Modeling laser-plasma EUV sources

Moza Al-Rabban, *Dept of Physics, Qatar University, Qatar*
Franck Gilleron ,*CEA/DIF, Bruyères-le-Châtel, BP 12, F91680 Bruyères-le-Châtel, France*
Michel Poirier & Thomas Blenski, *DSM/DRECAM/SPAM, CEA-Saclay, F91191 Gif-sur-Yvette, France*
Howard Scott, *Lawrence Livermore National Lab, USA*
Martin Richardson, *School of Optics/CREOL, UCF, Florida, USA*

A Comprehensive approach to modeling EUV emission from laser plasmas

Review of fundamental laser interaction, electron transport and radiation physics associated with EUV laser plasma sources

Modeling EUV radiation from lasers plasmas involves:

- *hydrodynamic plasma fluid models, containing laser-plasma interaction physics and electron transport, to self-consistently predict plasma expansion ,electron and ion density and temperature distributions.*

- *detailed physics data of energy levels, radiation transition probabilities, collision cross-sections, radiation transport ionization and excitation, recombination coefficients etc.*

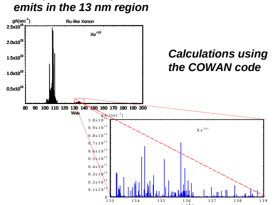
- *comprehensive 1D or 2D radiation transport and emission modeling within plasma.*

Review of computer codes currently in use, or under development to model EUV laser plasma sources

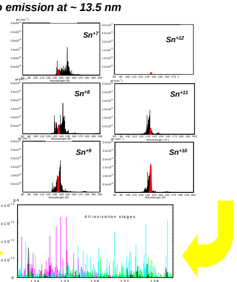
Different challenges for modeling Xe and Sn laser plasmas

In Xe plasmas, only one Xe ion emits in the 13 nm region

In Sn plasmas many ions can contribute to emission at ~ 13.5 nm



Calculations using the COWAN code

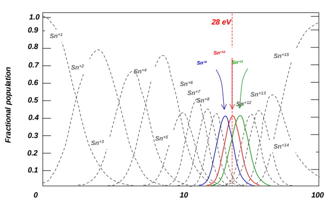


Many more Sn transitions contribute to 13. 5 nm EUV emission.

gA values are larger

Collisional Radiative Equilibrium Model predicts the Relative population of ionized states

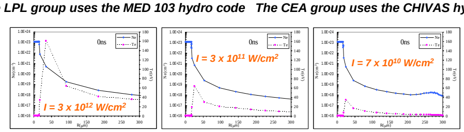
Colombant and Tonon J.Appl. Phys.44,3524, 1973



Laser coupling, energy transport and plasma expansion are usually modeled with Lagrangian fluid codes

These are one-dimensional, multi-cell (i.e. 90), two fluid, Lagrangian hydrodynamic codes containing models for most laser-plasma coupling physics, electron and radiation transport. Energy balance transport from one cell to the next is calculated self-consistently in a series of time steps. In each cell the electron and ion densities, temperatures, the average ion state and many other plasma parameters (plasma viscosity, velocity pressure etc,) are determined.

The LPL group uses the MED 103 hydro code   The CEA group uses the CHIVAS hydro code

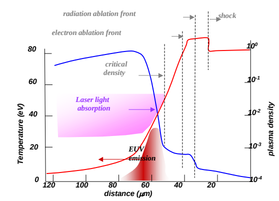


Med 103 calculation of n_e and T_e at peak of 11.5 ns laser pulse for 30% Sn-doped, 35 μm dia target

Laser plasma interaction processes

Inverse Bremsstrahlung Absorption (IBA) plays a central role in heating the plasma.

