X-Ray Thomson scattering of non-equilibrium and inhomogeneous Warm Dense Matter

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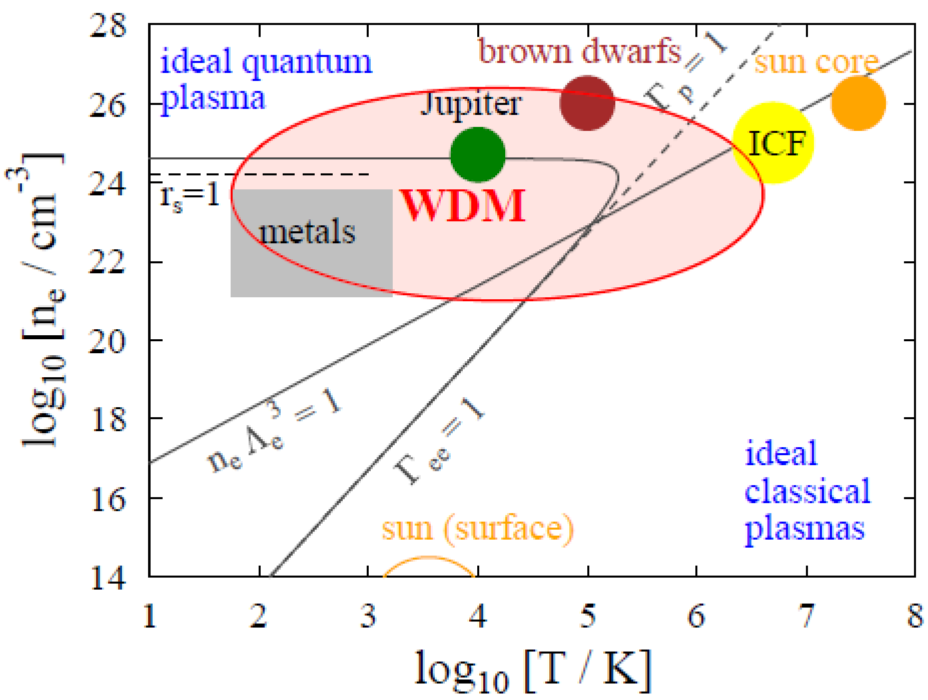
Outline

- Warm Dense Matter
- Plasma parameter
- Generation of WDM
- Dielectric function
- HELIOS results and Monte Carlo simulation results
- X-ray Thomson scattering results

Warm Dense Matter



K. Wünsch

- WDM:
  - Temperature of few electronvolts
  - Solid state density and beyond
- ICF, shock experiments, giant planets, and brown dwarfs
- Theories of solid, condensed matter, or ideal plasma are not valid
- No single theoretical model describes the behavior of WDM
  - Partial ionization
  - Arbitrary degeneracy
  - Strong ionic correlations

Glenzer et al PRL 98 065002(2007)

Generation of Warm Dense Matter

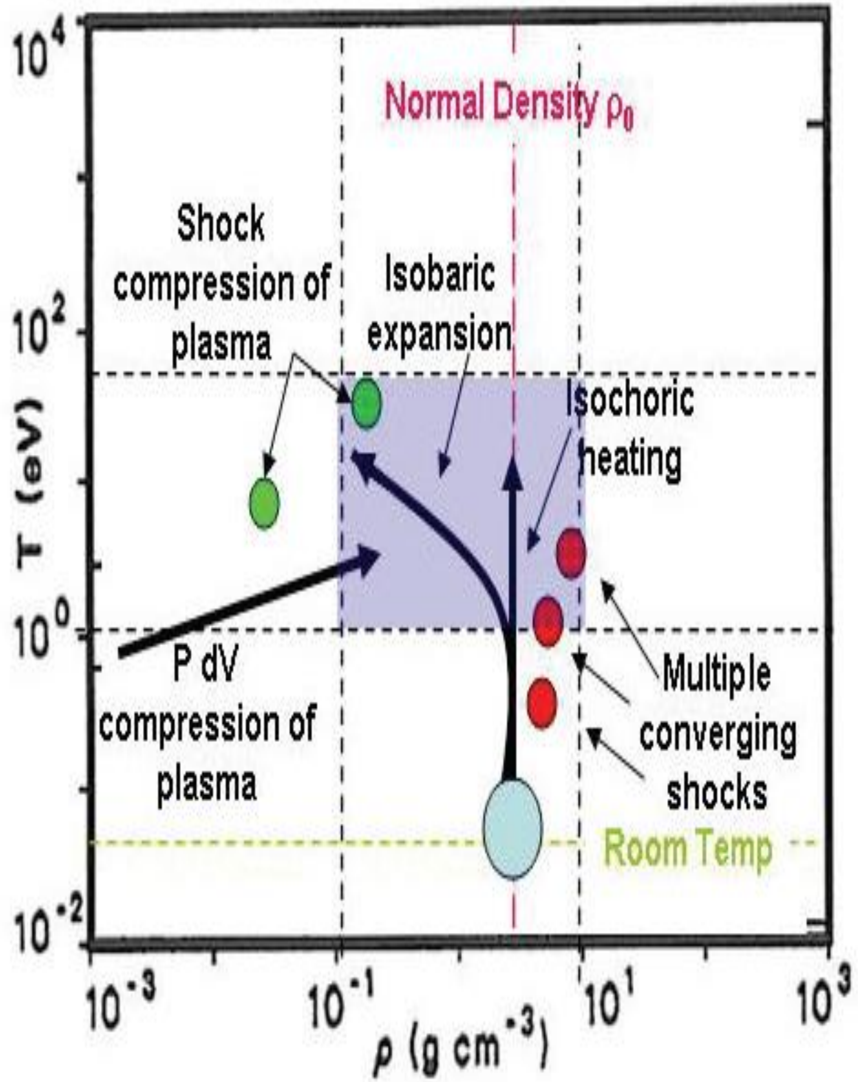
There are several experimental techniques to produce WDM such as:

- Isochoric heating by ultra-short pulsed laser and short pulse particle beams
- Isobaric expansion of ohmically heated wires confined by compressible medium
- Pdv compression of conventional plasma

