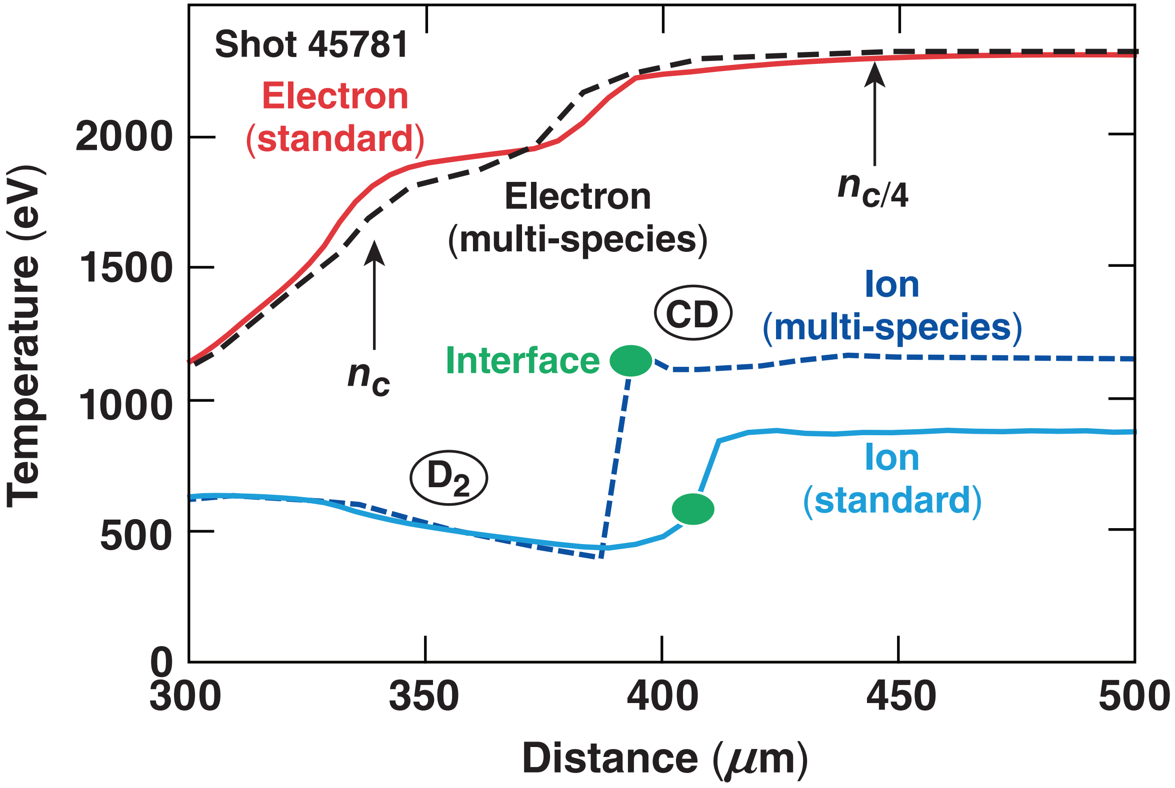
- **Temperature profiles at t = 1.4 ns**



Laser–plasma interaction takes place in the plastic.

In the cryo implosion, the electron-temperature profile is modified, when the interface is between the critical density and the quarter-critical density

- Temperature profiles at *t* = 1.9 ns



Laser–plasma interaction takes place in the plastic and in D_2.

The coefficients for the electron-collision frequency, energy-transfer rate, ion conductivity, and ion viscosity are significantly modified when the plasma composition changes

	$\frac{\nu_{e\Sigma}}{\sqrt{2}\,\nu_{ee}} = Z_{\text{eff}}$	$\frac{\nu^{\Sigma}_{T}}{\sqrt{2}\,\nu_{ee}}$	$\frac{\kappa_{\Sigma}}{\kappa_{D_2}}$	$\frac{\eta^{\Sigma}}{\eta_{D_2}}$
D_2	1.0	$0.50\,(m/m_p)$	1.000	1.000
CD	5.3	$0.50\,(m/m_p)$	0.032	0.027
CHSi(0.06)	7.1	$0.56\,(m/m_p)$	0.032	0.017

In the collisional (i-i) regime, the ion-acoustic damping is determined by the ion viscosity and ion heat conductivity.

