Implementation of a Super-Shell Refinement Algorithm for Plasma Opacities

Daniel Åberg*, Paul E. Grabowski, Carlos A. Iglesias, and Brian G. Wilson

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550, USA

The spectral fidelity of opacity spectra generated using Super-Transition Array (STA) formalism is strongly dependent by the choice of super-shell structure. We report on an algorithm where a parent super-configuration (SC) is iteratively refined into daughter SCs until the probabilities of the parent and daughter SCs are equal within a small tolerance. This naturally leads to an SC-dependent super-shell structure, avoiding redundant refinement of SCs that are already converged using a small number of super-shells. We further discuss some modifications of the scheme necessary to accelerate convergence of STA spectra when orbital relaxation, or finite-state effects, are considered. Benchmark calculations illustrating computational efficiency using LLNL's LTE opacity code OPUS will be showcased and discussed. Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-868727.

*E-mail: aberg2@llnl.gov

Modelling non-thermal XFEL heating of Iron

L. Ansia[1,2]*, P. Velarde[2], M. Fajardo[1] and G. O. Williams[1]

[1] GoLP/Instituto de Plasmas e Fusão Nuclear, Universidade de Lisboa, 1049-001, Portugal.
[2]Instituto de Fusión Nuclear, Universidad Politécnica de Madrid, José Gutiérrez Abascal 2, 28006, Spain.

Over the past two decades, X-ray free-electron lasers (XFELs) have made significant progress, achieving peak brightness in the XUV and X-ray regions that were previously only attainable in the optical and infrared ranges. This advancement has opened up new possibilities in high-energy density science. It enables the creation of solid-density plasmas with larger volumes, greater uniformity, and well-defined properties, including temperature and density. XFEL heating proceeds through photoionisation and thermalisation, and as such initially creates a non-thermal electron distribution.

In the last years, several experiments have been focus in the creation of solid density plasmas of mid-Z materials, especially transition metals. Since collisional models have been proven to be a successful method to understand the time resolved atomic kinetics, we have adapted the non-thermal collisional radiative model BigBarT [1, 2, 3, 4] in order to simulate arbitrary elements.

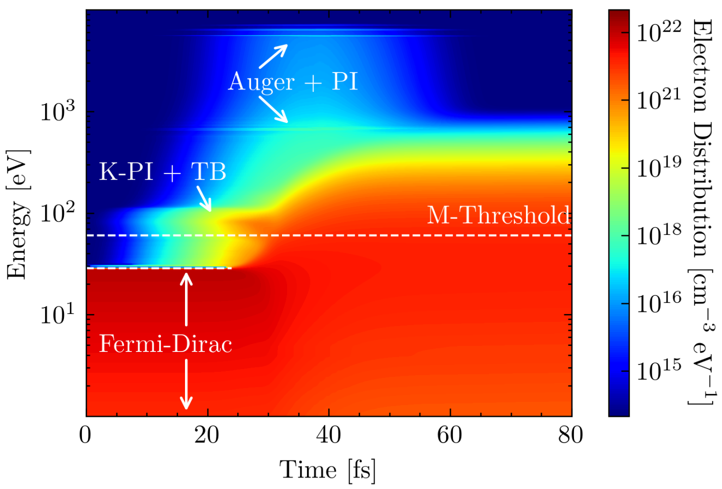

Figure 1. Electronic distribution temporal evolution of an Iron XFEL produced plasma, for a 15 fs FWHM pulse at 5×10^{17} W/cm^2

We investigate the effects of inelastic thermalization in iron under intense X-ray irradiation using the atomic model BigBarT , suited for the self-consistent evolution of the electron continuum, including degeneracy effects. A typical evolution of the distribution function is showed in Figure 1, for a 15 fs FWHM pulse at 5×10^{17} W/cm^2, and an incoming photon energy of 7200 eV. Our study focuses particularly on collisional M-shell ionization, which we identify as the most efficient relaxation process of non-thermal electrons. Comparison of calculated spectra with data could be used to refine collisional cross sections, that are otherwise difficult to compute due to their proximity to the continuum and the associated plasma screening effects.

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*E-mail: lucas.ansia.fernandez@tecnico.ulisboa.pt

Laser-irradiated X-ray sources for X-ray diffraction of dynamically compressed matter on Sandia's Z-Machine

T. Ao*, M. Geissel, K. Fulford, P. Rambo and C. Yang

Sandia National Laboratories, Albuquerque, USA

Experiments on Sandia's Z-Machine have demonstrated the ability to produce dynamically compressed extreme-pressure states of matter with unique uniformity, duration, and size, which are ideal for investigations of fundamental material properties. X-ray diffraction (XRD) is a key material science measurement since it provides direct observation of the compression and strain of the crystal lattice, and is used to detect and identify phase transitions. To characterize phase transitions of dynamically compressed matter, XRD require both sufficient photon energy and fluence to produce data with high fidelity in a single shot. Recently, a novel XRD diagnostic has been implemented on the Z-Machine which enabled probing the phase changes of carbon samples that were dynamically compressed to pressures of 150–320 GPa [1].