Shock compression of a lower density plasma

- shock compression of solid density material

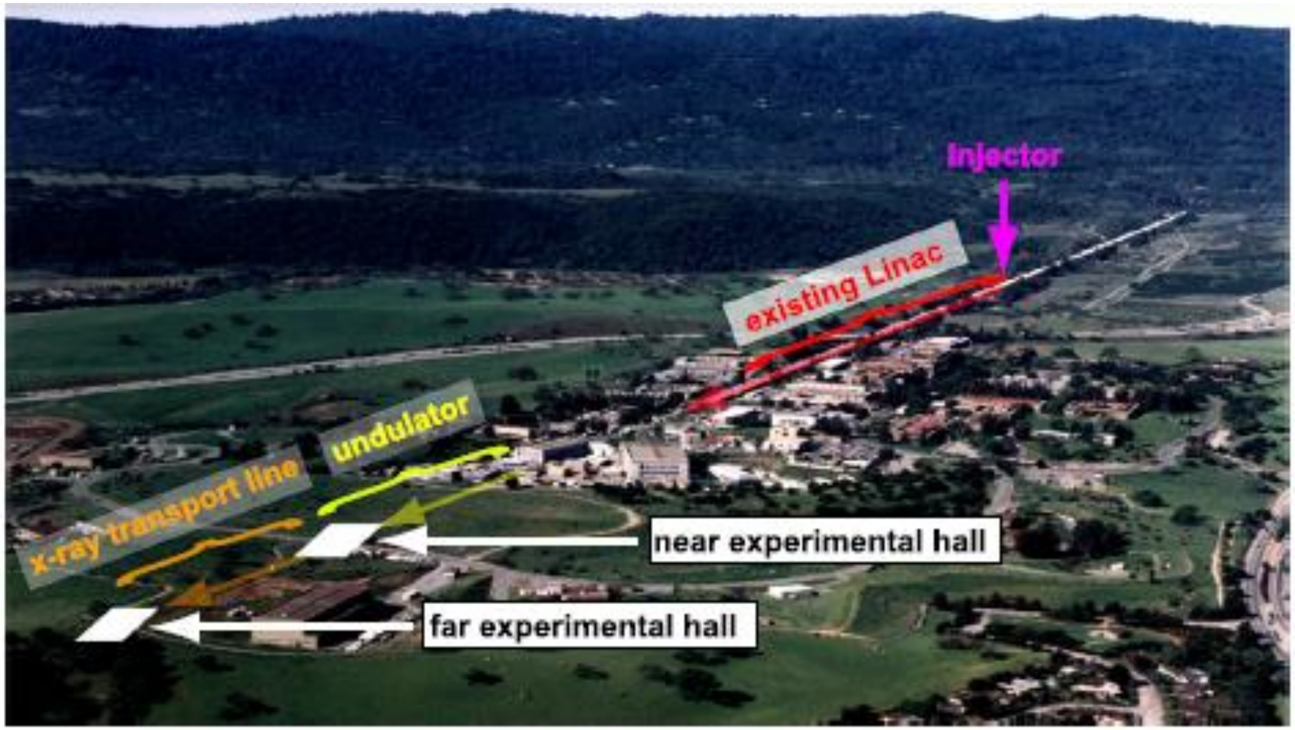
and many other method but we used isochoric heating by ultra-short pulsed laser.



Isochoric heating

- Isochoric heating techniques include fast visible laser, free electron laser, particle beam sources to fastly heat material at constant density.
- particle energy or photon frequency and the target material set the absorption range.
- Target's thickness efficiently absorb incident energy (using 30 % of the incident beam energy).
- Pulse length requirements are set by the need . To supply energy more quickly than hydrodynamic expansion can allow target to expand.
- These criteria imply very rabid, very high power sources and put very high time resolution requirements on the diagnostics.
- To convert beam energy to x-ray introduces cost in conversion efficiency but introduces savings by increasing absorption range and allowing the use of larger targets.

Set-up of an XRTS experiment



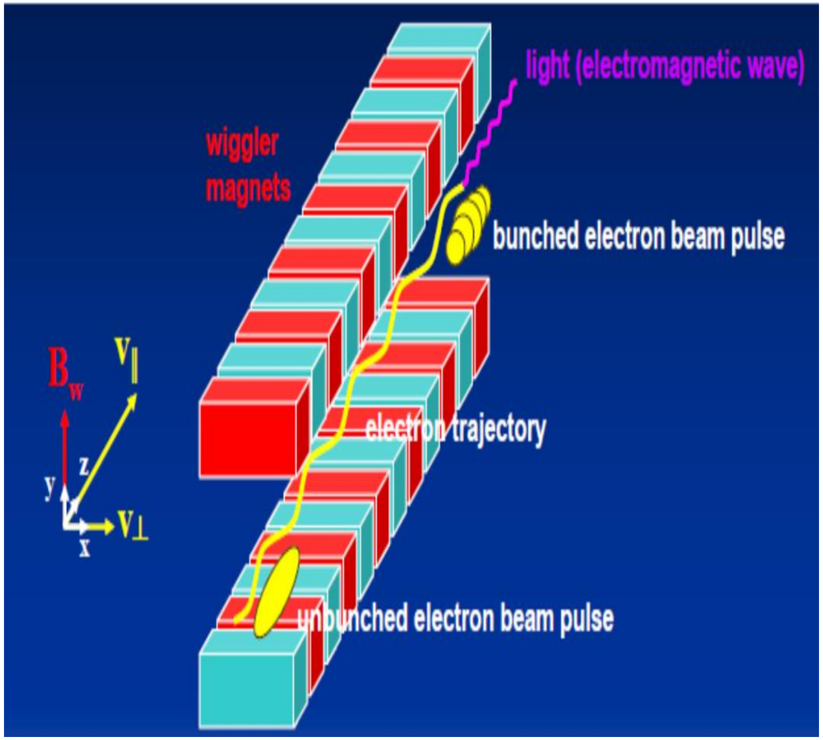
S.H. Glenzer et al., (2016): Stanford University

Free electron laser

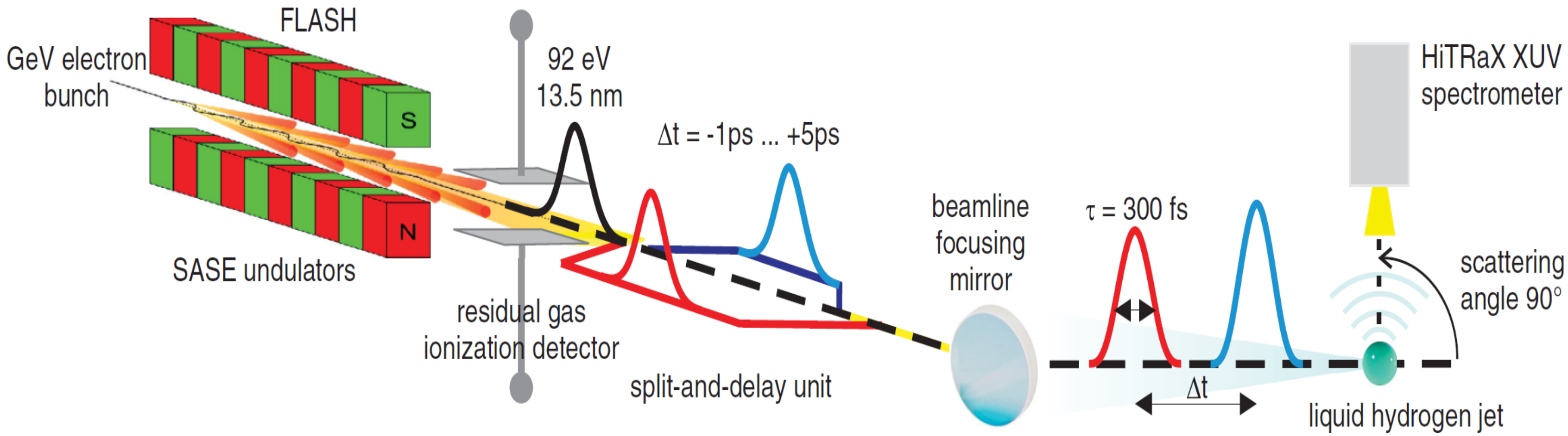
❖The free electron laser (FEL) is a device that transforms the kinetic energy of a relativistic electron beam into electromagnetic (EM) radiation.

❖Electrons in an FEL are not bound to atoms or molecules.

❖The “free” electrons traverse a series of alternating magnets, called a “wiggler,” and radiate light at wavelengths depending on electrons’ energy, wiggler period and magnetic field.