For parameters of OMEGA plasmas, the TPD instability threshold is influenced by the interplay of plasma inhomogeneity, wave damping, and resonance detuning due to beam incoherence

- Plasma-wave damping

$$\left(\frac{\gamma_e}{\omega_{p0}}\right)_{\mathrm{coll}} = 0.5 \times 10^{-3} \frac{(Z/5.3)}{\left(T_e/2\,\mathrm{keV}\right)^{3/2}}$$

- Detuning due to inhomogeneity

$$\frac{1}{2\,k_0 L} = \frac{2.1 \times 10^{-4}}{(L/150\,\mu m)}$$

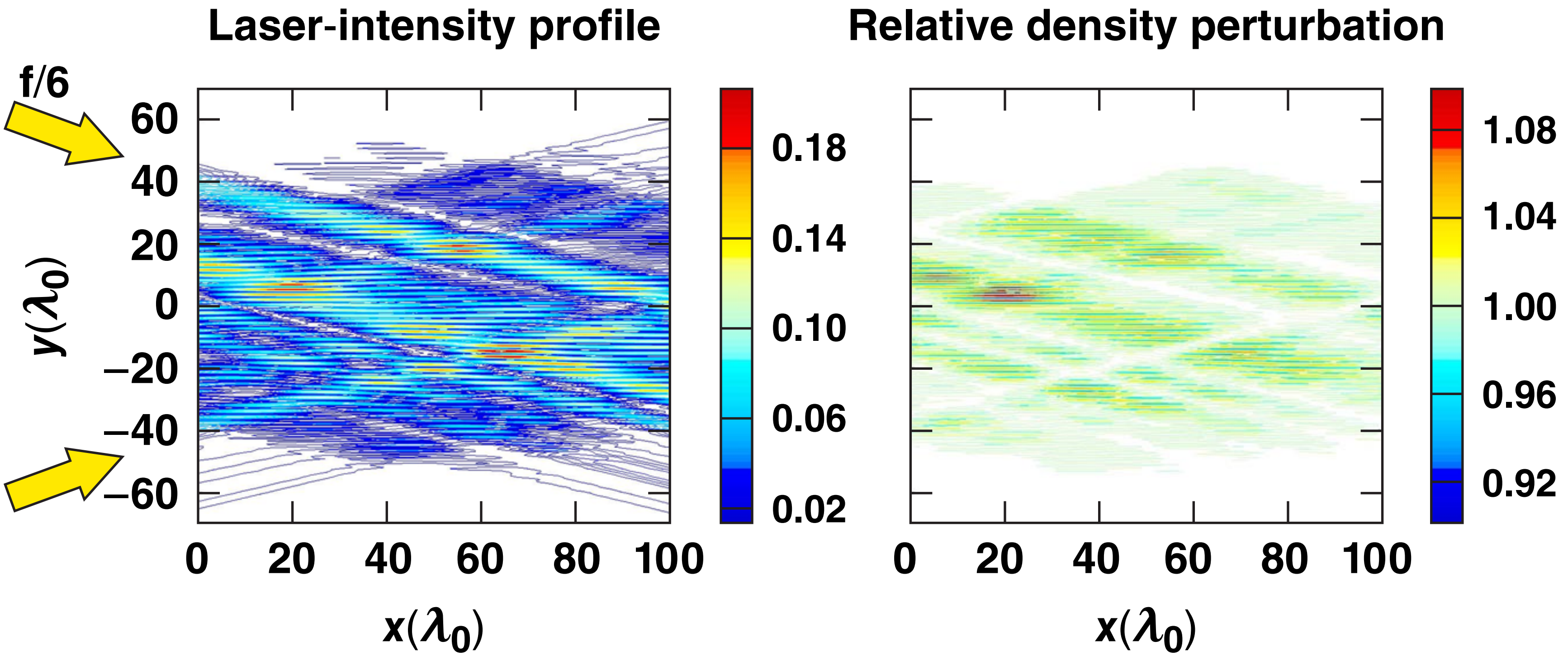
- Homogeneous 3-wave growth rate

$$\gamma^0 = \frac{k_0 |V_0|}{\omega_{p0}} = 0.26 \times 10^{-2} \sqrt{I_{14}}$$

- Detuning due to beam incoherence

$$\frac{\Delta\omega}{\omega_{p0}} = 4 \times 10^{-2} \left(T_e/2\,\mathrm{keV}\right) \Delta\theta \sin\theta_c$$