Sandia's high-energy laser systems associated with the Z-Machine consist of the nanosecond Z-Beamlet (ZBL) laser and the sub-nanosecond Z-Petawatt (ZPW) laser. While the ZBL laser is currently being used to generate X-rays for the Z-XRD experiments, the ZPW laser is being developed as an X-ray source option for future campaigns. We present our latest data on absolute X-ray yields for mid-Z K-shell emission produced with ZBL and compare them to those produced with ZPW. We found that ZBL is a suitable X-ray driver up to 10 keV (Ge He_{α}), though the efficiency is very sensitive to pulse energy/intensity at this limit. However, for 15 keV (Zr K_{α}) X-rays and above, ZPW outperforms ZBL. We will compare the impact of target geometry, surface structure, and observation angle for X-ray generation with ZPW before and after recent improvements to focusability and pulse duration. These results will have important implications for future Z-XRD experiments, especially for high-Z materials.

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* E-mail: tao@sandia.gov

Evaluation of Au L-shell spectroscopy as a T_e diagnostic for NIF hohlraum plasmas

N. Aybar[1 *], D. Liedahl[1], T. Woods[1], H. Chen[1], D. E. Hinkel[1], O. Landen[1], J. S. Ross[1], and M. B. Schneider[1]

[1]Lawrence Livermore National Laboratory, Livermore, USA

Obtaining accurate measurements of hohlraum plasma conditions is challenging, yet highly valuable in understanding hohlraum energy transport and achieving predictive modeling capabilities of indirect drive inertial confinement fusion. This is particularly true in the gold bubble region, a plasma plume generated where the outer beams strike the hohlraum, as subsequent laser energy propagates through and heats the gold bubble plasma. To attain such measurements, high quality spectral data were obtained from L-shell transitions of gold plasma self-emission which can serve as a powerful Te diagnostic, as the observed spectral features shift in energy depending on the charge state distribution. Experimental data collected from dedicated hohlraum science experiments include time resolved spectra of the Au L-shell. The measured spectra are compared against synthetic spectra produced by postprocessing radiation-hydrodynamics simulations performed in Lasnex [1] with atomic kinetics code SCRAM [2]. As a benchmark, these results are compared with dopant K-shell spectra from He-like and H-like charge states of Zn co-located in the gold. The differences obtained from both Te sensitive diagnostic approaches will be discussed and compared against simulation results.

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* E-mail: aybar1@llnl.gov

Towards opacity measurements at the LMJ facility: preliminary experiments with the atomic physics platform

C. Bowen[1*], M. Bonneau[1], Q. Alexandre[1], M. Brochier[3], T. Chirac[1], C. Courtois[1], S. Debesset[3], V. Denis[3], R. du Jeu[3], P. Dupré[3], S. Ferré[1], T. Fonseca[1], I. Geoffray[2], D. Gontier[1], L. Jacquet[1], S. Khieu[2], L. Le-Deroff[3], C. Meyer[1], J.-C. Pain[1], V. Prévot[1], P. Prunet[1], C. Reverdin[1], G. Soullie[1], M. Sozet[1], B. Vauzour[1] and B. Villette[1]

[1] CEA, DAM, DIF, F-91297 Arpajon, France
[2] CEA, CVA, F-21120 Is-sur-tille, France
[3] CEA-CESTA, F-33116, Le Barp, France

The new High Resolution X-ray Spectrometer (HRXS) of the Laser Mega Joule facility (LMJ) was commissioned at the end of 2023. Combined with the broadband X-ray spectrometers DMX and mini-DMX and with X-ray imaging diagnostics [1], it constitutes a platform for atomic physics experiments at LMJ. In particular, we are interested in opacity measurements, for which the control of the sample hydrodynamics and the quality of the transmission measurement are cornerstones [2]. We plan to measure the transmission of a copper plasma, generated in a laser-heated baffle Hohlraum. The center channels of HRXS provide time resolution, and spatial resolution along one axis. The time resolution should suppress the background signal, while we can use the spatial resolution to select the signal transmitted by the Cu plasma on the one hand and the signal that propagated through a witness area on the other hand. Following the HRXS commissioning, we performed preliminary experiments with HRXS, testing separately different backlighters and the Hohlraum, in order to assess the accessible quality of the transmission measurement and the sample preparation.

