Book of Abstracts

Schedule for the RPHDM 2018 Workshop

Talk durations 30 min or 20 min, including discussion

Monday 22.10.18

Welcome 9:00

E. Weckert (Photon Science Director at DESY) & T. Tschentscher (Scientific Director at EuXFEL)

30'

Session 1 9:30-11:10 ***Plasma Spectroscopy***
Chairperson: R. W. Lee

E. Stambulchik
Forbidden-Line Satellites as a Probe of HED Plasmas
30 '

C. Brown Absorption spectroscopy of low-density, low-temperature and low-Z plasmas
30 '

O. Renner X-ray spectroscopic characterization of hot electron evolution inside kJ-laser irradiated Cu foil
20 '

F. Dipti Analysis of Nike x-ray spectra from highly-charged ions of Al and Si
20 '

Monday 22.10.18

Session 2 11:30-13:00 ***Plasma Theory I***
Chairperson: U. Zastrau

J. Meyer-Ter-Vehn New results on photon absorption in high-energy-density matter
30 '

H. Kitamura Femtosecond thermalization dynamics of keV electrons in metals
20 '

Z. Moldabekov Structure factor of strongly coupled ions in dense quantum plasmas
20 '

F. Gilleron Statistical modeling of Stark-broadened levels and lines of hydrogenic system
20 '

Monday 22.10.18

Session 3 14:00-16:00 ***Plasma Theory II***
Chairperson: F. Wang

J. Yuan	Enhanced Photoionization Cross Section of Ions In Hot Dense Plasma By the Temporal Space Localization of the Ejected Electron	30 '
C. Gao	Multiple-core hole states production in the interaction of solid-state density plasmas with a relativistic optical and x-ray free electron laser	30 '
G. Williams	The impact of free electron degeneracy on collisional rates in plasmas	20 '
Y. Hou	Multi-ion molecular dynamics and elastic X-ray Thomson scattering of dense plasmas	20 '
P. Sterne	Ionization Potential Depression Calculations for Compressed Materials	20 '

Monday 22.10.18

Session 4 16:30-18:20 ***Plasma Simulations***
Chairperson: Y. Ralchenko

S. Hansen	Review of the 10th Non-LTE Code Comparison Workshop	30'
H. K. Chung	Recent developments of the generalized collisional-radiative model using screened hydrogenic configurations for high energy density physics applications	20'
I. Golovkin	New Prism EOS and Opacity Tables with NLTE Atomic Kinetics	20'
I. Vichev	THERMOS Toolkit: Software and databases package for properties calculations of LTE and Non-LTE plasmas	20'
M. Sherrill	Pursuing Large Scale Self-Consistent Atomic Kinetic and Radiation Transport Simulations	20'

Tuesday 23.10.18

Session 5 9:00-11:10 ***Astrophysics & Magnetized Plasmas***
Chairperson: S. Toleikis

J. Bailey	Benchmark experiments for the radiative properties of astrophysical plasmas 30'
S. Rose	Observing the two-photon Breit-Wheeler process for the first time 30'
R. Mancini	Plasma heating and atomic kinetics of laboratory photoionized plasmas 30'
R. Doron	Magnetized plasma compression: measurement of the compressed magnetic field and what can we learn from it? 20'
S. Ferri	Atomic physics developments for the characterization of highly-magnetized HED plasmas 20'

Tuesday 23.10.18

Session 6 11:30-13:00 ***Opacity I***
Chairperson: M. Fajardo

D. Hoarty A burnthrough experiment to measure iron opacity at conditions close to the solar radiative zone/convection zone boundary

30'

R. Shepherd Line transfer effects on inferring plasma conditions in buried layer experiments
30'

T. Gomez An Effort to Reconcile Electron-Broadening Theories
30'

Tuesday 23.10.18

PhD Students' Session 14:00-16:00
Chairperson: H. Yoneda

M. Banjafar	Theoretical study on grazing-incidence x-ray scattering of surfaces upon high-intensity laser irradiation 30'
J. J. Bekx	Ab initio calculation of electron impact ionization for ions in exotic electronic configurations 30'
Y. Michine	1s-4p hard x-ray lasers of Cu atoms with strong injection seeding 30'
R. R. Sheeba	Synthetic diagnostics based on hydrogen Balmer series in recombining plasmas in magnetic fusion devices 30'

Poster Session 16:30 – 18:00

Wednesday 24.10.18

Session 7 9:00-11:00 ***Opacity II***
Chairperson: S. Pikuz

W. Johnson	Opacity of Shock-Heated Plasmas 30'
T. Nagayama	Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions 30'
A. Neukirch	Atomic data for low temperature mid-Z elements for lithography applications 20'
J. -C. Pain	Uncertainties in opacity measurements 20'
J. Rosato	Questioning the validity of the radiative transfer equation in regimes of strongly coherent radiation 20'

Special Session 11:30-13:00

Thursday 25.10.18

Session 8 9:00-11:00 ***XFELs – developments & applications I***
Chairperson: J. Wark

H. Yoneda Bragg diffraction type hard x-ray laser pumped with intense XFEL pulses
30 '

M. Yurkov Potential of the European XFEL for generating radiation with TW-level peak power and Joule-level pulse energy#
30 '

S. Glenzer Resolving the ongoing controversy about the conductivity of warm dense Aluminum
30'

F. Rosmej First observation of resonance pumping in seeded mode of X-ray line profiles of highly charged ions in dense plasmas at LCLS
30'

Thursday 25.10.18

Session 9 11:30-13:10 ***XFELs – developments & applications II***
Chairperson: T. Tschentscher

R. Santra Molecular imaging and plasma formation
30'

H. J. Lee A spectroscopic study of keV solid-density Fe plasma isochorically heated by LCLS X-ray FEL

30'

N. Medvedev Solids underway to warm dense matter state

30'

Friday 26.10.18

Session 10 9:00-11:00 ***ICF and High -Intensity-Laser Related Experiments***
Chairperson: S. Bastiani-Ceccotti

M. Macdonald

Diagnosing the hot-spot electron temperature from x-ray continnum emission measurements on NIF and OMEGA implosions

30'

M. Poirier Extreme-UV absorption processes in a laser-produced mid-Z plasma : measurements and theoretical interpretation

30'

E. Marley The Study of M-shell Gold Ionization in NLTE Plasmas Using a Buried Layer Platform at the OMEGA Laser

30'

D. Mariscal Proton Isochoric Heating and Warm Dense Matter Studies in the Multi-ps, kJ-class Laser Regime

30'

Friday 26.10.18

Session 11 11:30-13:10 ***ICF - simulations***
Chairperson: R. Cauble

H. Scott — Using Tabulated Non-LTE Data for Hohlraum Simulations

30'

P. Hatfield — Machine learning and algorithmic methods in Plasma Physics

30'

D. B. Thorn — Mass-temperature distributions within ICF implosions on the National Ignition Facility

20 '

Y. Frank — Analysis of the hydrodynamic conditions in non-LTE buried layers experiments using 1 & 2 D simulations

20 '

Workshop Adjourns

Posters:

1	
D. Benredjem	Plasma potential and opacity calculations
2	
T. Doeppner	X-ray Scattering Measurements from 30-fold Compressed, Near-Degenerate Plasmas at the National Ignition Facility
3	
S. Frydrych	Species separation in warm dense matter
4	
C. Gao	Ultrafast electron dynamics in a solid-density aluminium interacting with an ultra-intense ultrafast x-ray pulse
5	
V. Golovkina	Efficient Modelling of K-shell Emission for Short-Pulse Laser Experiments in SPECT3D
6	
M. Jullien	Neon photo-ionized plasma at LULI
7	
G. Kang	Femtosecond measurement of d electron dynamics in non-equilibrium warm dense copper using XFEL
8	
D. Kim	EUV-source modeling using radiation-hydrodynamics method with RALEF-2D code
9	
M. Kruse	Two-photon absorption cross section calculations related to the Iron opacity Sandia Z-experiment
10	
Y. Kurzweil	Surrogate Experiments for Evaluating the Opacity Model accuracy in the Deep Solar Interior Using the Micro-Equivalence Principle

11

R. Mancini — Stark-broadened line shapes of Ar K-shell ions: a comparison between molecular dynamics simulations and MERL results

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A. Morana — X and XUV spectroscopy of ps laser-produced Al and C plasmas

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K. McLean — Corrections to 3T Modelling of radiation-matter energy exchange

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C. Min Sang — Ultrafast Dynamics of Excited Electron Distribution in Warm Dense Aluminum

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Z. Moldabekov — Effect of the dynamical electron collision frequency on the quantum wakefield around an ion in dense plasmas

16

J. -C. Pain — Theory of opacity from two-photon absorption processes

17

G. Perez-Callejo — The use of geometric effects in diagnosing ion density in ICF related Dot Spectroscopy experiments

18

R. Piron — Average atom model calculations of dense plasma properties relevant to white dwarf stars

19

J. Rosato — Stark-Zeeman line shape models for the diagnostic of magnetic fusion plasmas

Forbidden-Line Satellites as a Probe of HED Plasmas

Oscillations and instabilities of various types are ubiquitous in plasma. With the dispersion relations dependent on plasma properties (such as density, temperature, and magnetic field), detection of the plasma oscillations can be used for diagnosing the plasmas. A diagnostics of this kind is based on the Thomson scattering off the collective plasmon (Langmuir) oscillations, usually employing visible or near-visible laser light for probing dilute or moderately dense plasmas, but also widely used in the HEDP science using x-ray sources.

Another spectroscopic phenomenon tightly related to the plasma waves is the appearance of so-called forbidden-line satellites. Such satellites have been observed in moderately dense plasmas using transitions in the visible spectrum. Similarly to the Thomson scattering, the application of this technique to high-density plasmas would require x-ray spectroscopy. To the best of our knowledge, this has not been previously considered or implemented, even though the oscillatory electric fields in transient HED plasmas may reach very high values, significantly exceeding the thermal- equilibrium levels.

Here, we present results of lineshape modeling demonstrating this effect in HED plasmas, including laser-induced WDM, with extensive PIC simulations confirming feasibility of such a diagnostics – and the first evidence of observing solid-state-density WDM oscillations with a _TV/m amplitude experimentally.

This work was supported by the German–Israeli Foundation for Scientific Research and Development (GIF), grant 712059.

Primary author(s) : Dr. STAMBULCHIK, Evgeny (Weizmann Institute of Science, Israel)

Absorption spectroscopy of low-density, low-temperature and low-Z plasmas

Measurements of the equation of state of low-Z materials at temperatures of 10 - 50 eV and densities of 0.004 - 0.01g/cc taken at the Orion laser facility will be presented. Samples of boron and magnesium fluoride were radiatively heated using ns-scale laser pulses and allowed to expand to mg/cc densities. Simultaneous measurements of drive temperature, sample density and sample ionization have been made to constrain the material equation of state in this regime for comparison to model predictions. The sample ionization was measured using high-resolution point-projection absorption spectroscopy in the photon energy range of 120 - 1200 eV, diagnosed with a reflection grating spectrometer. The K-shell opacity of the material of interest was matched with the population kinetics and spectral modeling codes FLYCHK and CASSANDRA to obtain average ionization. Results indicate that atom-in-jellium models such as Inferno/Purgatorio provide a better match to measurements than simpler Thomas-Fermi scaled models.