Low-frequency perturbations in electron density are produced by the interaction of incoherent laser beams with plasmas



$$\langle I \rangle = 9 \times 10^{14}\ \mathrm{W/cm^2},$$

$$T_e = 2\ \mathrm{keV}, \quad n_0 \approx \frac{n_c}{4}, D_2$$

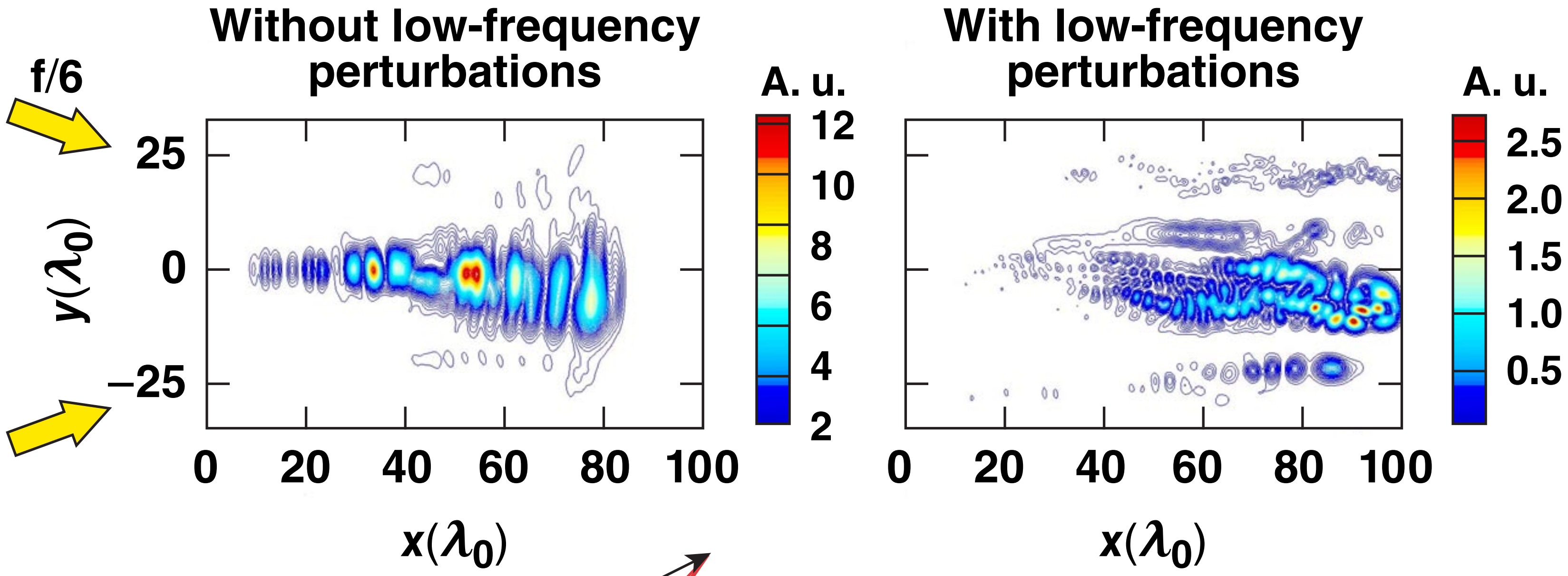
$$\left(\frac{n_e}{n_0} - 1\right) \sim \frac{I}{\langle I \rangle}$$

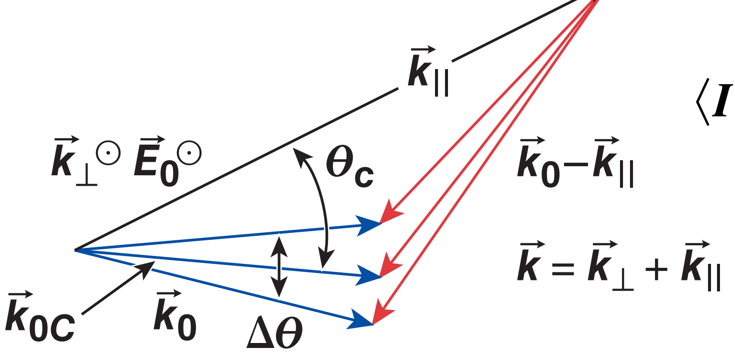
Ion-acoustic damping ↓

Density perturbations level ↑

TC7801a

The low-frequency perturbations in the electron density can detune the TPD resonance and reduce the TPD growth





$\langle I \rangle = 9 \times 10^{14}$ W/cm^2, $\gamma_e/\omega_{p0} = 10^{-3}$

Summary/Conclusions

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