IBA converts laser energy to ions through electron excitation and collisions.
Electron excitation of ions results in EUV emission from excited ion states



Laser light absorption coefficient $\alpha_{IB} = \frac{1.08\times10^{-5}}{\lambda^2} Z^* \left(\frac{n_e}{n_c}\right)^2 \frac{\ln\Lambda}{\sqrt{1-\frac{n_e}{n_c}}} \frac{1}{T_e^{3/2}}$

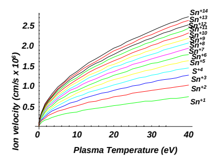
electron plasma frequency $\left(\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}\right)$ critical electron density $n_c = \frac{m_e \varepsilon_0 \omega^2}{e^2}$, $n_c[m^{-3}] = \frac{1.12\times10^{15}}{\lambda^2[m]}$

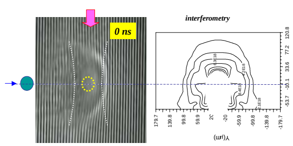
Laser light can be coupled to plasmas by other processes (Resonance Absorption, SRS, TPD…), but these processes channel laser energy to collisionless electrons -

Coulomb parameter $\ln\Lambda = \ln\left(\frac{3k_B T_e 4\pi\varepsilon_0}{Ze^2}\sqrt{\frac{k_B T_e \varepsilon_0}{e^2 n_e}}\right) = \ln\left(1.55\times10^{13}\frac{\hat{T}_e^{3/2}}{Zn_e^{1/2}}\right)$

Plasma expansion depends on target and irradiation geometry

For planar geometry $\upsilon_{exp} \approx c_s = \sqrt{\frac{Z\gamma k_B T_e}{M_i}}$ $\upsilon_{exp} = 1.26\left(\frac{Zk_B T_e}{M_i}\right)^{1/2}$ cm / s





Xe and Sn plasmas produced by nanosecond laser pulses

Simple models of laser plasmas, particularly those from low Z materials assume that radiation produced by the plasma is not absorbed (the plasma is optically thin). This is the condition of Local Thermal Equilibrium (LTE).

For a given transition, for a plasma considered to be in thermal equilibrium (LTE)

$$n_e \geq 1.7\times10^{14} T_e^{1/2} \Delta E_{u,1}^3 cm^{-3}$$

D. Giulietti & L.A. Gizzi, La Rivista del Nuovo Cimento,, (1998)

Plasmas produced by nanosecond duration lasers pulses from high Z materials cannot generally be considered to be in LTE. Considerable energy is converted into radiation, both line radiation and blackbody Planckian emission, and this radiation plays an important part in determining the population of the available energy states. This is the so-called non-LTE regime. A much more complicated energy transfer situation exists, with the opportunity for many more physics processes to occur. In addition to electron collisions, radiative de-excitation, photo-electric and recombination processes will come into play. Modeling these processes in a way is more challenging.

Low Z plasma emission line emission can be modeled with an LTE radiation transfer code

Line emission is calculated by using atomic physics codes as post-processors of the hydro code. For LTE, low Z plasmas the LPL group uses the SPECTRA code

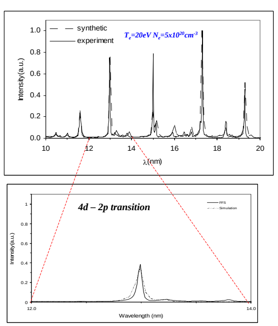
(D. Heading, et. al, Phys Rev. 1997)

This code calculates the ionization distribution, excited state populations, and allowed transitions. The atomic physics data required is acquired from the Opacity project database

Saha equation is used in conjunction with atomic database And the calculated line shapes are assumed to be Lorentzian and the line widths are based on the modified semi-empirical method (MSEM)

Width of individual lines calculated from impact approximation

$$w = N\left(v\left[\sum_{i'}\sigma_{i'i} + \sum_{f'}\sigma_{f'f}\right]\right)_{av} + w_{el}$$



Atomic models of radiative properties of Xe and Sn

Models based on single configuration approximation (viz. Average Atom model or the mono-configurational Hartree-Fock or Dirac-Fock formalism, are insufficient for modeling Xe and Sn

DTA methods require the diagonalization of the Hamiltonian in a multi-configurational basis. Different treatments lead to different codes

Direct diagonalization of the Hamiltonian
- *MCHF code - COWAN codes*
- *MCDF – GRANT & BRUNEAU codes*
- *HULLAC — HULLAC uses a parametric potential instead of an 'ab initio' potential*

