Wide-range models for optical, transport and thermodynamic properties of WDM and laser plasmas

M. Veysman, N.E. Andreev, K. Khischenko, P. Levashov

Laboratory for Theory of Laser Plasma Interaction
Joint Institute for Hight Temperatures, Moscow, Russia

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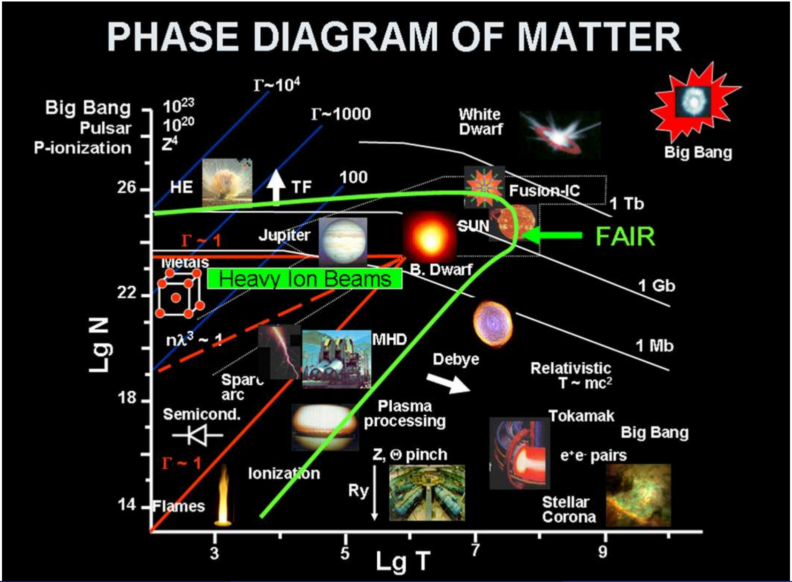
IHED JIHT RAS LTLPI EMMI GSI PHELIX Petawatt High-Energy Laser for Heavy Ion Experiments

Description of matter at extreme conditions requires elaboration of wide range models



Global aims of experimental-theoretical project:

- Diagnostic of strongly coupled laser plasma at fs time scale
- Elaboration of wide-range models for:
  - plasma permittivity ε
  - effective frequency of collisions of electrons ν_{ef}
  - Rate of electron-ion relaxation Q_{ei}
  - Thermoconductivity coefficient $q_T = K' T_e \nabla T_e$
  - Rate of thermal ionization $\varkappa_Z$
  - equilibrium average ion charge Z and potentials of ionization U_z in dens matter
  - looses of thermal energy on thermal radiation Q_{rad}; radiation thermoconductivity K_{rad} for heavy ions

Idea of combined experimental-theoretical approach:

Pump-probe measurements of complex reflection coefficient; measurements of self-reflectivity

$$\Downarrow$$

Fitting of numerical constants to experimental data in wide-range models for optical, transport & thermodynamic properties of plasma

$$+$$

Comparison with first - principle calculations

$$\Downarrow$$

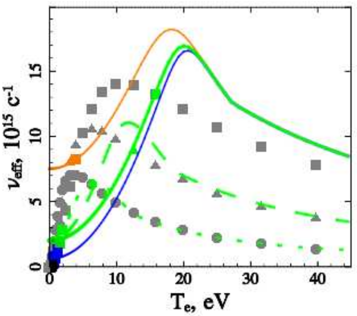
Hybrid hydro-electro-ionization code

$$\Downarrow$$

Calculation of parameters of laser plasmas in space & time

Proposal 1: measurements of maximum of absorption:

Theoretical results: comparison [1] of Quantum statistical and wide-range models for effective frequency of collisions ν_{eff}



calculations for $\lambda_L = 0.4$mkm, Al:

Lines: semi-empirical theory.

Green lines: $T_i = 0.4$eV, $\varrho = \varrho_{solid}, \varrho_{solid}/3, \varrho_{solid}/10$ for solid, dashed, dotted lines.

Blue line: $T_i = 0.1$eV, $\varrho = \varrho_{solid}$.

Orange line: $T_i = 1.5$eV, $\varrho = \varrho_{solid}$.