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X-ray spectroscopic characterization of hot electron evolution inside kJ-laser irradiated Cu foils

Hot electron (HE) production driven by instabilities accompanying the laser plasma interaction [1] is of paramount interest for the inertial confinement fusion science and high energy density physics. Their accurate characterization is crucial for interpretation of high-intensity laser matter experiments. Here we report studies of non-thermal atomic states in kJ-laser produced plasmas allowing to characterize HE generation with respect to their fraction and temporal evolution. The action of HE was visualized via high-resolution x-ray spectra emitted from the laser-deflected part of the 1.5-μm-thick Cu foil. Hot electrons are penetrating the accelerated foil and produce the K-shell emission in rather cold dense matter that otherwise would not emit x-rays. A quantitative analysis of the measured spectra based on 2D hydrosimulations [2] and non-Maxwellian kinetics [3] indicates that hot electrons are produced significantly after the laser maximum. Good agreement between experimental observations and simulations indicates that a combination of advanced high-resolution x-ray spectroscopy and non-thermal atomic physics spectral modelling offers a novel method to characterize hot electrons inside the laser accelerated solid density matter. In the same time, fine spectral features identified in x-ray emission originating from several Cu charge states represent a set of precise spectroscopic data capable to benchmark the state-of-the-art multiscale nonlinear hydrodynamic modelling of the laser-plasma interaction.

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[1] G. Cristoforetti et al, Phys. Plasmas 25 (2018) 012702.
[2] A. Colaitis et al, Phys. Rev. E 92 (2015) 041101.
[3] F.B. Rosmej, X-ray emission spectroscopy and diagnostics of non-equilibrium fusion and laser produced plasmas. Taylor & Francis (2012).

Primary author(s) : Dr. RENNER, Oldrich (Institute of Physics & ELI-Beamlines, Academy of Sciences, CR)

Analysis of Nike x-ray spectra from highly-charged ions of Al and Si

Highly-ionized plasma was produced by focusing the Nike multibeam KrF laser UV radiation onto flat thin foils of Al and Si. The overlapping 44 focused beams create a smooth profile of 750 μm FWHM and 375 mm flat top thus producing plasma of a submillimeter size.

Each shot delivers 1540 J of 246.8 nm radiation in a 4-ns pulse [1]. The x-ray spectra were recorded by a survey spectrometer based on a convex mica crystal with the 2d spacing of approximately 19.95 Å. The target was observed from about 20 cm at approximately 45 degrees to the normal. A wide range of the Bragg angles from glancing to almost normal brings the x-ray wavelength coverage from just above 0 Å to about 18 Å. Crystals of mica are known to have good efficiency in many orders of Bragg reflection. In this experiment, spectra with the best resolution were observed in the third order of reflection.
The measured spectra contain well-identifiable lines from H-like and He-like ions of both elements. The Lyman series up to Le with n = 6 and He resonance lines up to n = 4 along with the dielectronic satellite lines originating from these ions were clearly resolved.

The Inglis-Teller limit of the Lyman series gives the estimates of the electron density ne_ 4.8x10ˆ20 cmˆ{-3} and ne _ 6.0x10ˆ20 cmˆ{-3} for Al and Si plasmas, respectively. A detailed analysis of the spectra was performed with the collisional-radiative code NOMAD [2] with account of ionization potential lowering, opacity effects, and spectral line broadening.

Several line ratios that show strong dependence on the electron density and/or temperature Te were used for plasma diagnostics. The Stark-broadened profiles of the Lyman series and the continuum spectra were analyzed as well to provide independent estimates of ne and Te, respectively.

[1] S. Obenschain, R. Lehmberg, D. Kehne, F. Hegeler, M. Wolford, J. Sethian, J. Weaver, and M. Karasik, Applied Optics 54 (2015) F103-F122.

[2] Yu. Ralchenko and Y. Maron, J. Quant. Spectr. Rad. Transf. 71 (2001) 609-621.

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New results on photon absorption in high-energy-density matter

Photon absorption in fully ionized, hot dense matter is treated as inverse bremsstrahlung, starting from Sommerfeld's quantum-mechanical cross-section for bremsstrahlung and using detailed balance relations. The underlying dynamic electron-ion collision frequency is found as an integral over the bremsstrahlung cross-section and Fermi distribution functions. This is evaluated numerically and in terms of limiting asymptotic expressions. They apply to photon frequencies above the plasma frequency. Smooth transitions from well-known results for classical high-temperature plasma (they are reproduced) to low-temperature high-density plasma of arbitrary degeneracy are naturally obtained without making any ad hoc assumptions concerning cutoffs of logarithmic terms. New results are found concerning the scaling with photon energy as well as plasma temperature, density, and ion charge Z. They apply, in particular, to warm dense matter and photon energies now available at FEL facilities.

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Femtosecond thermalization dynamics of keV electrons in metals

Collisional relaxation of high-energy electrons (with kinetic energies on the order of keV) generated in a metal is studied through numerical solutions to the quantum Boltzmann equation for electron gas taking into account dynamic screening. It is shown that the kinetic energies are rapidly transferred to the conduction electrons through plasmon excitation, leading to generation of secondary electrons above the Fermi level; femtosecond dynamics of these processes is discussed in relation to the radiation damage caused by an intense XFEL pulse. The energy distribution function of the entire electrons eventually approaches the equilibrium Fermi-Dirac distribution, corroborating the quantum H-theorem; the final electron temperature is consistent with the value estimated from the total energy conservation. A formula for the total number of secondary electrons is presented and compared with earlier results.

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Structure factor of strongly coupled ions in dense quantum plasmas

The structural characteristics of strongly coupled ions of a plasma with partially degenerate and non-ideal electrons have been actively investigated due to interest in extreme states of matter upon laser compression of materials, laboratory astrophysics, and experiments on inertial confinement fusion (ICF). In experiments, dynamic and static ionic structure factors can be measured using, e.g., the x-ray Thomson scattering technique. The most accurate theoretical studies are based on quantum molecular dynamics where electrons are treated by density functional theory and quantum Monte Carlo [1]. To have a picture about the importance of quantum effects, non-ideality, and non-linear effects, the results of *ab initio* simulations are often compared to the data computed using a Yukawa type screened ion-ion potential [2], where the Yukawa type exponential screening corresponds to the long wave-length limit of the linear response result [3]. Besides, the Yukawa potential is often used to study the properties of the strongly coupled ions by assuming that by properly choosing the screening length one can approximately reproduce physical properties of real systems (e.g., warm dense matter or dense plasmas) [4]. However, for weak electron-ion coupling, the latter assumption has not been checked for the case of a plasma with partially (or strongly) degenerate non-ideal electrons and strongly coupled ions. Therefore, to provide such an examination is the goal of this contribution.

In this work we present our results for dynamic and static ionic structure factors computed using a screened ion potential in molecular dynamics simulations and in the solution of the Ornstein-Zernike integral equations. The screening due to electrons is described taking into account the electronic correlations on the basis of linear response theory. Recently, considering the ionic static structural properties, we showed that in dense plasmas with weakly correlated and strongly or partially degenerate electrons, the Yukawa potential is a poor approximation to the exact linear response result [5]. In addition, in Ref. [5] we reported the plasma parameters at which the famous STLS approach [6] is accurate for the description of the electronic screening. Based on this, here we extend our considerations by computing the dynamic ionic structure factor. We found that, in contrast to the static structure factor, the dynamical structure factor of ions at small values of the wave-number can be correctly described using the Yukawa potential, but with a properly adjusted screening length. In addition, our results provide information about the plasma parameters at which the electronic quantum and correlation effects, in linear response, are significant.

[1] S. Zhang et al., Phys, Rev. E 98, 023205 (2018); T. Sjostrom and S. Crockett L., Phys. Rev. E 97, 053209 (2018); Liu et al., Phys. Rev. E 97, 063204 (2018).
[2] K. Wuensch, J. Vorberger, and D. O. Gericke, Phys. Rev. E 79, 010201 (R) (2009); H. D. Whitley et al., Contrib. Plasma Phys. 55, 390 (2015)
[3] Zh. Moldabekov et al., Phys. Plasmas 22, 102104 (2015).
[4] T. Haxhimali et al., Phys. Rev. E 92, 053110 (2015); K. Wuensch et al., Phys. Rev. E 77, 056404 (2008); J. P. Mithen et al., Phys. Rev. E 84, 046401 (2011).
[5] Zh. A. Moldabekov et al., Phys. Rev. E 98, 023207 (2018).
[6] K. S. Singwi, M. P. Tosi, R. H. Land, and A. Sjölandar, Phys. Rev. 176, 589 (1968); S. Tanaka and S. Ichimaru, J. Phys. Soc. Jpn. 55, 2278 (1986).

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Statistical modeling of Stark-broadened levels and lines of hydrogenic system

When accounting for electric fields produced by the charged perturbers in the plasma (electrons or ions), levels and lines of the radiator system are split into complex patterns due to Stark effect. The calculation of lineshapes is an old and complex subject [1,2] that is still debated today on many points [3,4]. The usual approach (often referred to as the « Standard Theory ») consists in considering the ion as quasi-static during the emission process, whereas the electrons are dynamic and treated in the framework of a binary collision theory. The model can be improved thereafter by including ion-dynamics effects, high-order multipole terms in the perturber-radiator interaction, penetrating collisions, etc. In general, the modeling of lineshapes is a very tedious task even for a one-electron system. We propose a statistical approach for Stark-broadening of hydrogenic system, which represents a fast and accurate alternative to detailed calculations. The method is based on the derivation of closed-form formulas for the moments of Stark-broadened energy levels and lines. Using second-quantization techniques, these moments are expressed as traces of particular operators, which are then evaluated by using the Racah algebra. Different types of formulas were obtained: i) the arbitrary moments of state energies within a shell n for a static electric field; ii) the variance of the strength-weighted line energies for $\Delta n = 0$ and $\Delta n \neq 0$ transitions assuming a static electric field; iii) the average strength-weighted matrix element of the electron broadening operator, including the interference terms. We will see that these formulas can be used to build an average statistical profile for any one-electron Starkbroadened transition arrays n-n'. We will show some examples and comparisons with the ZEST code [5], that we have developed recently for detailed and accurate Zeeman-Stark calculations.

[1] Griem, H.R. Principles of Plasma Spectroscopy; Cambridge University Press: Cambridge, UK, 1997.

[2] Baranger, M. General Impact Theory of Pressure Broadening. Phys. Rev. 1958, 112, 855-865.

[3] Stambulchik, E. Review of the 1st Spectral Line Shapes in Plasmas code comparison workshop. High Energy Density Phys. 2013, 9, 528-534.

4] Ferri, S.; Calisti, A.; Mossé, C.; Rosato, J.; Talin, B.; Alexiou, S.; Gigosos, M.A.; Gonzalez, M.A.; Gonzalez-Herrero, D.; Lara, N.; Gomez, T.; Iglesias, C.; Lorenzen, S.; Mancini, R.C.; Stambulchik, E. Ion Dynamics Effect on Stark-Broadened Line Shapes: A Cross-Comparison of Various Models. Atoms 2014, 2, 299-318.

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Enhanced Photoionization Cross Section of Ions In Hot Dense Plasma By the Temporal Space Localization of the Ejected Electron

Continuum atomic processes initiated by photons and electrons occurring in a plasma are fundamental in plasma physics, playing a key role in the determination of ionization balance, equation of state, and opacity. Here we propose the notion of a temporal space localization of electrons produced during the ionization of atoms immersed in a hot dense plasma, which can significantly modify the fundamental properties of ionization processes. A theoretical formalism is developed to study the wavefunctions of the continuum electrons that takes into consideration the quantum de-coherence caused by coupling with the plasma environment. The method is applied to the photoionization of Fe^{16+} embedded in hot dense plasmas. We find that the cross section is considerably enhanced compared with the predictions of the existing free-atom model, and thereby partly explains the big difference between the measured opacity of Fe plasma [1] and the existing standard models for short wavelengths.