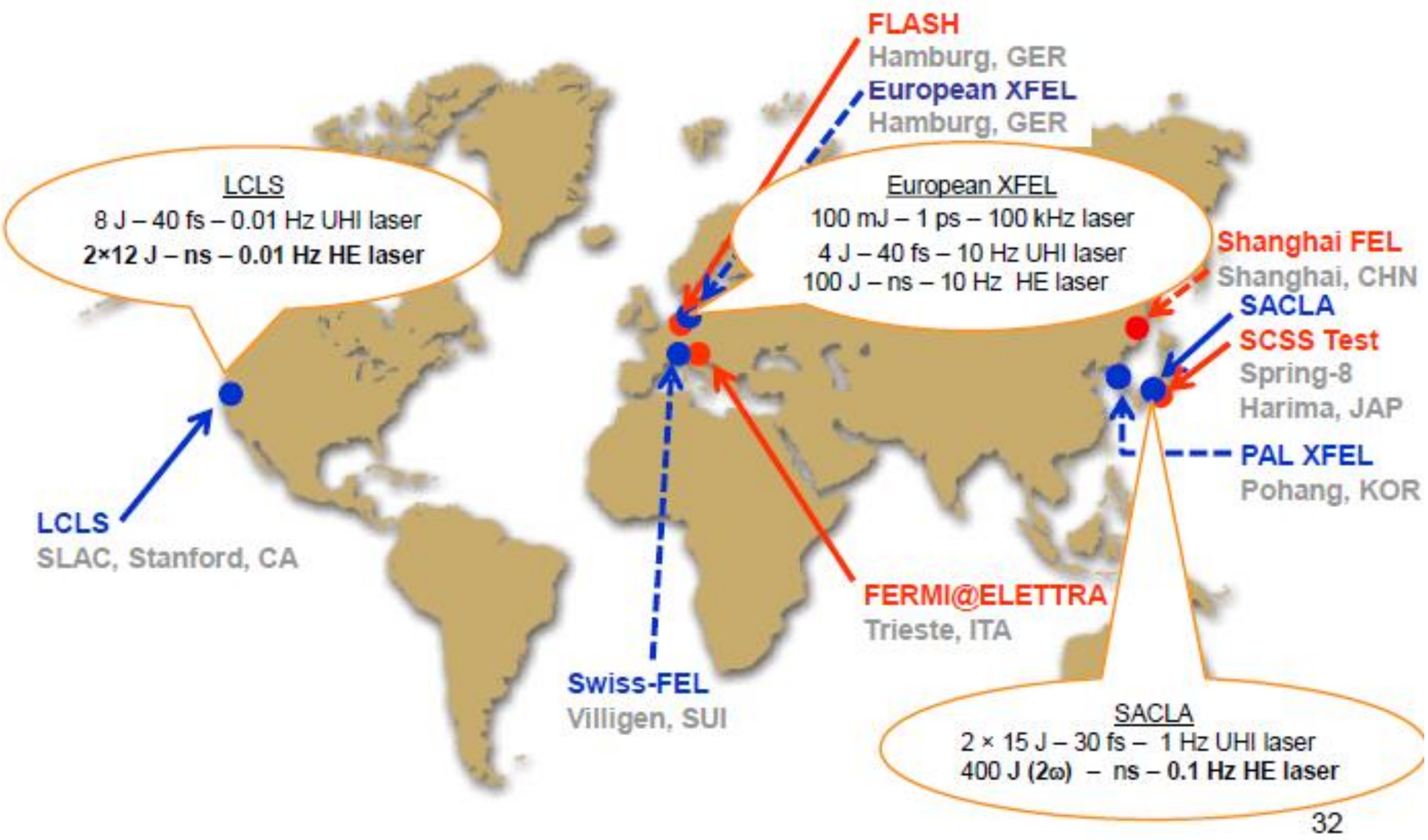


Time Delay experiment



U. Zastrau 2014: FLASH(Hamburg)

Soft/Hard x-ray lasers



Plasma Dielectric Function

- Dielectric function is a measure of how a material responds to an electric field .
- in general the response of a material to an external electric field is very complicated.
- in simple material we need a good understanding of the quantum mechanics of the atoms and molecules within the material if we want to calculate the polarization .

$$\epsilon^{l}(\vec{k},\omega) = 1 - \sum_{\alpha} \frac{\omega_{p\alpha}^{2}}{\left[(\omega + i\delta) - \vec{k}.\vec{U}_{\alpha}\right]^{2}}$$

For a non-drift plasma or non-moving plasma and collision-less plasma

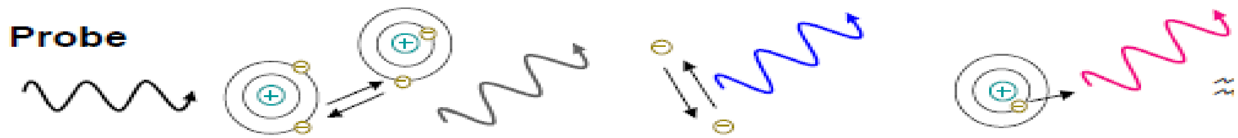
$$U_{\alpha} = 0 \;, \qquad \delta = 0$$

$$\epsilon^{l}(\vec{k},\omega) = 1 - \sum \frac{\omega_{p\alpha}^{2}}{\omega^{2}}$$

Chihara formula for

$$S_{\rm ee}^{\rm tot}(\vec{k},\omega) = Z_{\rm f} S_{\rm ee}^{0}(\vec{k},\omega) + |f(\vec{k}) + q(\vec{k})|^2 S_{\rm ii}(\vec{k},\omega) + Z_{\rm c} \int d\omega' \tilde{S}_{\rm ce}(\vec{k},\omega) S_{\rm s}(\vec{k},\omega)$$

$$S(\mathbf{k},\omega) = |f_I(k) + q(k)|^2 \, S_{\rm ii}(\mathbf{k},\omega) + Z_f \, S_{\rm ee}^{0}(\mathbf{k},\omega) + Z_c \, S_{\rm core}(\mathbf{k},\omega)$$



- First term: Dynamic structure factor of free electrons
- Second term: called the ion feature
  - $f(\vec{k})$: Form factor of the bound state density
  - $q(\vec{k})$: Screening cloud of free electrons
  - $S_{\rm ii}(\vec{k},\omega)$: Ion-ion structure factor represents the ion-ion density correlation function
- Third term: Describes inelastic scattering of strongly bound (core) electrons due to transitions to continuum states

Chihara, J.Phys.Condens.Matter 12, 123(2000)

Born-Mermin approximation

- Fluctuation-dissipation theorem :

$$S^0_{\mathrm{ee}}(k,\omega) = -\frac{\epsilon_0 \hbar k^2}{\pi e^2 n_{\mathrm{e}}} \frac{\mathrm{Im}\epsilon^{-1}(\mathrm{k},\omega)}{1-\exp(-\hbar\omega/k_{\mathrm{B}}T_{\mathrm{e}})}$$

- RPA gien by Lindhard:

- $$\epsilon^{\mathrm{RPA}}(\vec{k},\omega) = 1 - \frac{1}{\epsilon_0 \Omega_0 k^2} \sum_p e^2 \frac{f^e_{p+k/2} - f^e_{p-k/2}}{\Delta E^e_{p,k} - \hbar(i\omega + i\eta)}$$

Glenzer and Redmer, RMP 81, 1625(2009)

$$\varepsilon(k,\omega) = 1 + \frac{4}{\pi k^2}\int_0^\infty \mathcal{F}(P)p^2\,dp \times \int_{-1}^{1} d\mu\ \left[\frac{1}{k^2-2pk\mu+2\omega+i\upsilon} + \frac{1}{k^2+2pk\mu-2\omega-i\upsilon}\right]$$

$$\mathcal{F}(p) = \frac{1}{1+exp[(p^2/2-\mu)/k_BT]}$$

Real part

$$R_e[\varepsilon(k,\omega)] = 1 + \frac{2}{\pi k^3}\int_0^\infty \mathcal{F}(p)p\,dp \times [\ln\left|\frac{k^2+2pk+2\omega}{k^2-2pk+2\omega}\right| + \ln\left|\frac{k^2+2pk-2\omega}{k^2-2pk-2\omega}\right|]$$