Detailed Configuration Accounting (DCA) with with statistical Unresolved Array (UTA) approach allows the avoidance of direct diagonalization of the Hamiltonian and leads to a fast method of predicting the form of absorption and emission structures in the case of many close   All these methods assume the plasma is in LTE   *Bauche-Arnoult, J. Bauche, and M. Klapisch, Phys. Rev. A 20, 2424 (1979)*

Configuration Interaction – effect of multiple configurations on emission

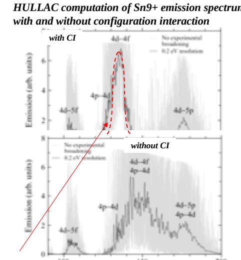
Emission from Xe and Sn plasmas in the 13 nm region primarily come from 4d–4f and 4d-5p transition arrays.

The diagonalization procedure of the multi-electron level is expanded to include one or more configurations

TWO EFFECTS
[1] For large ion charge state, the 4f wavefunction "collapses" in the inner well and the main oscillator strengths shift to the 4d–4f transition since then the 4d and 4f wavefunctions significantly overlap.

[2] CI is present in the excited states belonging to $4p^6 4d^{N-1} 4f$ and $4p^5 4d^{N+1}$ and $4p^6 4d^{N-1} 5p$ configurations

HULLAC computation of Sn9+ emission spectrum with and without configuration interaction



when CI is included, some prominent 4p–4d lines appear on the low-wavelength side of the main 130–140 Å peak.

Radiation Transfer models

Equation of Radiative Transfer $\frac{dI_\nu(s)}{ds} = \left(\frac{1}{c}\frac{\partial}{\partial t} + \vec{\Omega}\cdot\nabla\right) I_\nu(s) = \eta_\nu(s) - \alpha_\nu(s) I_\nu(s)$

s = propagation direction , I_n is specific intensity (W m^{-2} Hz^{-1} ster^{-1}).
α_ν = macroscopic absorption (m^{-1}) η_ν = emission coefficient (W m^{-3} Hz^{-1} ster^{-1})

Optical depth $\tau_\nu(s) = \int_0^s \alpha_\nu(s')ds'$

In thermal equilibrium, emission = absorption, $\eta_\nu = B_\nu\, \alpha_\nu$ Kirchoff's law $B_\nu(T) = \frac{2\pi h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$

CODES
- *CHIVAS - uses screened-hydrogenic average atom model, multi-group diffusion*
  S. Jacquemot and A. Decoster, Laser and Particle Beams 9, 517 (1991)
- *CRETIN - detailed atomic physics + general radiation transfer algorithms*
  H.A. Scott, JQSRT 71, 689 (2001)

Radiation diffusion

TWO CASES

optically thick $\tau_\nu << 1$ *optically thin $\tau_\nu >> 1$*

Radiation diffusion equation $\frac{1}{c}\frac{\partial J_\nu}{\partial t} - \frac{1}{3\alpha_\nu}\nabla J_\nu = \eta_\nu - \alpha_\nu J_\nu$ $J_\nu = \frac{1}{4\pi}\int d\Omega I_\nu$

If spectrum is Planckian

Rosseland mean absorption coefficient used to model radiative energy transport $\frac{1}{\alpha_R} = \frac{\int_0^\infty \frac{1}{\alpha_\nu}\frac{dB_\nu(T)}{dT}d\nu}{\int_0^\infty \frac{dB_\nu(T)}{dT}d\nu} = \frac{\pi}{4\sigma T^3}\int_0^\infty \frac{1}{\alpha_\nu}\frac{dB_\nu(T)}{dT}d\nu$

Planckian mean absorption coefficient models spatial energy transfer between radiation and matter $\alpha_P = \frac{\int_0^\infty \alpha_\nu B_\nu(T)d\nu}{\int_0^\infty B_\nu(T)d\nu} = \frac{1}{\sigma T^4}\int_0^\infty \alpha_\nu B_\nu(T)d\nu$