[1] J. E. Bailey et al, A higher-than-predicted measurement of iron opacity at solar interior temperatures. Nature (London) 517, 56 (2015).

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Multiple-core hole states production in the interaction of solid-state density plasmas with a relativistic optical and x-ray free electron laser

Much research on SCH and DCH states have been carried out in the past decades, however, very few work is reported in the literature on the observation of production for triple-corehole (TCH) states. The investigation of TCH states gives rise to a great challenge both experimentally and theoretically. Multiple-core states of a silver foil are investigated in the interaction with a relativistic femtosecond optical laser and x-ray free electron laser. Strong x-ray emission of TCH atoms with three L-shell electrons being ionized can be observed at pulse intensities of 3e21 W/cmˆ2. Detailed kinetic calculations showed that the emissivity originating from the TCH states exceeds that from the single- and double-core-hole states in Ne-like Agˆ37+ and is comparable in the neighbouring ionization stages of Agˆ36+ and Agˆ38+ in the produced plasmas at electron temperature of ˜500 eV and raidative temperature of ˜1500 eV using optical laser. These extremely exotic dense matter states are produced by an intense polychromatic x-ray field formed by hot electrons produced in the interaction of the laser. This work opens new ways to the deep insight into investigation of extremely exotic states properties which is important in high energy density physics, astrophysics and laser physics.

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The impact of free electron degeneracy on collisional rates in plasmas

The use of x-ray free electron lasers to create and characterise solid density plasmas has opened a new window to the microphysics of extreme states of matter. In this study, we use this method to explore the impact of free-electron degeneracy on the collisional rates in solid density plasmas. We observe experimentally ion satellites of the k-alpha transition in warm dense aluminium with a magnitude far above those predicted with standard collisional-radiative treatments. We attribute the prominence of the ion satellites to a reduction in collisional recombination within the L-shell, due to the degeneracy of the free electrons.

This effect can be included in existing codes in the form of correction factors to the various transition rates. We show that by including a correction factor in the collisional-radiative code FLYCHK, a much-improved fit to the experimental data is found.

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Multi-ion molecular dynamics and elastic X-ray Thomson scattering of dense plasmas

We present a consistent method to describe the density effects on Saha equation and calculate x-ray elastic scattering of different charge-state ions in warm/hot dense plasmas. Firstly, the method is self-consistently used to calculate electron structures of different charge-state ions in the ionic sphere, in which the ion-sphere radii are determined by the plasma density and their charges. And then the ionic fraction is obtained by solving the Saha equation, taking account of interactions among different charge-state ions in the system, and ion-ion pair potentials are computed by the modified Gordon-Kim method in the framework of the temperature-dependent density functional theory on the basis of the electron structures. After self-consistently calculating the ionic and electronic structures, Multi-ion molecular dynamic simulations are performed to compute the ion features of x-ray elastic scattering.

[1] Yong Hou, Richard Bredow, Jianmin Yuan, and Ronald Redmer, Phys. Rev. E, 91, 033114 (2015)
[2] Yong Hou, Jiayu Dai, Dongdong Kang, Wen Ma, and Jianmin Yuan, Phys. Plasma, 22, 022711(2015).
[3] Yongsheng Fu, Yong Hou, Dongdong Kang, Cheng Gao, Fengtao Jin, and Jianmin Yuan, Phys. Plasma, 25, 012701(2018).
[4] Carlos A. Iglesias, High Energy Density Physics, 26, 81-85.

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Ionization Potential Depression Calculations for Compressed Materials

There has been a recent resurgence of interest in measurements and calculations of ionization potential depression (IPD) in materials. This has been initiated by novel experimental approaches that can access states of higher temperature, density, and charge state than were previously attainable under well-characterized conditions. These new results provide a challenge to long-established IPD models, such as Stewart-Pyatt, and raise concerns about some of the ways that these models are implemented in practice in application codes. For example, depending on assumptions about which atomic configurations are included or excluded in a Stewart-Pyatt-based model for cobalt under compression, it is possible to predict that the K-beta fluorescence will undergo either a blue-shift, or a red-shift, or even a non-monotonic variation that shifts from red to blue.

One theoretical approach to compute IPDs is to use quantum mechanical calculations, such as atom-in-jellium models. Constrained occupancy of the core orbitals is often used to enforce the integer-occupancy constraint that is exhibited by the optical spectra. This can be problematic for some transition metal systems, however. Calculations on cobalt show that the d-states are already in the continuum at equilibrium density. Constraining the occupancy of the bound orbitals is feasible for a limited density range, but even that fails as the number of d-electrons is decreased. Once the constraint limits the number of d-electrons to fewer than the nearly 8 d-electron occupancy given by the unconstrained calculation, the self-consistent calculation will tend to promote the bound d-orbital to a resonance in the continuum. This eliminates the constraint on the bound orbital occupancy, thereby enabling the calculation to achieve a lower total energy by putting nearly 8 d-electrons into the resonance. One solution is to change the occupancy constraint to apply to both bound and continuum electrons, which raises concerns about how and when to apply an integer constraint to continuum electrons.

The purpose of this presentation is to point out that apparently reasonable approaches can result in contradictory predictions for experimental results. Progress will need to be guided by experimental results for a range of materials, and by more sophisticated theory than either Stewart-Pyatt or unconstrained density function theory.

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Review of the 10th Non-LTE Code Comparison Workshop

We report on the results of the 10th Non-LTE code comparison workshop, which was held at the University of San Diego campus November 28 through December 1, 2017. Nonequilibrium collisional-radiative models predict the electronic state populations and attendant emission and absorption characteristics of hot, dense matter and are used to help design and diagnose high-energy-density experiments. At this workshop, fifteen codes from eleven institutions contributed results for steady-state and time-dependent neon, aluminum, silicon, and chlorine cases relevant to a variety of high-density experimental and radiation-driven astrophysical systems. This talk will focus on differences in the predictions from codes with different internal structure, completeness, density effects, and rate fidelity and the impact of those differences on hot, dense plasma diagnostics.

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Recent developments of the generalized collisional-radiative model using screened hydrogenic configurations for high energy density physics applications

Over the last decade, the generalized collisional-radiative (CR) models based on screened hydrogenic configurations, FLYCHK and SCFLY, have been applied to a wide range of plasmas in high energy density physics (HEDP). The number of registered users at the NIST FLYCHK website (nlte.nist.gov/FLY) reached 1000 in 2018. These models helped researchers understand x-ray free electron laser (XFEL) produced plasmas where atomic level populations and electron energy distributions are tightly coupled during the beam pulse, ultra short-pulse laser (USPL) produced plasmas where thermal and non-thermal electron distributions result in interesting K-shell spectroscopic signatures, long-pulse laser produced plasmas where x-ray spectroscopy provides time-dependent plasma parameters, and tokamak plasmas where the average charge states and radiative loss of impurity high Z elements play an important role in determining the energy balance and time-dependent evolution of plasma parameters.

Researchers from the HEDP community have recently been actively involved in the development of these CR models for more general problems. The models have been extended to include Fermi-Dirac distributions for the highly degenerate plasmas encountered in the studies of dense matter and to couple with a Boltzmann solver to track the evolution of Auger and photo electrons in XFEL generated plasmas. On-going developments include implementing a smaller version of SCFLY in a PIC (Particle-in-Cell) code and developing a CR code based on the physics in SCFLY but using more detailed atomic structures than the screened-hydrogenic model. In this presentation, we summarize these developments and discuss their significance.

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New Prism EOS and Opacity Tables with NLTE Atomic Kinetics

New Prism EOS and Opacity Tables with NLTE Atomic Kinetics I. E. Golovkin, J. J. MacFarlane Prism Computational Sciences, Madison, WI We present new features of PROPACEOS, a code that generates equation-of-state (EOS) and opacity tables for radiation-hydrodynamics and spectroscopic simulations. In addition to existing capabilities to produce tables for LTE and optically thin NLTE plasmas, these new features allow PROPACEOS to perform calculations that include other effect of NLTE atomic kinetics. The primary purpose of this development is to facilitate efficient spectroscopic simulations for short-pulse laser experiments. The simulations are based on post-processing of PIC calculations and focus on the analysis of K-alpha/K-beta emission signatures. PROPACEOS can now produce emissivity and opacity databases on a grid with up to six independent parameters, for example: plasma temperature, plasma density, and hot electron parameters. Hot electron distributions are specified in terms of analytic functions.

We will also discuss new capabilities that allow for computing opacities for optically thick NLTE plasmas. We will present simulation results relevant to ongoing experiments on Omega EP laser facility.

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THERMOS Toolkit: Software and databases package for properties calculations of LTE and Non-LTE plasmas

THERMOS Toolkit [1] has been developed at the Keldysh Institute of Applied Mathematics, it consists of set of atomic databases and software package, which is designed for calculation of thermodynamic and radiative properties of plasma at various conditions over wide range of temperatures and densities.
The software package includes codes for numerical simulation of transparent and optically thick plasmas. The local thermodynamical equilibrium (LTE) plasma properties are calculated by using the self-consistent Hartree-Fock-Slater model or Saha-Boltzmann statistics with atomic database. For Non-LTE cases the system of level kinetics equations is solved in the quasi-stationary approach with a fixed radiation field by using the collisional-radiative (CR) model with atomic databases.

The atomic databases calculation process is based on the non-relativistic model, supplemented by a procedure of building the RDCA (Reduced Detailed Conguration Accounting) database [2]. The latter improves positions and strengths of spectral lines by using data from detailed atomic codes, such as RCG [3], FAC [4] or available experimental data. In addition to that, a special technique has been developed and implemented for averaging the atomic data on a given photon energy grid - Radiative Unresolved Spectra Atomic Model or RUSAM [5, 6], which is aimed at reducing calculation time with little to none detriment to accuracy.
Opacity and thermodynamic properties tables are being calculated over wide range of electron temperatures and densities for two limiting cases (transparent and optically thick plasma layer). These tables can be used in RHD calculations with escape-factor interpolation [7]. The interpolation method is efficient and gives reasonable results in a wide range of electron densities.

The THERMOS Toolkit takes part in the NLTE Code Comparison Workshops [8], and its calculation results are comparable to those of some reputed codes from over the world.

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Pursuing Large Scale Self-Consistent Atomic Kinetic and Radiation Transport Simulations

In 1969, Auer and Mihalas presented the first fully self-consistent steady state non-LTE stellar atmosphere model based on a multi-dimensional Newton-Raphson (NR) technique—the Complete Linearization Method [1,2]. Follow on models over the last four decades by the astrophysics community continued to refine and develop methods to reduce the computational resource requirements to solve more realistic atmospheres. In RPHDM 2016, we reported on a reformulation of the original NR Jacobian matrix that was more conducive to simulating moderately dense laboratory HED plasmas in the NORA code [3]. As we continue to pursue more complete atomic models for the mid-Z elements, additional algorithmic improvements and linear algebra libraries have been employed to further accelerate convergence and computation execution—sometimes by factors of hundreds. In this work we will present these new computational techniques and corresponding simulations. (LA-UR-18-28083)

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BENCHMARK EXPERIMENTS FOR THE RADIATIVE PROPERTIES OF ASTROPHYSICAL PLASMAS

Analysis of astrophysical spectroscopic observations and building detailed physical descriptions of cosmic objects both require models for the behavior of atoms in hot dense plasma. Benchmarking those models is critical but not often achieved. Benchmark experiments require reproducibility, uniform conditions with size and duration large enough to enable accurate measurements, and diagnostics for the conditions achieved. We evaluate these requirements using Z experiments that simultaneously investigate multiple topics in radiative properties of hot dense matter. The four astrophysics questions presently guiding this research are:
1) Why can't we predict the location of the convection zone base in the Sun?
2) How does radiation transport affect spectrum formation in accretion-powered objects?
3) How accurately can we determine White Dwarf stellar masses using spectroscopy? and
4) How well do we understand the physics of heating and ionization in photoionized plasmas?