Imaginary part

$$im[\varepsilon(k,\omega)]$$

$$= \frac{2}{k^3}\int_a^b \mathcal{F}(p)p\,dp$$

$$= \frac{2k_BT}{K^3}\log[\frac{1+\exp[(\mu-\frac{a^2}{2})/k_BT}{1+\exp[(\mu-b^2/2)/k_BT}$$

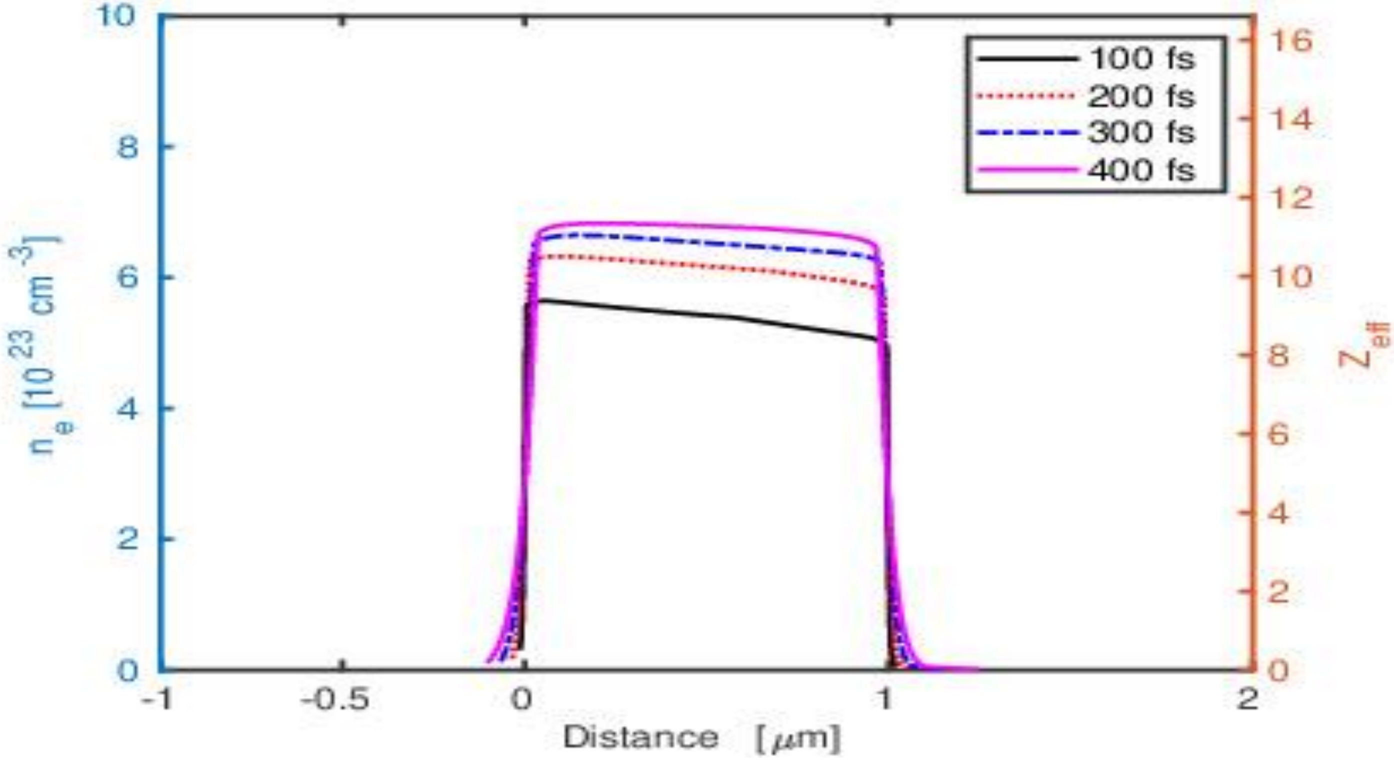
$$a = |2\omega - k^2|/2k$$

$$b = (2\omega + k^2)/2k$$

Radiation Hydrodynamic Simulation

- Helios-CR is a 1-D radiation hydrodynamic code is utilized to calculate the interaction of X-ray laser pulses with the Al foil.
- The Thickness of the foil is $1.0\ \mu m$, laser pulses 100fs, 200 fs, 300 fs, 400fs , photon energy is 1830 eV and the pulse intensity is $10^{17}\ W/cm^2$. The simulation provides a macroscopic description of the interaction

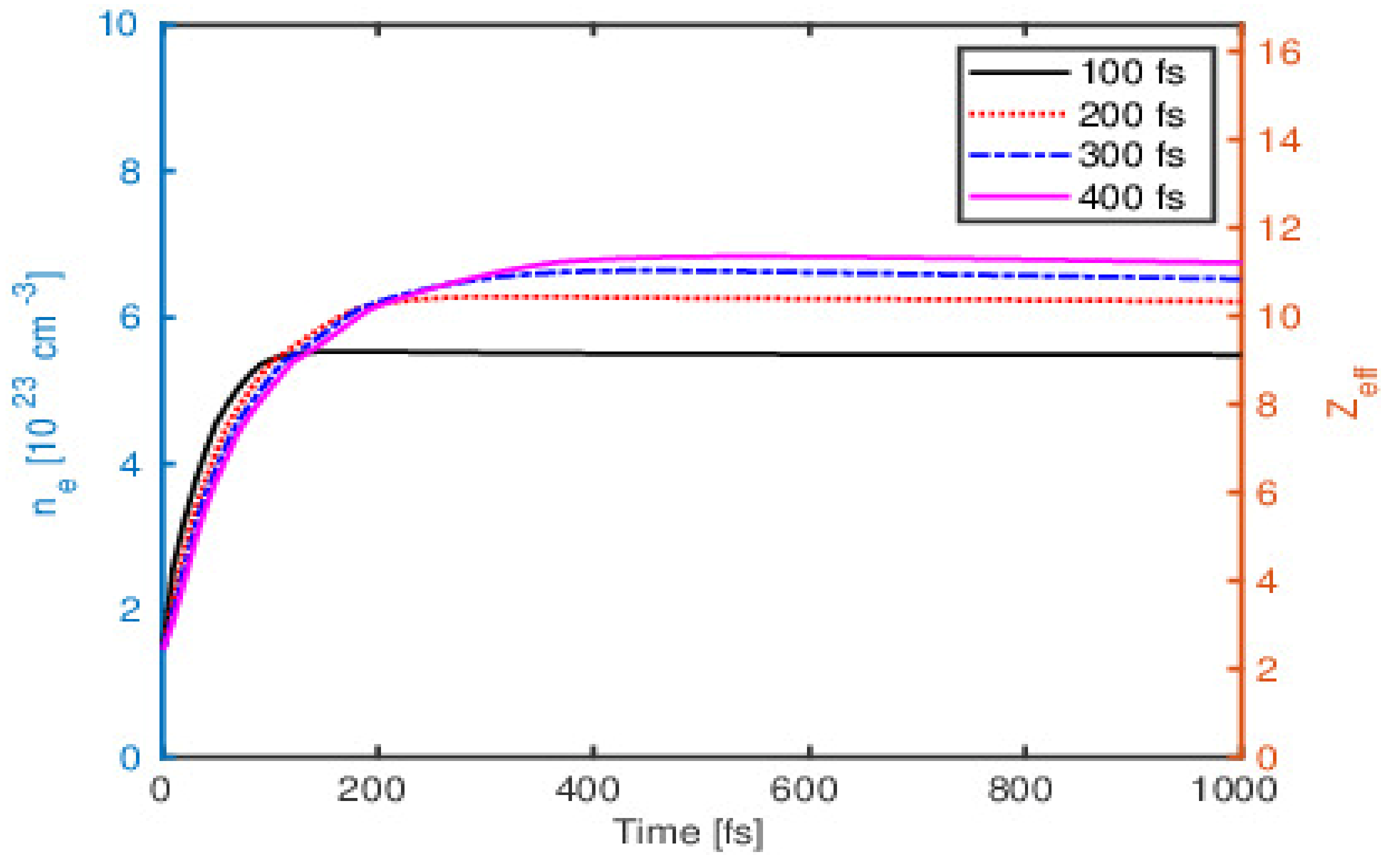
Helios Results



With increasing the pulse length deposits additional energy to the target consequently the free electrons density is increased.