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* E-mail: christopher.bowen@cea.fr

Helioseismic inference of the solar radiative opacity

G. Buldgen[1 *], J. C. Pain[2,3], P. Cossé[2,3], A. Pradhan[4],C. Blancard[2,3], F.Gilleron[2,3], C.J. Fontes[5], J.Colgan[5], A. Noels[1]

[1]Star Institute, Université de Liège, Belgique
[2]CEA, DAM, DIF, F-91297 Arpajon, France
[3]Université Paris-Saclay, CEA, LMCE, F-91680 Bruyères le Châtel, France
[4]Dept. Astronomy,Ohio State University, Columbus, OH, 43210, USA
[5]Los Alamos National Laboratory, Los Alamos, NM, 87545, USA

The Sun is the most studied of all stars and constitutes a benchmark for stellar models. However, our vision of the Sun is still incomplete, as illustrated by the current debate on its chemical composition [1,2]. The problem reaches far beyond chemical abundances and is intimately linked to microscopic and macroscopic physical ingredients of solar models such as radiative opacity (see e.g. [3] for a review), for which experimental results have been recently measured that still await theoretical explanations. We present for the first time opacity profiles derived from helioseismic inferences and compare them with detailed computations of individual element contributions using four different opacity codes (OPAS, OP, SCO-RCG and OPLIB) in a complementary way to experimental results. We find that our seismic opacity is ~10% higher than theoretical values used in current solar models around 2 million degrees, but lower by 35% than some available theoretical values (See Figure 1 below). Using the Sun as a laboratory of fundamental physics [4], we show that quantitative comparisons between various opacity tables are required to understand the origin of the discrepancies between reported helioseismic, theoretical and experimental opacity values.

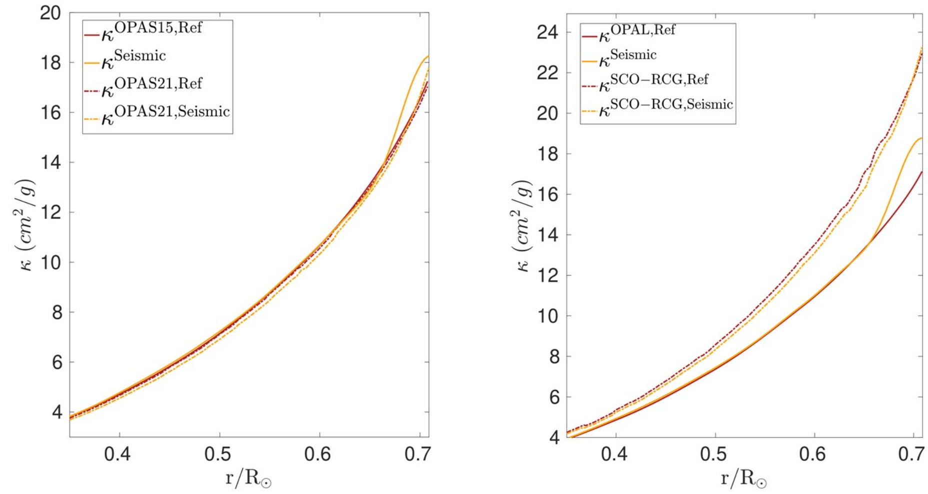

Figure 1. Comparison of the mean Rosseland opacity profiles of solar models, seismic reconstruction and theoretical computations for the thermodynamical. *Left panel:* Opacity profiles from evolutionary computations with 2015 OPAS tables (brown-plain line), from seismic reconstruction (orange-plain line), and from detailed computations with the OPAS code for both model and seismic thermodynamical paths (brown and orange dashed lines, respectively). *Right panel:* Opacity profiles for evolutionary computations using OPAL tables (brown-plain line), from seismic reconstruction (orange-plain line) and from detailed SCO-RCG computations for both model and seismic thermodynamical paths (brown and orange dashed lines, respectively).

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[*] E-mail: gbuldgen@uliege.be

Review of the 7th Spectral Line Shapes in Plasmas code comparison workshop.

A. Calisti[1 *]

[1]Aix-Marseille University, CNRS, PIIM laboratory, Marseille, France.

Spectroscopy is one of the richest sources of plasma diagnostics [1]. Since diagnostics are based on the comparison of observed and modeled data, accurate theoretical models of atomic physics and radiation are required to be reliable.

The modeling of spectral lines in plasmas, which involves a complex combination of atomic physics, statistical physics and plasma physics, plays a crucial role in the interpretation of spectroscopic observations. Except for a few special cases, the calculation of line profiles in plasmas requires the use of numerical codes. There are a number of such codes, more or less complex, which necessarily differ in their scope and accuracy. To verify the accuracy and validity of models and codes, it is necessary to compare them to well-characterized reference experiments, when these exist, or to test them by comparing them to other models.