Recent progress will be described, with an emphasis on elucidating the challenges for benchmark experiments rather than on the detailed physics results for each topic. We evaluate how well each experiment satisfies the requirements and assess future opportunities.

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Observing the two-photon Breit-Wheeler process for the first time

The two-photon Breit-Wheeler process [1] is the inverse of electron-positron Dirac annihilation and is the simplest mechanism by which light can be transformed into matter. It is important in high-energy astrophysics, both in the context of the dense radiation fields of compact objects [2] and the absorption of high-energy gamma-rays travelling intergalactic distances [3]. However, in the 80 years since its theoretical prediction, this process has never been observed. In this talk I will present recent work [4] on the design of an experiment to detect significant numbers of Breit-Wheeler pairs. The experiment was undertaken in 2018 on the Gemini laser at the Central Laser Facility in the UK by a team from Imperial College London and the University of Jena in Germany. It involved laser-driven electron acceleration followed by conversion to gamma-ray photons which then interacted with X-ray photons in a quasi-thermal radiation field generated by a second laser interacting with a thin foil of Germanium.

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Plasma heating and atomic kinetics of laboratory photoionized plasmas

In separate experiments performed at the Z facility of Sandia National Laboratories two different samples were employed to produce and characterize photoionized plasmas. Onewas a gas cell filled with neon, and the other was a thin silicon-oxygen layer coated with plastic. Both samples were driven by the broadband x-ray flux produced at the collapse of a wire array z-pinch implosion. Transmission spectroscopy of a narrowband portion of the x-ray flux was used to diagnose the charge state distribution, and the electron temperature was extracted from a Li-like ion level population ratio. To interpret the temperature measurement, we performed Boltzmann kinetics and radiation-hydrodynamic simulations.

For both photoionized plasmas, we found that non-equilibrium atomic physics and the coupling of the radiation flux to the atomic level population kinetics play a critical role in the x-ray heating of the plasma. Calculations performed with astrophysical codes overestimated the electron temperature.

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Magnetized plasma compression: measurement of the compressed magnetic field and what can we learn from it?

The physics of magnetized plasma implosion is studied using a gas-puff Z-pinch with pre-embedded axial magnetic field (Bz). Recent measurements of the distribution of the compressing azimuthal magnetic field (Bj) showed that the pre-embedded magnetic field has a dramatic effect on the current distribution. It was demonstrated that in the presence of even a weak pre-embedded Bz, much of the Z-pinch current flows at large radii through low-density plasma that is practically not imploding. Here, we focus on the challenging measurement of the compressed pre-embedded Bz. In the experiment, a pulsed-power generator (300 kA, 1.6 μs) implodes a plasma column in an initial Bz up to 0.5 T. Polarization spectroscopy in the visible-UV, combined with laser-ablation doping technique, are employed to determine the magnetic field and plasma parameters. Knowledge of the evolution of Bz provides rich information. It gives the confinement efficiency, the plasma resistivity, and enables studying the pressure balance in the system, and exploring the role of Bz in the formation of plasma structures (filaments). The axial distribution of Bz demonstrates the effect of the conducting electrodes on the implosion, and the origin of fields in the radial direction that may explain plasma rotation, recently observed. Future measurements of Bz with improved sensitivity may shed light on the mechanism that prevents a significant portion of the current from taking part in the plasma compression in the presence of Bz.

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Atomic physics developments for the characterization of highly-magnetized HED plasmas.

Spectroscopic measurements in the visible range are often used in low-density plasmas experiments to measure B-field induced Zeeman splitting, electron densities via Stark broadening, and temperatures from Doppler broadening. Deconvolving the two later mechanisms from Zeeman broadening, and therefore enabling simultaneous measurement of B-field, density and temperature, can be accessible from measurements of the circularly polarized emission and/or by resolving the fine structure components of a given multiplet, split differently according to the embedded B-field [1]. However, for typical HED plasmas, Stark and Doppler broadening effects may significantly obscure the Zeeman effects. Besides, the present relevant theories are nearly untested in the HED regime and require experimental validation.

Here, novel atomic physics developments for the characterization of highly-magnetized HED plasmas are presented. An atomic physics code, MASC-B, used to generate B-field dependent atomic physics quantities needed for the computation of line profiles namely energy levels and dipole matrix elements, has been developed. It provides atomic databases to be used by a new version of the PPP-B code [2] now designed to allow calculations of atomic spectrum line shapes in conditions where the coupling of an external B-field to the atomic magnetic moment dominates the spin-orbit interaction. Numerical molecular dynamics simulation codes have been elaborated in parallel to accompany those developments [3].

Besides, progress has been made in the atomic-kinetics code ABAKO [4] to include magnetic sub-levels in the calculation of population distribution and consistently solve NLTE atomic kinetics of a plasma mixture. Also, the radiation transport module has been modified for X-ray polarization spectroscopy applications and efficient post-processing of hydrodynamic simulations.

Calculations performed in conditions relevant to laser-driven implosions in the presence of frozen-in seed B-fields have shown that spectral emission signatures of enough strong B-fields ($>$ 5 kT) embedded into high density and high temperature plasmas (such as MagLIF targets at or close to stagnation) are expected to be observable in the X-ray range by using mid-Z atoms as dopants [5].

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A burnthrough experiment to measure iron opacity at conditions close to the solar radiative zone/convection zone boundary

The talk describes the design of an experiment to investigate the radiative opacity of iron at conditions close to the convection zone boundary in the sun and similar to those of the Sandia Z pinch opacity experiments by Bailey et al that showed a marked difference from theory prediction. The experiment uses a different technique from the frequency resolved measurements of the Z experiments and also the NIF experiments currently underway to confirm the Z results. The proposed experiment would use the burn-through of a supersonic diffusive radiation wave through an iron oxide foam to infer the frequency integrated Rosseland mean opacity of iron at the relevant conditions.

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Line transfer effects on inferring plasma conditions in buried layer experiments

Short pulse laser heated buried layers have demonstrated a promising capability in determining opacities of high temperature, high-density plasma. A critical aspect of utilizing these data is inferring the plasma conditions using a K-shell tracer. Often diagnostic limitations require utilizing spectral lines that are not optically thin, thus requiring a model to determine the spectral line intensity. We compare codes using optical depth models versus full radiation transport to infer the temperature and density. Additionally, we compare the accuracy of the two methods to experimental data where spectrometers are fielded at different angles and the resonance lines are optically thick but the satellites are optically thin.

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An Effort to Reconcile Electron-Broadening Theories

Calculations of line broadening are important for many different applications including plasma diagnostics and opacity calculations. One concern is that line-shape models employ many approximations that are not experimentally validated for most element conditions due to challenges with high-fidelity line-shape benchmark experiments. Until such experiments become available, we need to test approximations with ab-initio line-shape calculations.

There are three primary formalisms to derive an electron-broadening operator: the impact theory (Baranger, Griem), relaxation theory (Fano), and kinetic theories (Zwanzig, Hussey), all of which give different expressions for electron broadening. The impact and relaxation theories approximate the density matrix as factorizeable while the kinetic theory has a more general density matrix. The impact and kinetic theories relate the electron broadening operator to collision amplitudes, while the relaxation theory has a more complicated formula using projection operators. Each theory has a different prediction for the width and shift of spectral lines, which will become apparent in strongly-coupled plasmas.

We have made an effort to better understand the approximations and limitations of all of these approaches and to try to reconcile the differences between them. Here, we present the current status of our understanding of the electron-broadening theories and our preliminary attempt to unify the various formulae. Currently, we have found the projection operator to be necessary part of line broadening. We will be showing (for the first time) how the projection operator broadens spectral lines.

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Theoretical study on grazing-incidence x-ray scattering of surfaces upon high-intensity laser irradiation

High-intensity laser-matter interaction creates transient states of warm and hot dense matter on a solid target surface. The femtosecond evolution of the surface structure determines the laser absorption and subsequent heat transport and particle acceleration in the target's volume. We propose here to measure the time-resolved structure of the high-intensity laser irradiated solid-density plasma surface by x-ray reflectometry and grazing-incidence x-ray diffraction using femtosecond x-ray free electron laser radiation. To support the feasibility of the experiment and to optimize the experimental configuration, we employ particle-in-cell simulations to model the laser-target interaction. We then extract the reflectivity and the scattered intensity from our simulation data. We demonstrate how the use of a multilayer structure improves the signal quality over an unstructured target and permits to measure the volumetric dynamics by observing the position and shape of the multilayer Bragg reflection peak at various time delays between the optical laser pulse and the x-ray probe pulse.

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Ab initio calculation of electron impact ionization for ions in exotic electronic configurations

We provide *ab initio* calculations of electron impact ionization cross sections for ions in exotic electron configurations, with the purpose of exploring their effect on ionization dynamics triggered by inelastically scattered electrons.

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1s-4p hard x-ray lasers of Cu atoms with strong injection seeding

In material pumped by an intense x-ray free electron laser (XFEL), very large laser amplification gain is obtained. From theoretical calculations, gain above 104 cm-1 is expected when the pumping intensity exceeds several 1019W/cmˆ2. In such conditions, a strong resonant laser wave is initiated and amplified. Then due to the induced emission process, the emission is affected by this resonant light. In a previous experiment, we succeeded to produce selective control of K-shell laser lines. The Ka1 and Ka2 laser lines are selected by an external seeding laser.

Now, we will use higher Rydberg states for this lasing. The goal is to produce the 4p-1s transition in Cu atoms. The neutral Cu atom has the electronic configuration 1sˆ2 2sˆ2 2pˆ6 3sˆ2 3pˆ6 3dˆ10 4sˆ1. When the 1s electron is excited by 9.1 keV XFEL, a 1s electron moves to the conduction band of Cu metal. After that, due to the vacancy in the 1s electron state and the other electron state, resonant emission will occur. The highest energy level in this case is the conduction band, which consists of 3d, 4s and 4p energy states. By using intense seeding matched to the energy between this higher level and the 1s electron state, we can expect lasing.
In the experiment, we use two-color X-ray pulses from Japanese SACLA XFEL facility. One color is tuned to the pump for 1s electron, the other is for seeding the near K-absorption edge energy. After optimization of overlap of the pump and the seed beam and the energy balance of these beams, we have succeeded to observe strong gain spectrum at the K-absorption range (˜9keV). The average amplification is as large as 200 and the gain spectral width is 8eV. By comparison to absorption features of neutral Cu metal, we consider that this is a 4p-1s transition laser. As is well-known, Cu has no 4p electron in the cold condition, therefore, 4p-1s lines cannot be observed with normal excitation. That means this is the first observation of 4p-1s transition line in Cu atoms. We think this is a new method to measure the transient energy state of inner shell excited atoms with a strong induced emission process.