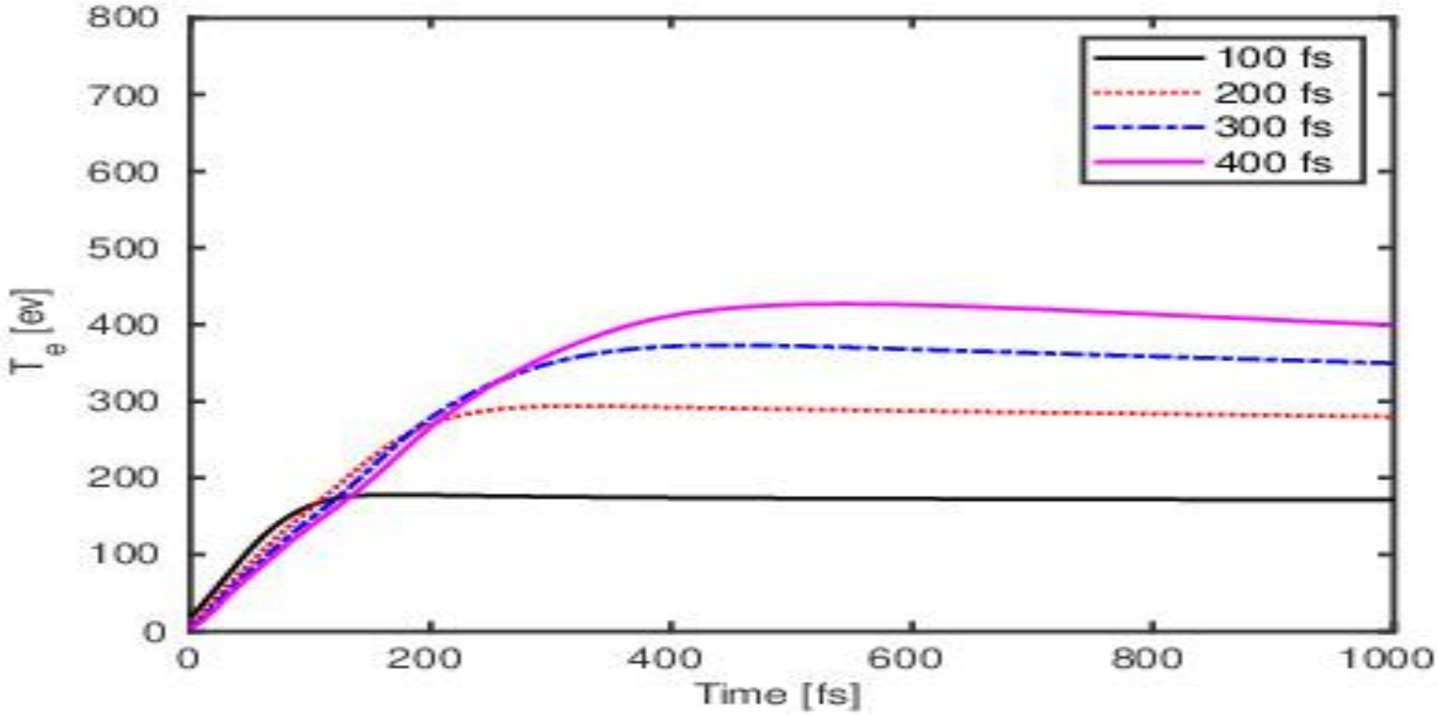
The free electron density is increases from $5.5x\ 10^{23} cm^{-3}$due to the 100 fs pulse to $7x10^{23} cm^{-3}$due to 400 fs pulse.

Helios Results



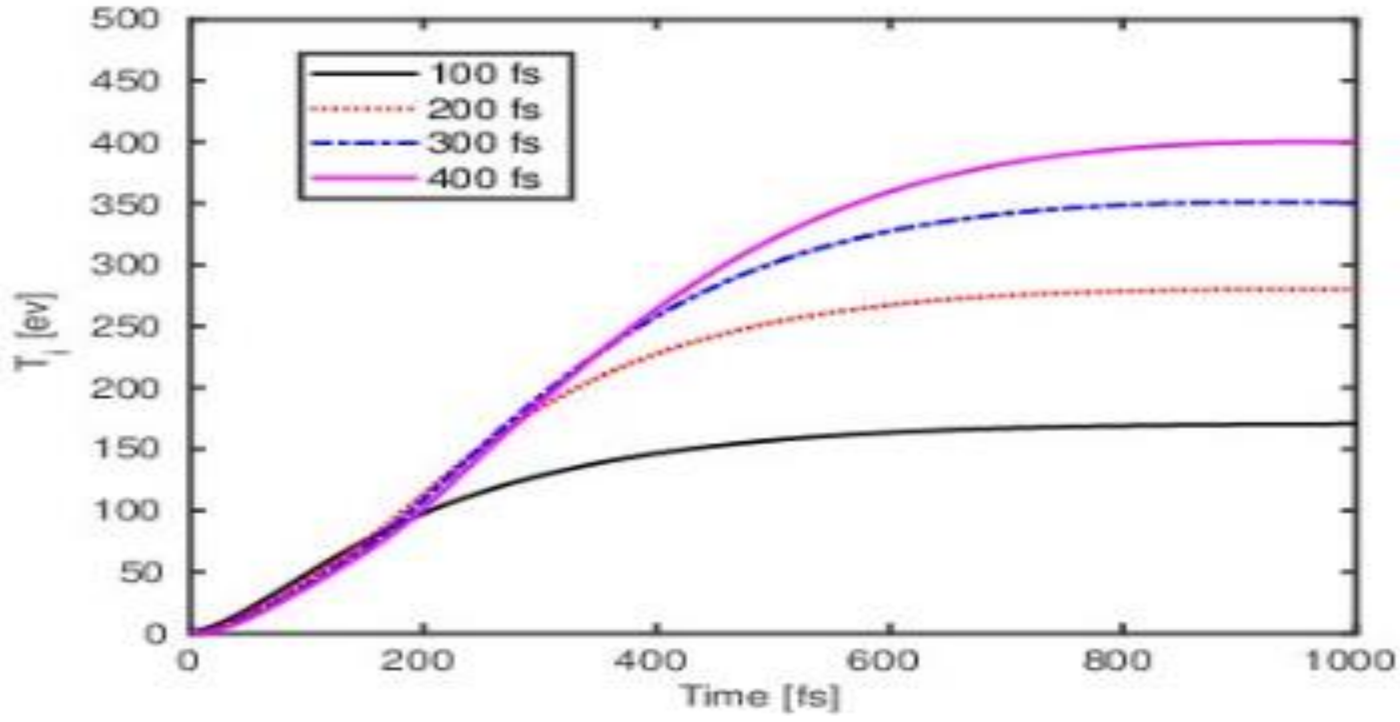
The temporal evolution of the density of free electrons and the effective charge state at the middle of the target.