Markers: Quantum Statistical approach, $T_i = T_e$, $\varrho = \varrho_{solid}$(squares), $\varrho_{solid}/3$ (triangles), $\varrho_{solid}/10$ (circles)

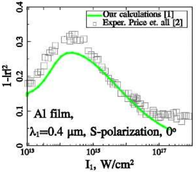
1 M. Veysman, N.E. Andreev, P. Levashov, K. Khishchenko, H. Reinholz, G. Roepke, A. Wierling, M. Winkel, report on XXX European Conference on Laser Interaction with Matter, 31.08 5.09.2008, Darmstadt, Germany

Proposal 1: measurements of maximum of absorption:

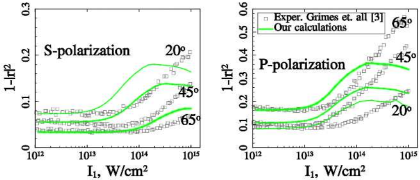
Experimental results: Different experiments [1-3] give different results for maximum of absorption $A = 1 - |r|^2$!

Where is the maximum? $I_{A=max}(\tau_L) = ?$ $I_{A=max}(\lambda_L) = ?$

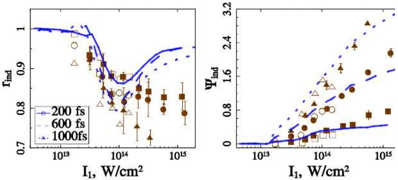
Self-reflectivity: experiment of Price et. all [2] and our calculations [1] (lines).
$\lambda_L = 0.4$, $\theta = 0^o$, $\tau_{FWHM} = 120$fs



Self-reflectivity: Experiment of Grimes et. all [4] and our calculations [1] (lines). $\lambda_L = 0.62\mu$m, $\tau_{FWHM} = 120$fs.



Experiment of Sitnikov et. all [3] and our calculations [1] (lines).
$\lambda_{pump} = 1.24$, $\theta_{pump} = 45^o$,P-polar.;
$\lambda_{prob} = 0.62$, $\theta_{prob} = 0^o$,S-polar.; $\tau_{FWHM} = 100$fs



1 Agranat M B, Andreev N E, Ashitkov S I, Veisman M E at. all, 2007 *JETP Lett.* **85** 271; Veysman M E, Agranat M B, Andreev N E, Ashitkov S I et. all, 2008 *J. Phys. B: At. Mol. Opt. Phys.* **41** 125704.

2 D.F. Price, R.M. More, R.S. Wang, G. Guethlein et. all, Phys. Rev. Lett., **75**, 252 (1995).

3 D S Sitnikov, S I Ashitkov, P S Komarov, A V Ovchinnikov, submitted to SCCS proceedings, 2008

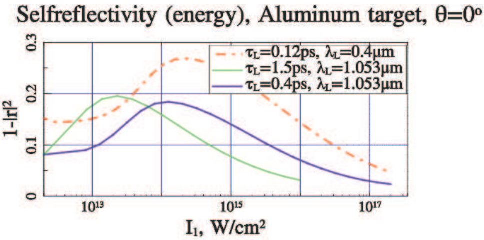
4 M. K. Grimes, A. R. Rundquist, Y.-S. Lee, and M. C. Downer Phys. Rev. Lett., **82**, 4010 (1999).

Proposal 2: role of plasma expansion:

comparison of optical properties of plasmas created by:

- ▷ short laser pulses ($\leq$ 0.4ps)

  calculation of self-reflectivity of laser pulse with different durations as function of laser intensity I_L



- ▷ longer laser pulses ($1.5 \div 50$ps)
- ▷ ion beams

Proposal 3: diagnostic of ionization:

- **Spectroscopic diagnostic of multiply charged ions, created during thermal ionization of matter at the surface of solid target irradiated by heating laser pulse**

What is experimental dependence of $Z(I_L)$, $Z(\tau_L)$, $Z(t)$?