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Synthetic diagnostics based on hydrogen Balmer series in recombining plasmas in magnetic fusion devices

The creation of a radiative mantle in the divertor region of a tokamak allows to protect its plasma facing components from the huge power and particle fluxes escaping from the plasma core. This leads to the plasma "detachment" from the wall by reaching conditions relevant to recombining plasmas. A large effort is being devoted to the study of plasma detachment in both L- and H-modes especially in the framework of EUROfusion MST1 [1] and JET1 programs [2] as this scenario is foreseen for future large-scale fusion devices like ITER and ultimately DEMO. In support of such studies, the work presented here relies on the development of a synthetic diagnostic for detached divertor plasmas.

The synthetic diagnostic approach consists in forward modeling of complete spectra from plasma simulation results, so as to allow for direct comparison to experimental data, accounting for e.g. spatial inhomogeneities of the plasma along the line of sights as well as technical properties of the measurement systems. Such comparisons provide strong checks on models used for plasma simulations on actual devices, thus strengthening confidence in predictions for ITER/DEMO.

On the modeling side, increasingly realistic simulations are being performed using simulation codes such as transport code Soledge2D-EIRENE [3] in order to account for the spatial inhomogeneity of the plasma. Following the spatial distributions of plasma parameters, and given by simulations, complete spectra of the hydrogen Balmer series can be calculated.

For modeling of the spectrum from the recombining region, the Stark broadened high-n lines can be calculated using the PPP code [4] and continuum emission using analytical equations for radiative recombination and bremsstrahlung. Discrete to continuum transition can be modeled using a dissolution factor approach. Simulation results confronting spectrum modeling incorporating the full geometry and response characteristics of the diagnostic will provide synthetic profiles. The synthetic profiles will be confronted to experimental data for model validation.

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Opacity of Shock-Heated Plasmas

Standard measures of opacity, the imaginary-part of the atomic scattering factor and the mass attenuation coefficient are evaluated in shock-heated boron, boron carbide and boron nitride plasmas. The Hugoniot equation, relating the temperature behind a shockwave to the compression ratio across the shock front, is used in connection with the plasma equation of state to determine the pressure, effective plasma charge,_ and the K-shell occupation. Solutions of the Hugoniot equation (determined within the framework of the generalized Thomas-Fermi theory) reveal that the K-shell occupation in low-Z ions decreases rapidly from 2 to 0 as the temperature increases from 20eV to 500eV; a temperature range in which the shock compression ratio is near 4. The average-atom model (a quantum mechanical version of the generalized Thomas-Fermi theory) is used to determine K-shell and continuum wave functions and the photoionization cross section for x-rays in the energy range, $1 - 10$ keV, where the opacity is dominated by the atomic photoionization process. For an uncompressed boron plasma at $T = 10$ eV, where the K-shell is filled, the average atom cross section, the atomic scattering factor and the mass attenuation coefficient are all shown to agree closely with previous (cold matter) tabulations. For shock-compressed plasmas, the opacity is found to be well approximated by scaling the previous cold-matter values by the relative K-shell occupation. Attenuation coefficients μ for an 9 keV x-ray are illustrated as functions of T along the Hugoniot for B, B4C and BN plasmas.

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Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions

Model predictions for iron opacity are notably different from measurements performed at matter conditions similar to the boundary between the solar radiation and convection zones [J.E. Bailey et al., Nature 517, 56 (2015)]. The calculated iron opacities have narrower spectral lines, weaker quasi-continuum at short wavelength, and deeper opacity windows than the measurements. If correct, these measurements help resolve a decade old problem in solar physics. A key question is therefore: What is responsible for the model-data discrepancy?
The answer is complex because the experiments are challenging and opacity theories depend on multiple entangled physical processes such as the influence of completeness and accuracy of atomic states, line broadening, contributions from myriad transitions from excited states, and multi-photon absorption processes. To help determine the cause of this discrepancy, a systematic study of opacity variation with temperature, density, and atomic number is underway. Measurements of chromium, iron, and nickel opacities have been performed at two different temperatures and densities, and the opacity analysis method has been substantially improved. The collection of measured opacities provides constraints on hypotheses to explain the discrepancy. We will discuss the new analysis method, implications of measured opacities, experimental errors, and possible opacity model refinements.

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Atomic data for low temperature mid-Z elements for lithography applications

The strong emission from plasmas of mid-Z elements, such as tin and xenon, in the 11-14 nm wavelength has long been acknowledged as a powerful source of EUV light with significant applications for lithography. The atomic physics and opacity modeling group at Los Alamos National Laboratory has an extended history of research in atomic structure and collision physics. To this end, recent work has been carried out in an effort to calculate the emission from the relevant atomic ions, and to perform numerically predictive simulations of EUV sources. We have recently performed investigations into the atomic structure and opacity of mid-Z elements at low temperatures (< 50 eV), and explored the accuracy of some approximations used in the atomic structure models for the relevant ion stages with regards to Sn [1] and Xe. We find that full configuration-interaction is required to properly describe the strong mixing between the various n=4 sub-shells that give rise to the Dn=0 transitions that dominate the opacity spectrum at low temperatures.

Since calculations that involve full configuration-interaction for large numbers of configurations rapidly become computationally prohibitive, we have investigated hybrid calculations, in which full configuration-interactions is utilized for the most vital transitions, while intermediate-coupling is used for all other transitions [1]. Our calculations are performed using the Los Alamos suite of atomic physics codes (for an overview, see [2]). Localthermodynamic- equilibrium (LTE) opacities are generated using the ATOMIC code [3,4,5] at a number of chosen temperatures and densities. Preliminary results indicate that our models are in good agreement with transmission measurements from laser-produced Sn plasmas [6,7]. We plan to report related calculations on the structure of Xe ions.

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Uncertainties in opacity measurements

In laser or Z-pinch absorption-spectroscopy experiments, X rays heat volumetrically a thin sample tamped with low-Z materials and the opacity is inferred from spectrally resolved measured transmission. Imperfect knowledge of the areal mass, irregularities of the sample, plasma self-emission, background radiation, homogeneity and intensity of the backlighter, tamper attenuation, as well as temporal variations and spatial gradients of density and temperature can all cause systematic errors in the measured spectra. In this work, we discuss the impact of some of these potential errors and exhibit experimental requirements for an accurate determination of opacity. We also consider different defects of the sample (holes, corrugations, flattening, bending, bulges, etc.) and provide quantitative evaluation of their effect on the transmission.

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Questioning the validity of the radiative transfer equation in regimes of strongly coherent radiation

The radiative transfer equation is commonly interpreted as a kinetic equation for a gas of photons interacting with massive particles (atoms, ions, electrons) through emission, absorption, and scattering processes. A numerical implementation starting from an already written particle kinetic transport code, e.g., for neutrons, is straightforward, due to its formal analogy to the kinetic Boltzmann equation (sometimes, it is referred to as a "strangely" normalized Boltzmann equation [1]). The purpose of this work is to investigate the validity of the radiative transfer equation at regimes such that the radiation presents features intrinsic to the wave nature of light, e.g., diffraction. A possible picture of the radiation field is that of a set of wave packets, emitted from accelerated charged particles and propagating through some given medium. The size of such wave packets – the coherence length – provides an estimate of the spatial scale the radiation field is able to interfere with itself. In a recent study, it was suggested that the neglect of coherence in radiation transport models would result in a misuse of basic formulas in opacity calculations, such as the Beer-Lambert exponential attenuation ([2] and Refs. therein). A possible explanation of this is the ambiguity in defining an absorption process at a spatial scale smaller than the coherence length; this can be made clear through the use of photon Wigner functions and this was discussed previously in the case of atomic line radiation. Presently, these results are still qualitative and the issue of retaining coherence in radiative transfer models require further investigations. Here, we report on the current status on this work. New calculations of line radiation transport will be performed and comparisons to a pure wave model will be done.

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Bragg diffraction type hard x-ray laser pumped with intense XFEL pulses

The intense hard x-rays from recently developed x-ray free electron lasers can create a high excitation density state of atoms in solid materials. At 1020W/cm2, about 20% of the atoms in a solid can be ionized within a very short time (˜10fs). This produces a non-equilibrium condition that is suitable for lasing. With this method, we have succeeded to produce inner shell K-alpha (1s-2p) laser emission from ionized Cu atoms, with 0.15nm wavelength and 8keV photon energy. In this condition, intense resonant light emission can stimulate emission of the excited Cu atoms. By using this mechanism, spectral control of laser emission with an injection seeding method has also been demonstrated. Even though several demonstration experiments have succeeded to achieve spectral control by different methods with this laser, there is still large difference from the usual optical lasers. The big difference is the lack of a cavity control method for the hard x-ray lasers. That is because it is difficult to prepare a normal incidence reflection mirror for hard x-ray photons. Here we propose a new type of hard x-ray laser, similar to the mechanism of cavity lasers. In the Fabry-Perot type cavity laser, forward- and backward-moving light waves make a standing wave inside the laser medium. In our newly proposed lasers, a crystal Bragg resonance condition is used for achieving the standing wave. The crystal angle is adjusted so that the lattice spacing of normal surfaces matches the wavelength of the K-shell laser. By this scheme, we demonstrate a spatial mode-controlled laser, cavity controlled emission wavelength laser, and anti-resonance lasers. Again, for the hard x-ray laser, it is very difficult to prepare a good mirror for cavity. Therefore, this Bragg standing wave laser will be useful to achieve a hard x-ray laser with a cavity-type control method.

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Potential of the European XFEL for generating radiation with TW-level peak power and Joule-level pulse energy

With the 1.3 GHz superconducting accelerator developed in the framework of TESLA the European XFEL project holds the potential to accelerate high charge electron beams. This feature has been successfully demonstrated during the first run of the free electron laser at the TESLA Test Facility with lasing driven by electron bunches with a charge of up to 4 nC. In this report we discuss a potential option of operation of the European XFEL driven by high charge (1 nC to 3 nC) electron beams. We present the results of the production and characterization of high charge electron bunches. Experiments have been performed at PITZ and demonstrated good properties of the electron beam in terms of emittance. Simulations of the radiation properties of the European FEL show that application of high charge electron beams will open up the possibility to generate radiation pulse energies up to the few hundred milli-Joule level. This will alow to increase radiation densities on a sample by up to three orders of magnitude with respect to the values attainable at the present day x-ray FELs.

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Resolving the ongoing controversy about the conductivity of warm dense Aluminum

The first data of the collective plasmon scattering spectra from isochorically-heated aluminum obtained with the Linac Coherent Light Source (LCLS) have provided information about the electrical conductivity to temperatures up to 6 eV [1]. The plasmon feature shows significant broadening from which we extract the collision frequency and thus the conductivity. Density functional theory simulations provide excellent agreement with the measured spectra and compare well with the observed scaling of conductivity with temperature [2]. However, recent criticism was voiced regarding both the experiment and theory [3-5]. For example, calculations based on time-dependent theory [3] suggested lower temperatures than quoted in the original paper. Further, questions about the LCLS focal spot size have been raised [4], and, finally, confusion about comparisons with the existing data set from liquid aluminum have arisen [5]. In this presentation, we will 1) show experimental data from LCLS that support the choice of the structure factor used in our calculations, 2) provide evidence for the LCLS focal spot size, and 3) clarify the use of existing isobaric versus isochoric data in the liquid regime [6]. We will then go on and lay out a new experimental program aimed at delivering much improved conductivity data in the warm dense matter regime. For this purpose, we will take advantage of multiple recent experimental capabilities; they are free-electron lasers [7], ultrafast electron diffraction [8], ultrafast pump-probe measurements [9], and single-shot THz spectroscopy [10]. We will present new experimental data demonstrating that these techniques will provide well-characterized conditions in concert with the first direct measurements of both ac and dc conductivity in the warm dense matter regime.