The average charge increase from 8.3 to 10.6.

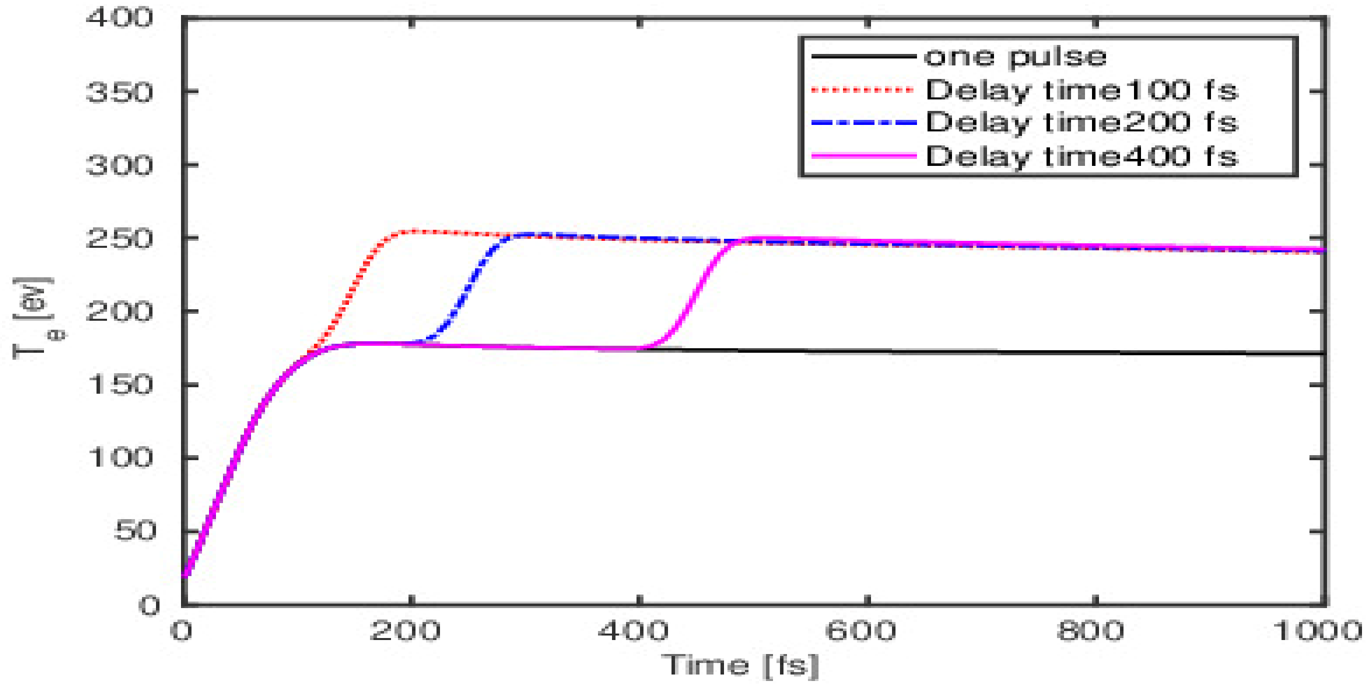


- The temporal evolution of electron temperature at the middle of the target.

- At the end of the 100 fs laser pulse, the temperature is 180 eV, while the temperature after the 400 fs laser pulse is 420 eV.



The temporal evolution of ion temperature at the middle of the target.

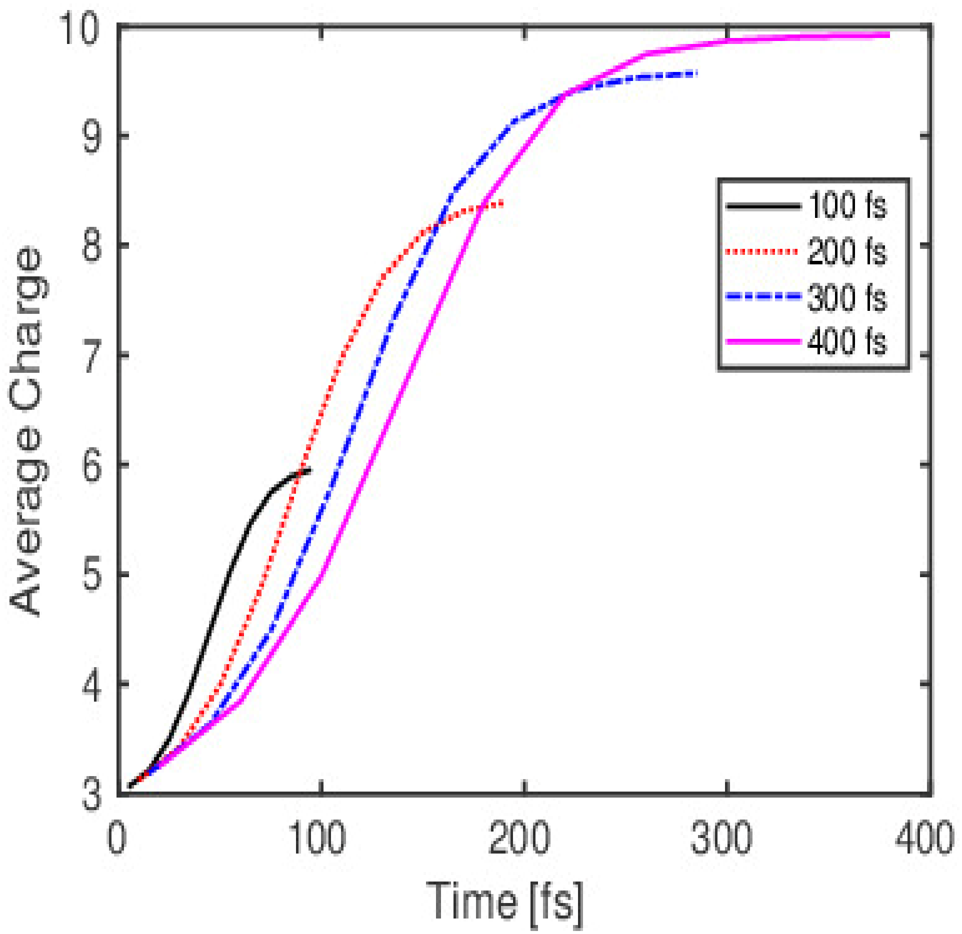


- The temporal evolution of electron temperature at the middle of target. The black solid line shows the variation of the electron temperature when one pulse is used. Other lines show the results when two pulses are used with different time.
- The second pulse increases electron temperature from 180 eV to 250 eV.