Semi-empirical lowering of ionization potentials:

$$\boxed{\Delta U_z = -U_z(\varrho/\varrho_0)^{1/3}\left[1 - \min(k_z z^{\beta_z})\right]}$$

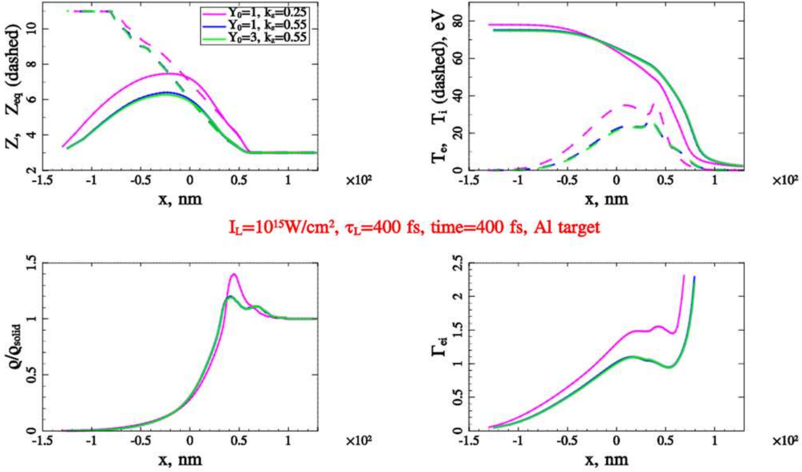
Semi-empirical formula [D. Fisher et. all, Laser Phys. 2006] for Ionization rate in dense plasmas:

$$\varkappa_z = 6\,10^{-8}\,\frac{\mathrm{cm}^3}{\mathrm{s}}\,\frac{U_H}{U_z}\sqrt{\frac{U_H}{T_e}}q_z\,\mathfrak{J}\left(\frac{U_z}{T_e},\frac{E_F}{T_e}\right),$$

$$\mathfrak{J} = \frac{3\sqrt{\pi}}{4}\frac{\epsilon_z}{\epsilon_F^{3/2}}\int_1^\infty \frac{\ln(t)(1-1/t)\boxed{Y(\epsilon_F)}\,dt}{\left[1+e^{\epsilon_z(1-t)/2+\epsilon_\mu}\right]^2\left[1+e^{\epsilon_z t-\epsilon_\mu}\right]},$$

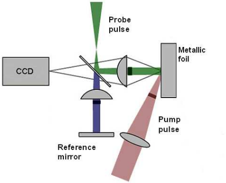
$\epsilon_z \equiv U_z/T_e,\ \epsilon_F \equiv E_F/T_e,\ \epsilon_\mu \equiv \mu(E_F/T_e)$

calculation for different models of ionization and ionization potentials



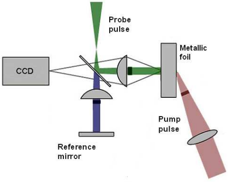
Proposal 4: measurements of heat propagation rate:

◇ **Reflection properties of the back side of irradiated foil will depend on the rate of thermal wave propagation (thermoconductivity)**



Experiment[1]: measurements of complex reflectivity by femtosecond time-rezolved interferometry

1 Agranat M B, Andreev N E, Ashitkov S I, Veisman M E at. all, 2007 *JETP Lett.* **85** 271; Veysman M E, Agranat M B, Andreev N E, Ashitkov S I et. all, 2008 *J. Phys. B: At. Mol. Opt. Phys.* **41** 125704.



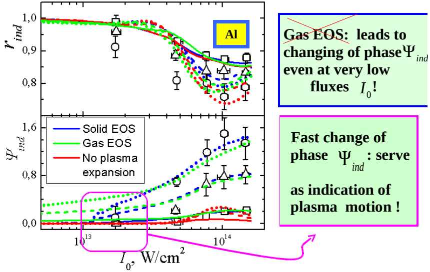
Proposed experiment: measurements of complex reflectivity of the back side of metallic foil by femtosecond time-rezolved interferometry

Proposal 5: study of phase transitions:

Influence of phase transitions on optical properties in the vicinity of melting temperature:

- ◇ depletion of interband transitions, $\sigma_{IB} \to 0$
- ◇ electron optical mass $m_{opt} \to 1$
- ◇ jump in ν_{ef}
- ◇ (?) jumps in thermocapacity, thermocoductivity, relaxation rate

Relative amplitude r_{ind} and phase Ψ_{ind} of reflected probe pulse with different models of plasma expansion:



Conclusions

- Studies of WDM created by laser or ions beams at (sub)picosecond time scales require wide-range models for optical, transport & thermodynamic properties
- Proposals for experiments at PHELIX are formulated:
  - measurements of maximum of absorption & it's dependence on beam parameters
  - role of plasma expansion
  - measurements of the rate of thermal wave propagation
  - experimental studies of ionization state of WDM
  - experimental studies of phase transitions