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First observation of resonance pumping in seeded mode of X-ray line profiles of highly charged ions in dense plasmas at LCLS

Radiation transport controls the energy balance and temperature profile in stars while opacity represents a key parameter to understand the evolution of various astrophysical objects [1]. The photon transport theory links the opacity τ_ω to the spectral distribution I_ω via the local source function S_ω that is the ratio between the local emission coefficient ε_ω and the absorption coefficient $\kappa_\omega = \varepsilon_\omega / \kappa_\omega$ while ε_ω and κ_ω themselves are the sum of the bound-bound, bound-free and free-free contributions, i.e. $\varepsilon_\omega = \varepsilon_\omega^{\beta\beta} + \varepsilon_\omega^{\beta\phi} + \varepsilon_\omega^{\phi\phi}$ and $\kappa_\omega = \kappa_\omega^{\beta\beta} + \kappa_\omega^{\beta\phi} + \kappa_\omega^{\phi\phi}$ [1,2]. Therefore, the emission and absorption line profiles impact not only to the bound state properties but to the continuum ones too.

In a first proof of principle experiment at LCLS [3] we have investigated the fundamental line shape properties of emission and absorption of ions in dense plasmas. For these purposes we employed the seeded mode to resonantly scan the frequency dependence of X-ray bound-bound transition of highly charged ions in dense plasmas that have been created with an auxiliary optical laser irradiating solid vanadium targets. We have observed asymmetries in the emission and absorption profiles for X-ray transitions in He-like ions that question standard theories.

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Molecular imaging and plasma formation

One of the key opportunities offered by the development of x-ray free-electron lasers is the determination, at atomic resolution, of the three-dimensional structure of biologically relevant macromolecules [1]. The basic idea underlying molecular imaging using x-ray free-electron lasers is the “diffract-and-destroy” concept: Since at a photon energy of 10 keV or so (corresponding to a potential spatial resolution near 1 ° A), the x-ray absorption cross section per carbon atom is higher by an order of magnitude than the x-ray elastic scattering cross section, radiation damage is unavoidable in x-ray diffractive imaging. However, if one uses an x-ray pulse that is sufficiently short, then in a single shot an x-ray scattering pattern may be obtained that is practically unaffected by atomic displacements triggered by ionization events during the x-ray pulse. What cannot be eliminated in this way is the impact of the electronic damage on the x-ray scattering patterns. The diffract- and-destroy method goes hand in hand with the formation of a nanoplasma within just a few femtoseconds.

Theory, therefore, plays an important role in the development of this new imaging technique: A quantitative understanding is required of the damage processes occurring during the exposure of a molecule to an ultraintense, ultrafast x-ray pulse. In this talk, I will present progress we have made in order to address this challenge. One tool we have developed, XMDYN [2], is a molecular-dynamics code that utilizes ab-initio atomic electronic-structure information, computed on the fly, within a Monte-Carlo framework. XMDYN has been successfully tested through experiments at LCLS [3] and SACLA [4]. XMDYN is part of a powerful start-to-end simulation framework for single-particle imag- ing at the European XFEL [5, 6]. Recently, we have taken first steps towards a full ab-initio framework for simulating high-intensity x-ray–matter interactions [7, 8]. Our new XMOLECULE software solves the polyatomic quantum-mechanical electronic-structure problem for every electronic state arising during the exposure of a molecule to a strong x-ray pulse. From this information, electronic transition rates (such as Auger decay rates) are computed on the fly, and the associated rate equations are integrated utilizing a Monte-Carlo method. XMOLECULE played a key role in a recent LCLS experiment on iodomethane, in which hard x-rays focused to a peak intensity exceeding 10 19 W/cm 2 produced the highest charge states ever formed using light [9]. Not only did XMOLECULE correctly predict the charge-state distribution observed, but it also helped identify a new molecular ionization enhancement mechanism based on intramolecular charge transfer.

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A spectroscopic study of keV solid-density Fe plasma isochorically heated by LCLS X-ray FEL

There has been much interest and effort dedicated to creating and probing solid-density plasma in-situ in controlled conditions at large-scale facilities and recently a few pioneering studies [1-5] using Free Electron Lasers or Z-pinches have led to a significant reexamination of theoretical models and calculations. While high energy density states at temperatures around 100 eV have been successfully created in low Z materials using soft X-ray at the Linac Coherent Light Source (LCLS), the isochoric X-ray heating of solid-density plasmas to temperatures approaching the keV region in mid and high Z systems remains elusive.

Recently we demonstrated creation of keV solid-density Fe plasma using 8 keV using the CXI instrument at LCLS and observed K shell emissions from highly ionized hot-dense Fe plasmas. Talbot interferometry characterized nano-focused beam of ˜140 nm by 100 nm in FWHM focused by KB mirrors. We present spectroscopic results and discuss the mechanisms creating keV hot-dense matter and electronic structure.

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Solids underway to warm dense matter state

The focus of this talk are diagnostics and modeling of radiation-induced structural transitions in solids. Two recent experiments are discussed in detail: (i) X-ray induced femtosecond graphitization of diamond [1], and (ii) amorphization of diamond by intense X-ray pulses [2,3]. Dedicated simulations reveal complex multistage evolution of these systems which diagnostics tools can confirm. Finally, challenges remaining for accurate modeling of transition of solids to warm dense matter state and the quest for further improvements of the necessary diagnostics tools are explored.

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Diagnosing the hot-spot electron temperature from x-ray continuum emission measurements on NIF and OMEGA implosions

The hot-spot electron temperature (Te) is a key metric in determining the performance of inertial confinement fusion (ICF) implosions. The Continuum Spectrometer (ConSpec) infers hot-spot Te from the slope of the x-ray continuum emission in the photon energy range of 20 to 30 keV, where ion velocity and opacity effects are negligible. Additionally, the ConSpec provides spatial resolution to resolve background x-ray sources from the hot-spot emission. We present initial x-ray spectra, from which we infer hot-spot Te for DT cryogenic implosions at both the National Ignition Facility (NIF) and the OMEGA laser facility. In the NIF experiments, we infer the hot-spot Te from the continuum emission and measure the emission spectra from the laser deposition region near the hohlraum wall (the gold bubble).

For the OMEGA direct-drive implosions, we evaluate the effectiveness of spatially resolving the hot-spot emission in the time-integrated measurement from coronal plasma emission.

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Extreme-UV absorption processes in a laser-produced mid-Z plasma : measurements and theoretical interpretation

A good knowledge of absorption properties of plasmas at temperature of few tens of eV is essential in several domains such as astrophysics and inertial fusion science. For instance the description of stellar envelopes or the analysis of beta-Cephei pulsation requires a good knowledge of the Rosseland absorption coefficient, which strongly depends on the radiative properties of plasmas in the extreme-UV (EUV) range. Contrary to measurements in X-ray range, the literature on the absorption properties of plasmas of mid-Z elements in EUV domain is less abundant. Furthermore the theoretical interpretation of such spectra represents a theoretical challenge since this energy range involves the transitions from n equal 3 to 3 which are highly sensitive to configuration interaction. In this presentation, we describe an experiment recently performed on the LULI 2000 laser facility, mostly devoted to measurements of the absorption in the 60 – 180 eV spectral region in a copper plasma at a temperature of 10 to 30 eV and a density of few mg/cc. The experimental scheme is based on an indirect heating of multilayer thin foils by two gold cavities symmetrically heated by two nanosecond doubled-frequency beams with an energy of several hundreds of J. This scheme allows one to obtain moderate temperature- and density-gradients and ensures conditions close to local thermodynamic equilibrium. The self-emission of cavities in EUV range is eliminated by the use of a time-dependent detection. A preliminary interpretation of these measurements is proposed. This analysis relies on three different codes: the hybrid code SCO-RCG, the Flexible Atomic Code in detailed or configuration-average mode, and the HULLAC code in level or configuration mode. A qualitative agreement is obtained between theory and experiment, though the account for temperature gradients is probably necessary to accurately describe the present measurements.

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The Study of M-shell Gold Ionization in NLTE Plasmas Using a Buried Layer Platform at the OMEGA Laser

Experiments have been done at the OMEGA laser using a buried layer platform to study the radiative properties of non-local thermodynamic equilibrium (NLTE) plasmas at electron temperatures of _1.5 – 2.5 keV of mid to high Z materials. The targets used consisted of a 250 μm diameter, 770 Å thick dot with a 3:4 atomic mix of gold and vanadium in the center of a 1000 μm diameter, 10 μm thick beryllium tamper. Lasers heat the target from both sides for 3.0 ns. The size of the microdot vs time was measured with x-ray imaging (face- on and side-on). The radiant x-ray power was measured with a low-resolution, absolutely calibrated x- ray spectrometer (DANTE). The temperature was measured from the V k-shell emission. The measured ionization balance from M-shell gold is presented for a range of temperatures indicating ionization states from Kr-like to Fe-like gold. These ionizations are compared to calculations from the atomic kinetics code SCRAM.

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Proton Isochoric Heating and Warm Dense Matter Studies in the Multi-ps, kJ-class Laser Regime

Tightly focused, large flux proton beams can be used to rapidly heat materials to many tens of eV to >100 eV, creating matter in the warm dense matter (WDM) regime. Early demonstrations of this technique using a 10 J, 100 fs laser to drive the proton source showed great promise but could only just begin to reach the WDM regime at ˜25 eV temperatures. A new class of laser facilities (Omega EP, NIF-ARC, LFEX, PETAL, and ORION) are capable of delivering multi-kJ laser pulses over multiple picoseconds. Such lasers have demonstrated the ability to substantially improve laser-to-proton conversion efficiency (˜2-5%) over their sub-ps, 100 J-class counterparts. With large driver energies this can result in proton sources containing >50 J of energy in short pulse durations (˜50 ps), rivaling smaller laser facilities in terms of power (>TW). Focusing such a proton source can lead to a dramatic increase in the proton beam intensity and coupled with strong proton stopping power, enables prompt heating of samples to 100's of eV before significant hydrodynamic expansion can occur.
Recent experiments were carried out at LLE's Omega EP laser facility where multi-ps, ˜kJ laser pulses were used to drive hemispherical targets in order to create an intense proton heating source. This source was directed to small Cu samples that were encased in plastic in order to filter out heavy ion heating contributions and minimize hydrodynamic expansion. Multiple spectrometers were used to observe k-shell spectra and a Spherical Crystal Imager observed the spatial profile of k-alpha emission from the Cu samples while the proton source and sample position was varied. The results of these experiments and comparison to modeling will be presented.

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Using Tabulated Non-LTE Data for Hohlraum Simulations

Non-LTE atomic kinetics is necessary in ICF hohlraum simulations for adequately modeling high-Z walls and dopants. Thanks to a concentrated effort over many years by the non- LTE community, codes are now available that can model non-LTE atomic kinetics in great detail[1]. These codes are now routinely used to help diagnose experiments by providing synthetic emission and absoprtion spectra for a set of specified conditions. However, their computational cost is far beyond that possible to use in radiation-hydrodynamic codes, which are still restricted to using highly averaged atomic models for inline calculations of non-LTE effects.

An alternative to inline calculations is the use of tabulated data, akin to the use of tabulated LTE opacities and equation-of-state (EOS) information. Much effort has gone towards calculating (and measuring) these properties in LTE, with the result that tabulated highquality data is available for many cases of interest. This task is considerably more complicated for non-LTE conditions, as material properties can depend on the radiation field and electron distribution function as well as the density and temperature, and may also be explicitly time-dependent. Even under the assumptions of a thermal electron distribution and steadystate non-LTE kinetics, calculating and tabulating data for the entire range of anticipated radiation spectra appears prohibitively expensive in both CPU time and memory.