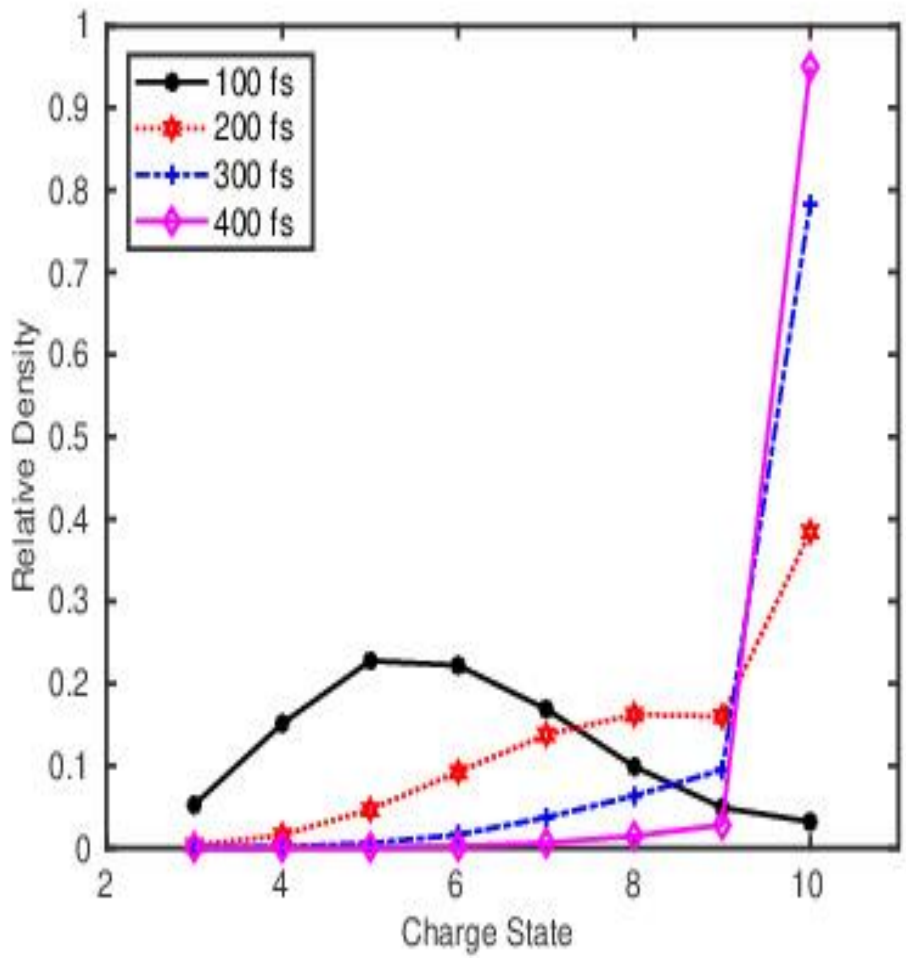
Monte Carlo Simulation

The average charge of the target as a function of time for different laser pulse lengths.

Monte Carlo calculations predict the increase of the electron density by increasing the pulse length.

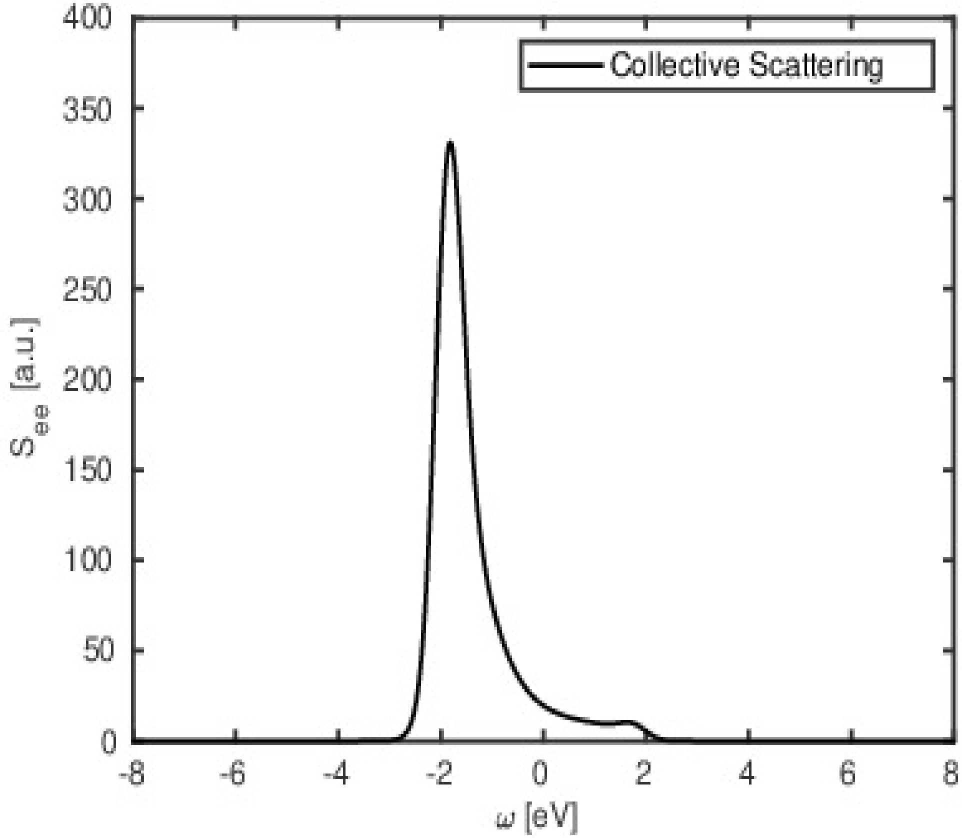


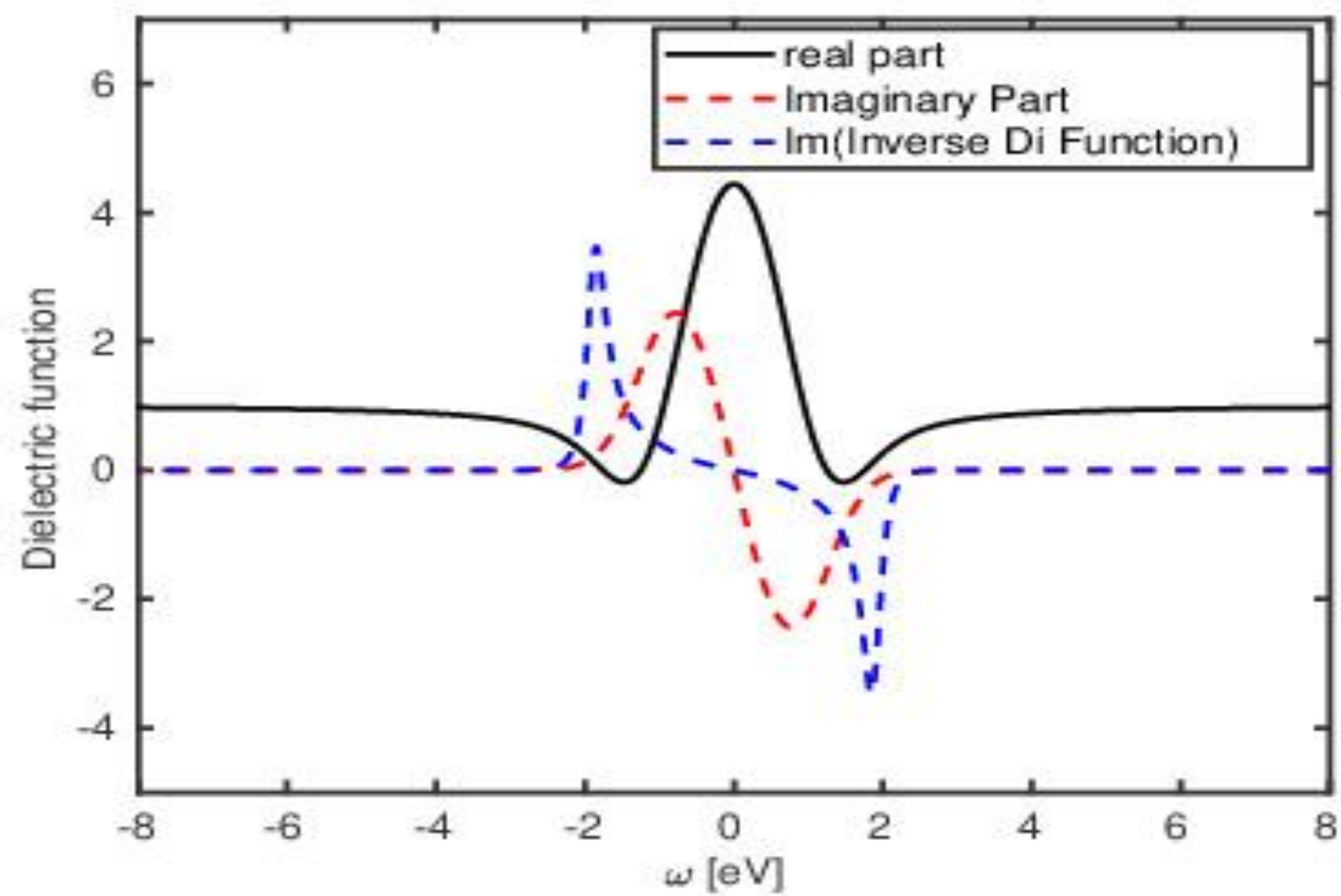
The charge state distribution at the end of each laser pulse for different pulse lengths calculated via Monte Carlo simulation.