The Linear Response Matrix (LRM) provides an approach for tabulating non-LTE material data in an economical manner. This method was originally developed[2] to use under near-LTE conditions. It focused on the energy exchange between material and radiation, tabulating only LTE opacities and the response matrix, which describes the change in energy absorption and emission at one frequency due to the deviation of the radiation field at another frequency from a Planckian. Full non-LTE simulations require not only this information, but also emissivities, EOS properties, and corresponding response terms both near and far from LTE.

In the context of full non-LTE simulations, we view the LRM as a framework for tabulating material properties and their response functions. We extend the tables to situations far from LTE, treating the material temperature and radiation spectrum independently and including response functions to characterize changes in all material properties to variations in the radiation field. This approach permits the use of tabulated data in simulations with strong radiation fields and radiation transport effects.

In this work, we focus on an application which depends critically on non-LTE physics but experiences only a restricted class of radiation fields – gold hohlraums used on the National Ignition Facility (NIF). The hohlraums convert absorbed laser energy into X-rays which are used to drive capsule implosions or other physics experiments. The radiation temperature Tr in the hohlraum at peak drive is nearly spatially-uniform at a few hundred eV while the non-LTE gold ranges in material temperature from ˜Tr at the wall to a few keV in the ablation bubbles. The radiation spectrum can be characterized as near-Planckian with the largest deviations occuring in the hohlraum interior at photon energies of ˜2-3 keV from gold M-band radiation, and in the hot plasma near the laser entrance hole (LEH) where the radiation field is highly non-isotropic and somewhat dilute relative to its spectral content.

This important application provides a restricted phase space for testing the LRM approach in a context where the time dependence of the atomic kinetics is also known to be unimportant. We have implemented the LRM method in a rad-hydro code which already does inline non-LTE calculations. We compare hohlraum simulations done with inline calculations with those done with the LRM method, using tables constructed from the same atomic data used by the inline calculations.

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Machine learning and algorithmic methods in Plasma Physics

In this talk we will discuss recent work in the UK on developing modern statistical and data science methods for HEDP and plasma physics. In particular we focus on how machine learning approaches to modelling and predicting the yield from NIF-like ICF implosions can support future campaigns. We present several new ensembles of 10ˆ3-10ˆ4 simulations, showing that the uncertainty on predictions can be accurately decomposed into uncertainty from lack of data, and uncertainty on input parameters. We also show new approaches to finding novel classes of design with comparatively little human intervention. Finally we will briefly discuss how modern data science techniques are being used to support and maximize the utility of other types of HEDP experiments undertaken in the UK, including interpreting x-ray spectra from photo-pumping experiments and quantifying uncertainty from probes of QED effects.

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MASS-TEMPERATURE DISTRIBUTIONS WITHIN ICF IMPLOSIONS ON THE NATIONAL IGNITION FACILITY

Describing the conditions at stagnation (temperature/density of hotspot, ice, ablator, mix, gradients, etc.) within an ICF implosion is a challenge of which only partial information has thus far been gleaned from NIF and other premier high-energy density facilities. Given the temperatures (several keV) and electron densities (˜ 0.1 - 1x10^25 e-/cm3) located within micron length scales and evolving over 10s of ps time scales, spectroscopy is the best candidate to investigate these effects. Stark broadening of K-shell He-ß lines and K-shell spectral line intensity from a wide range of charge states that change in time and space, can infer the local and global temperature and density profiles. Constraining the atomic data to the K-shell spectral features from multiple spectrometers located at varying lines of sight and making use of extensive neutron imaging and time-of-flight data along with x-ray imaging from multiple lines of sight allows us to improve accuracy of the spectroscopic interpretations and help elucidate the truth. In this work we will describe a reanalysis of the red wings in spectral features of NIF data to determine cold mass from ablatormix in the hotspot from early NIF implosions and attempt to measure densities and temperature of a stagnating plasma using mid-Z (Cu, Ge, Kr) dopants in the core and ablator regions.

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Analysis of the hydrodynamic conditions in non-LTE buried layers experiments using 1 & 2 D simulations.

In recent years the buried layers platform has been developed at LLNL. The main purpose of this platform is to measure the radiative properties of uniform plasmas at non-LTE conditions. Such measurements are vital in order to benchmark non-LTE atomic models. These models are currently being used as a part of the rad-hydro simulations in larger integrated simulations such as in ICF. However, the design of the buried layers experiments requires the use of rad-hydro simulations in order to answer several questions: Is it feasible to achieve uniform plasma conditions? At what time is the buried layer plasma uniform and for how long? What are the optimal target parameters to achieve the desired plasma conditions? We have performed both 1 & 2D simulations of the experiments to answer these questions and compared them to the experimental results. Good agreement was found between the simulations and the experimental results. These simulations give us important information about the dynamic conditions in the target. The comparison with the experimental results can also be used as an initial validation for the microscopic atomic models used in these calculations.

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POSTERS

Plasma potential and opacity calculations

The knowledge of the radiative properties is crucial when we study the absorption in the ablator of ICF capsules. For this purpose, we developed a new code (LACOC) that includes a collisional-radiative module. Atomic data, calculated by either Cowan [1] or FAC code [2], is the input.

In a previous work we investigated the absorption of C+Si mixtures, where the silicon is a dopant in the ablator. Atomic data was obtained by Cowan's code, and the ionization potential depression (IPD) was given by the Stewart and Pyatt formula. Classical semi-empirical formulas for the cross sections of the various processes occurring in a hot and dense plasma are modified with the help of correction factors in order to match the FAC results. Unfortunately, the classical formulas tend to over/underestimate the line shifts due to the IPD.

In this work we present the ion charge distribution and compare the calculated transmission of a pure silicon plasma at N_e=1.3×10^{21} cm^{-3} and T_e=72 eV to the experiment of Xiong et al. [3].

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X-ray Scattering Measurements from 30-fold Compressed, Near-Degenerate Plasmas at the National Ignition Facility

We have developed an experimental platform for x-ray Thomson scattering (XRTS) measurements at the National Ignition Facility [1-4] to characterize the plasma conditions in plastic and beryllium capsules in implosion experiments near stagnation. We have demonstrated XRTS measurements in the collective and non-collective regime from capsules that were compressed to 30 g/cc and inferred electron densities approaching 10^25 1/cc, corresponding to a Fermi energy of 170 eV and pressures exceeding 1 Gbar. We will discuss recent results, which show significantly higher ionization than predicted by widely-used ionization models like Stewart & Pyatt.

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Species separation in warm dense matter

The interiors of astrophysical objects like planets, brown dwarfs or neutron stars are compressed to densities of several grams per cubic centimeter and heated to temperatures that are on the order of the chemical bonding and above. In this environment, multicomponent materials start to react and to change, which can result in a mixture of different phases.

For gas planets like Jupiter and Saturn, a separation into helium-rich and helium-poor phases is assumed and the resulting boundary layer has a significant impact on the interpretation of observed data and our understanding of planetary formation.

In the atmosphere of icy giants like Uranus and Neptune, methane is highly abundant. The isentrope of these planets intersects a temperature-pressure regime, in which methane releases some hydrogen and transforms into a heavy fluid of different hydrocarbons. In even deeper layers, a separation into diamond and hydrogen is predicted. X-ray Thomson scattering (XRTS) is a suitable diagnostic for plasma parameters like density, temperature and ion charge state. Here, for the first time, we demonstrate the feasibility of using XRTS to measure the species separation of shock-compressed CH into a carbon-rich and a carbon-poor phase. These measurements were done at conditions similar to those found in the interior of Uranus and Neptune at a depth of about 10000 km, and for which complimentary diffraction measurements have shown the creation of diamonds.

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Ultrafast electron dynamics in a solid-density aluminium interacting with an ultra-intense ultrafast x-ray pulse

Ultrafast nonequilibrium dynamics of free electrons in a solid-density aluminium produced by an ultra-intense ultrafast x-ray pulse is investigated by solving Fokker-Planck equation. Electron energy distribution function (EEDF) contains two parts: a lower energy part at nearly equilibrium and a higher energy part at evident nonequilibrium. The former part accounts for the most population of the total electron number. X-ray transmission and bound-bound emissivity show little difference between the results with EEDF obtained by solving Fokker-Planck equation and by Maxwellian distribution assumption. Yet the bremsstrahlung emissivity shows great difference.

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Efficient Modelling of K-shell Emission for Short-Pulse Laser

WI Cold K-alpha and K-beta emission provides a diagnostic for hot electron distributions produced in short pulse laser experiments. Spect3D is able to post-process results of PIC simulations and compute high-resolution spectra for plasmas containing arbitrary distributions of hot electrons. These calculations, however, require comprehensive sets of atomic data and can become prohibitively expensive for modest and large simulation grids. To significantly increase calculation speed, it is desirable to use pre-computed emissivity/opacity tables that include effects of hot electrons, rather than calculating the data for every spatial zone. However, to tabulate results for arbitrary hot electron energy distributions, a general method must be found to describe arbitrary energy distributions with an analytic function of just a few parameters. We will present a set of PrismSPECT and Spect3D results validating the replacement of hot electron distributions with a Gaussian function determined by each hot electron distribution. Tests are performed on LSP simulations for experiments on Omega EP.

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Neon photo-ionized plasma at LULI

Recently Ne photo-ionized plasmas have been produced using the LULI2000 laser facility. During the campaign, the electron temperature (T_e) has been evaluated using Optical Thomson Scattering (OTS). The electronic density (N_e) has been deduced from interferometry measurements and X-ray emission spectra have been recorded. Here is presented a spectroscopic analysis of one of these spectra. From this analysis we evaluate that the photoionization parameter is near 9 erg.cm/s. Plasma parameters (T_e,N_e) we obtained are compared both to measured values and to results of simulations we performed using radiation-hydrodynamics codes.

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Femtosecond measurement of d electron dynamics in non-equilibrium warm dense copper using XFEL

We present an ultrafast x-ray absorption spectroscopy measurement of warm dense copper using the PAL-XFEL. In femtosecond and picosecond time scales, the d-band of non-equilibrium warm dense copper (WDCu) created by femtosecond laser excitation is probed by time-resolved x-ray absorption spectroscopy technique. Free-standing copper foil (70 nm thick) was isochorically heated with frequency doubled Ti;sapphire laser pulses. XFEL pulse has photon energy of 930 +/- 0.5 eV and probe the unoccupied density of state at the upper edge of Cu d-band. Evolution of X-ray absorption clearly demonstrate the non-equilibrium behavior which is different from the two-temperature model. In particular at times < 1 ps, the strong deviation from TTM illustrates an interesting thermalization process of hot electrons in a highly-excited system.

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EUV-source modeling using radiation-hydrodynamics method with RALEF-2D code

Modern EUV-lithography requires a stable source of emission with high power and conversion efficiency in 2% spectral band near 13.5 nm. The most promising source of EUV radiation is based on hot tin (Sn) plasma, produced by a CO2 or Nd:YAG laser. The existing industrial prototypes use so called optimized mass limited targets, which are produced by irradiating a liquid tin droplets few tens of micrometers in diameter by a laser pre-pulse with low intensity. After the pre-pulse the liquid droplet transforms into a distributed target (disk or some other form, depending on the pre-pulse parameters), which is in turn irradiated by a main high intensity laser pulse thus producing the EUV-emitting tin plasma. Numerical simulation of these processes is a non-trivial task. Complex self-consistent physical model is required. It should contain hydrodynamics (2D at least), radiation transport, thermal conduction, laser-matter interaction physics, two-phase equation of state and radiative properties. Such model was implemented in RALEF-2D code [1], [2] including spectral opacities calculated by using THERMOS toolkit [3] and equation of state obtained with FEOS[4]. The most interesting results related to simulation of laser impact on a tin droplet and subsequent target evolution and further EUV-source radiation, as well as results of comparison with available experimental measurement of laser absorption [5] and droplet velocity after laser prepulse [6], are presented in this report. Good agreement with experimental results have confirmed applicability of considered model and code [6], [7].

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Two-photon absorption cross section calculations related to the Iron opacity Sandia Z-experiment

Two-photon absorption was recently proposed as a possible explanation for extant discrepancies between theoretical and experimental x-ray transmission of iron samples at conditions relevant to the solar interior. The theoretical framework for calculating two-photon absorption specific to the experiments performed at the Sandia National Laboratory is developed.

Estimates suggest that the radiant flux attenuation by two-photon absorption is a few orders-of-magnitude smaller than the corresponding single-photon cross section.

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Surrogate Experiments for Evaluating the Opacity Model accuracy in the Deep Solar Interior Using the Micro-Equivalence Principle

A problem for stellar astrophysics is that existing opacity models have been called into question both by experiments [1] and by solar model comparisons with helioseismology, but an alternative opacity model does not yet exist. Importantly, the experiments measured opacity only for iron, at 182 eV – 195 eV temperatures (Te) comparable to the value at ˜ 0.7R_Solar. Experimental validation of opacity models at higher Te and density (ne) are required to understand the entire Sun. Unfortunately, controlled transmission measurements at the required conditions are extremely difficult to achieve at lab. We propose to help resolve this dilemma using experiments at achieved conditions combined with the "microscopic equivalence" principle. Two systems of atoms in plasma, in different T_e - n_e regimes, are considered "microscopically equivalent" if one of them can serve as a reliable emulator of the other, within a theoretical model framework. "Microscopically equivalence" between plasmas requires that the values of ratios between fundamental physical processes (e.g. plasma coupling parameters, expansion parameters of the atomic perturbation theory) will be similar for both plasmas. In addition, the ratio between the various atomic absorption contributions, like bound-bound, bound-free and free-free will be similar for each photon energy scaled to the temperature. Thus, we can use a lower-atomic-number surrogate element to test opacity model physics important for iron at higher Te and ne than can be reached in present experiments. Theoretical modeling to evaluate this idea, using the CRSTA[2,3]/PRCRSTA [4] models, and possible experiment designs will be discussed.

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Stark-broadened line shapes of Ar K-shell ions: a comparison between molecular dynamics simulations and MERL results

Analysis of Stark-broadened spectral line profiles is a powerful, non-intrusive diagnostic echnique to extract the electron density of high-energy-density plasmas. The increasing number of applications and availability of spectroscopic measurements has stimulated new research on line broadening theory calculations and molecular dynamics simulations, and their comparison [1-3]. Here, we discuss a comparative study of Stark-broadened line shapes calculated with molecular dynamics simulations [4] and with the multi-electron radiator line shape MERL code [5,6]. In particular, we focus on Ar K-shell X-ray line transitions in Heand H-like ions, i.e. He_, He_ and He in He-like Ar and Ly_, Ly_ and Ly in H-like Ar.

These lines have been extensively used for x-ray spectroscopy of Ar-doped implosion cores in indirect- and direct-drive inertial confinement fusion (ICF) experiments [7]. The calculations were done for electron densities ranging from 10^{23} to 5×10^{24} cm^{-3} and a representative electron temperature of 1 keV. Comparisons of electron broadening only and complete line profiles including electron and ion broadening effects, as well as Doppler, will be presented and discussed. Furthermore, we assess the impact of employing either molecular dynamics or MERL line profiles on the diagnosis of core conditions in implosion experiments performed at OMEGA.

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X and XUV spectroscopy of ps laser-produced Al and C plasmas

X-ray spectroscopy plays a key role in the domain of laser-generated plasmas as a crucial ool for the investigation of their atomic properties and hydrodynamic evolution. Its role is essential when the evolution of the plasma is mostly determined by radiative transfer phenomena. This is the case for both direct and indirect-drive in Inertial Confinement Fusion (ICF) configurations. Reliable atomic models are needed for hydrodynamic and atomic kinetic codes to simulate the evolution of the plasma. To validate their assumptions and approximations, experimental data must be provided that cover both the emission spectrum and the hydrodynamic evolution with mutually independent diagnostics. We will present the first stage of a pluri-annual project. We tested an experimental setup by characterizing well-known elements: C and Al. The configuration of the target structure and the drive laser parameters have been optimized in order to obtain a homogeneous plasma. The experimental campaign was realized on the ELFIE laser facility of the LULI laboratory. A 5 ps laser pulse at moderate intensity (I = 10ˆ15 – 10ˆ16 W/cm2) was focused onto a structured target composed by a Si3N4 substrate coated by a C or Al layer. The electronic density has been measured with a Nomarski interferometer using the standard Abel transform. The Al X-ray and the C XUV emission spectra was measured with a reflection grating spectrometer. A pinhole camera was used as lens-free X-ray optical tool to measure the plasma lateral dimension. The experimental results indicate that the plasma was fairly homogeneous. The results concerning hydrodynamic and spectral properties of the laser-generated plasma have been compared to the output of the MULTI hydrodynamic code and of the PrismSPECT atomic kinetic software, confirming the reliability of the setup. Future work should focus on the study of ICF ablators such as Ge.

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Corrections to 3T Modelling of radiation-matter energy exchange

Existing three-temperature (3T) radiation-hydrodynamics often assume that the energy exchange between electrons and radiation can be approximated by using the Planck opacity calculated at the electron temperature, $\kappa_P(T_e)$. This results in an approximate electron-radiation energy exchange rate, $\omega^{er^{\prime}}$. We present a study comparing solutions of the exchange rate when this assumption is relaxed. At high temperatures - where opacity, κ, is dominated by the free-free component, κ_{ff} - the exchange rate can be solved analytically using the digamma function. At lower temperatures, the Ionised Material Package (IMP) can be used to include bound-bound and bound-free effects, resulting in a more accurate exchange rate, ω^{er}. By solving for a correction factor of the form $Q = \frac{\omega^{er}}{\omega^{er^{\prime}}}$, it is shown that calculations using $\kappa_P(T_e)$ exclusively can cause results to be incorrect by a factor of 2.5 for iron of ρ= 0.1 gcm^{-3}, T_e= 0.5 keV, T_r= 2 keV and around 0.01 for aluminium of ρ= 1 g cm^{-3}, T_e= 1 keV, T_r= 8 keV.

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Ultrafast Dynamics of Excited Electron Distribution in Warm Dense Aluminum

With the development of ultrafast probing techniques such as XFEL, HHG and femto-second lasers, detailed microscopic understanding of thermalization and transition process from cold states to dense plasma states could be explored. In warm dense aluminum excited by a femtosecond laser pulse, on sub-picosecond time scale (< 1 ps), there was an observation of the aluminum absorption variation over a 10-eV range near L-edge with a non-equilibrium electron distribution. In this poster, we present a detailed simulation model of non-equilibrium electron–hole dynamics in highly excited warm dense aluminum plasma in order to explain the L-edge absorption variation. Conclusively, wecalculate the probabilistic free electron distribution of 1 fs time steps, so that an electronelectron thermalization time of a few hundred femto-seconds in laser-induced dense aluminum plasmas which obtain an excellent agreement on the experimental data.

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Effect of the dynamical electron collision frequency on the quantum wakefield around an ion in dense plasmas

The quantum wakefield around an ion was shown to be important in dense plasmas with a directed motion of fast electrons [1, 2]. Such a situation can appear due to impact by electron (ion) beams and electrons acceleration by laser. In previous works [1, 2], we have studied the wakefield in dense plasmas for different plasma parameters and streaming velocities using the dynamical quantum dielectric function of electrons (DF). The results clearly show a significant deviation of the potential and the electronic density distribution around an ion from that of in an equilibrium case. In addition, we showed that the wakefield in a plasma with partially or strongly degenerate electrons has essentially different features compared to that of classical and ultrarelativistic plasmas [2]. In Refs. [1, 2], the electronic correlations were included in a relaxation time approximation using Mermin dielectric function with a static collision frequency. However, it has been shown that taking into account the frequency dependence of the e-i collision frequency is crucial for the description of the transport and optical properties of dense plasmas and warm dense matter [3-5]. Therefore, in this contribution, we extend our analysis of the quantum wakefield by implementing the dynamical collision frequency in the second order Born approximation [6]. We show that the dynamically screened ion potential has stronger oscillations in upstream direction compared to the case with static collision frequency. We also revealed that the attraction between ions in downstream direction appears even at small values of the streaming velocity (in units of an electronic Fermi velocity). Furthermore, we analyze the applicability of various simplified formulas for the dynamical collision frequency [7].

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Theory of opacity from two-photon absorption processes

We describe recent research on plasma opacity produced by two-photon absorption.

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The use of geometric effects in diagnosing ion density in ICF related Dot Spectroscopy experiments

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Average-atom model calculations of dense-plasma properties relevant to white-dwarf stars

Methods using average-atom models in order to calculate dense-plasma equation-of-state, opacities and conductivities are reviewed. Dense plasmas at moderate temperatures, of interest in white-dwarf modelling, are considered. Due to their relative simplicity of implementation, compared to more detailed models (detailed-level accounting, detailed configuration accounting, etc.), average-atom models are a privileged framework for the application of the most involved dense-plasma statistical modelling. Moreover, the average-atom models are well suited to the calculation of some thermodynamic properties, such as the equation of state. They can also be used in order to estimate broadband radiative properties of dense plasmas.

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Stark-Zeeman line shape models for the diagnostic of magnetic fusion plasmas

Passive spectroscopy methods, which are based on a direct observation of the radiation emitted by the plasma, are convenient because they allow one to get information on relevant parameters (Ne, Te etc.) without perturbing the plasma. In this framework, our group has developed, improved, and used line shape codes for the interpretation of spectra observed in the divertor of several European tokamaks like ASDEX-Upgrade, TCV, and JET. A specific feature of edge and divertor plasmas with high electron densities (Ne > 1014 cm-3) is that all lines in the Balmer series are affected by the Stark broadening due to the plasma's microscopic electric field. This effect is strongly dependent on the electron density and can be used as a diagnostic. In contrast to other line broadening mechanisms (such as Doppler effect or natural broadening), the modeling of Stark broadening requires a careful description of the physics underlying the interaction between the emitter and the charged particles moving at its vicinity; there is so far no analytical formula which is applicable to all lines of the Balmer series in tokamak edge plasma conditions. Stark-broadened lines can be calculated in an efficient way using numerical models such as the FFM (PPP code [1,2]). On the other hand, computer simulations provide benchmark spectra but they are not suitable for a diagnostic application in real time because they are time-consuming. Recently, we applied such a method to the calculation of a set of line shapes for a grid of density, temperature and magnetic field values relevant to tokamak edge plasma conditions [3,4]. A focus was put on Balmer lines with a low or moderate principal quantum number (up to n = 7) in regimes where the ion dynamics is important. Because of the strong magnetic field present in tokamaks, such lines are split by Zeeman effect, so that it was necessary to retain this effect in the calculations. We will use the database for the analysis of new atomic spectra observed in the divertor of WEST (an upgrade of the Tore Supra tokamak) and other devices.

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