X-ray Thomson scattering Results

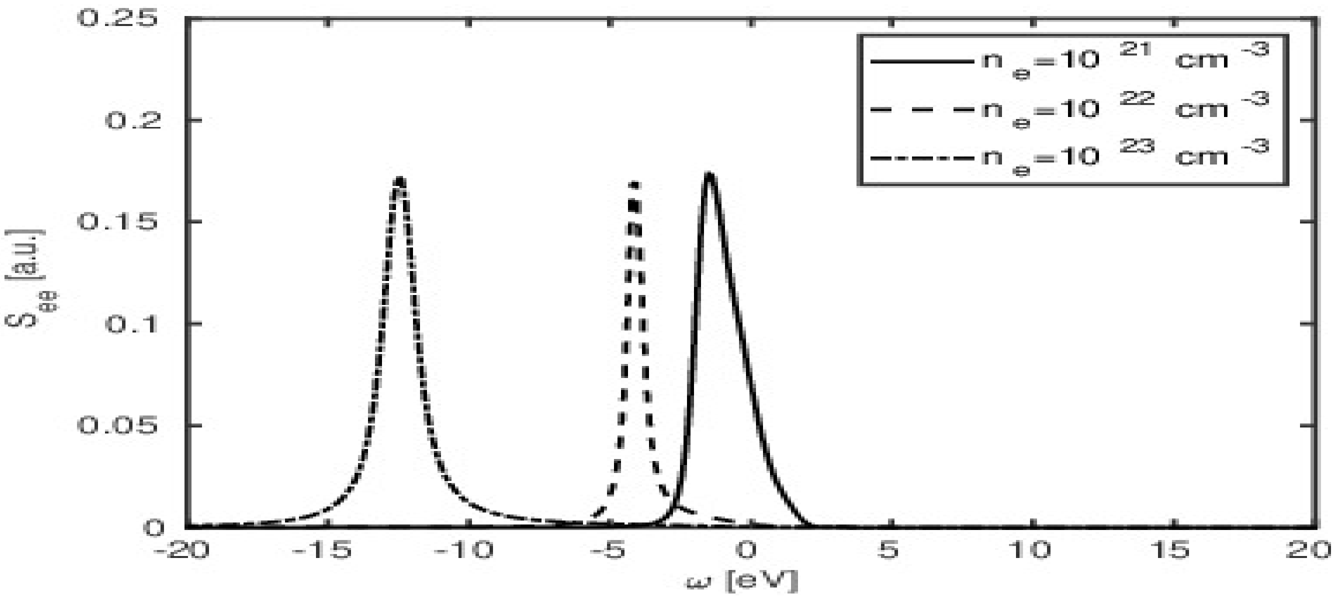
We use Warm Dense Matter with the following parameters, electron temperature $T_e = 0.5\ eV$ and $n_e = 10^{21} cm^{-3}$, laser wavelength $\lambda = 4.13\ nm$ and a scattering angle $\theta = 160$





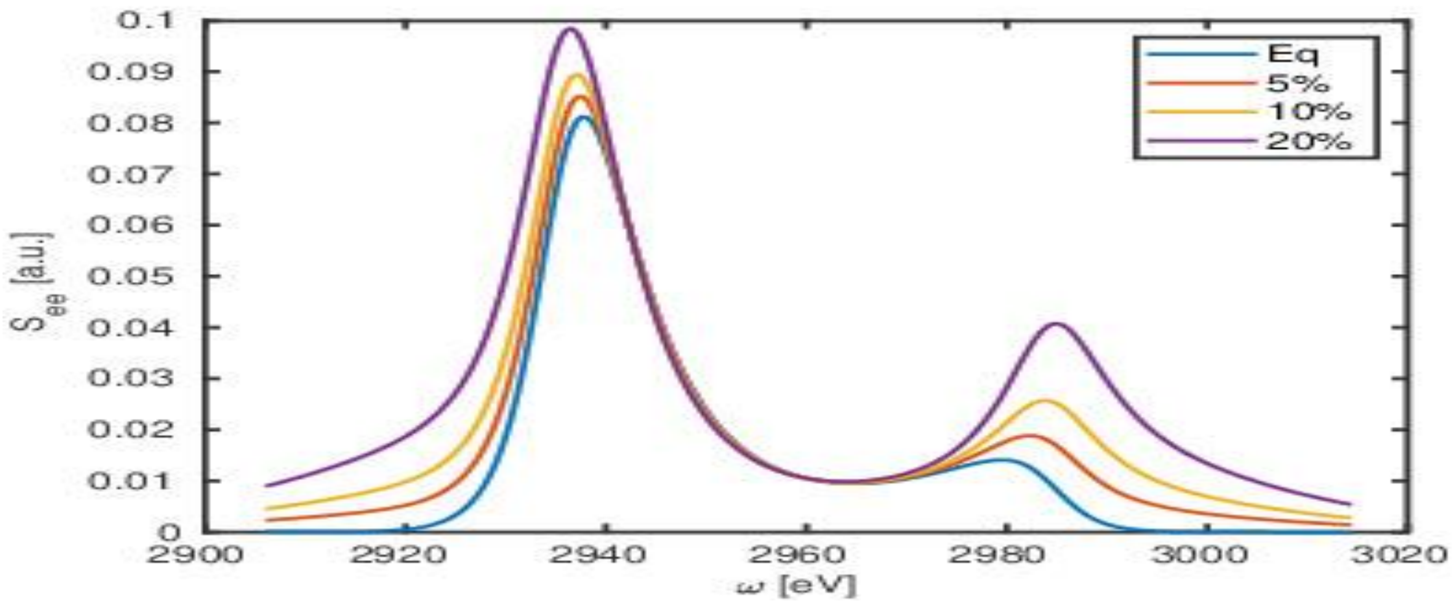
Dielectric function of electrons real part, imaginary part and inverse imaginary part

The effect of the target inhomogeneity



The calculations have been repeated again for densities 10^{22} cm^{-3} and 10^{23} cm^{-3}. The plasmon peak is shifted due to the increase of the target density. the shift of the plasmon due to the increase of the target density. Therefore, the position of the plasmon can help predicting the target density.

The effect of the temperature in-equilibrium



The electron density (n_e) is 2.46×10^{23} cm^{-3}. Four cases are considered: when the target at equilibrium with electron temperature of 12 eV, when the ratio of hot electrons with 100 eV is 5%, 10%, and 20%.

Thanks!

For more details:

M. Shihab, Y. Adel, and N.M. El-Siragy, Results in Physics 24 (2021) 104097

The financial support by ASRT is acknowledged