The SLSP (Spectral Line Shapes in Plasmas) Code Comparison Workshop was established in 2012 to encourage and facilitate such comparisons, which were almost non-existent [2]. Six editions of this workshop, organized in cooperation with the International Atomic Energy Agency (IAEA), have been held to date, during which a large number of diverse problems have been analyzed. The result has been a better understanding of the underlying phenomena and more accurate models [3, 4, 5, 6]. However, despite the progress made, several problems remain open, such as the interpretation of white dwarf spectra [7, 8] or those of WDM experiments [9].

In this talk, a report of the 7th SLSP, held in Gran Canaria, Spain, from 30 September to 4 October 2024, will be presented. A variety of topics were covered, ranging from standard cases that are highly demanding for codes and models to modeling experimental data and studying effects first addressed at SLSP such as Van der Waals broadening, the motional Stark effect (MSE), and periodic electric fields in the presence of a constant magnetic field.

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*E-mail: annette.calisti@univ-amu.fr

Evidence of gold NLTE model in the deficiency of NIF ICF hohlraum x-ray drive prediction

Hui Chen, D. T. Woods, W. A. Farmer, N. A. Aybar, D. A. Liedahl, S. A. MacLaren, M. B. Schneider, H. A. Scott, D. E. Hinkel, O. L. Landen, J. D. Moody, M. D. Rosen, J. S. Ross, S. Rogers, N. Roskopf, G. Swadling and S. Vonhof

Lawrence Livermore National Laboratory, Livermore, California, USA

In the indirect-drive inertial confinement fusion (ICF) experiments on the National Ignition Facility (NIF) that have achieved ignition with energy gain of greater than one [1-3], advances in experimental design using hydrodynamic codes [3] have played critical role. To date, a less-than-unity artificial multiplier is often used in the design code, often referred as « drive-deficit », to match the implosion performance of deuterium-tritium fuel capsule [3]. We have performed a set of dedicated experiments using pairs of viewfactor targets [4] to understand the cause for such multiplier. The target and diagnostic setup is shown in Figure 1. The data revealed that the discrepancy between the simulation and data is larger when the measurement focus on the hotter (2-5 keV) region of non-Local thermal equilibrium (NLTE) plasma. Using an opacity multiplier on gold "M-band" emission in the code is shown to produce a much improved match to the measurements for both the radiation drive and the bubble temperature via K-shell dopant spectroscopy data. These experiments conclude that the inaccuracies in the atomic modeling of the NLTE gold plasma is likely responsible for the long standing "drive-deficient" hohlraum modeling [5].

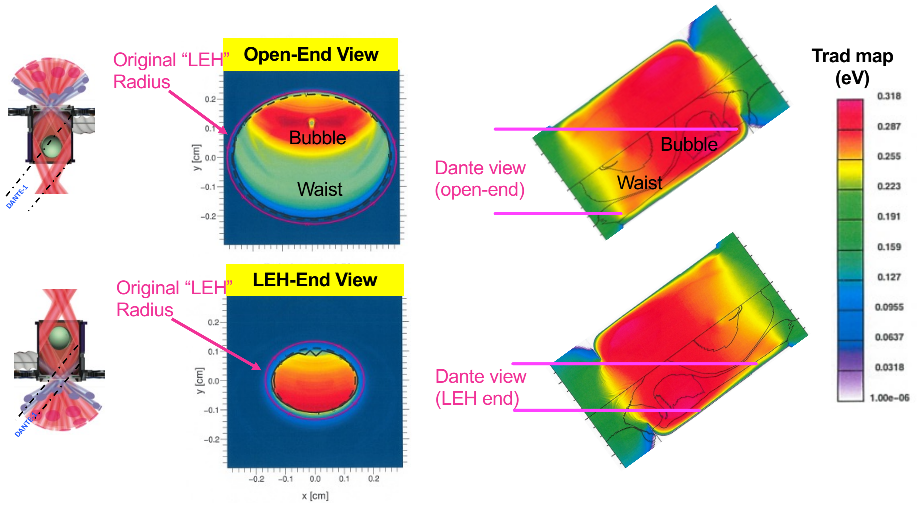

Figure 1. A pair of viewfactor targets provide different view of hohlraum internals and the target view of the Dante radiation flux diagnostic. The hohlraum plasma viewing through « LEH-end » is dominated by the NLTE Au bubble.

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* E-mail: chen33@llnl.gov

Testing High Density XSTAR models with Fe Photoionized Plasma Experiments on Z

Patricia Cho[1*], Guillaume Loisel[2], Jim Bailey[2], Dan Mayes[1], Isaac Huegel[1], Taisuke Nagayama[2], Chris Fontes[4], Stephanie Hansen[2], Tim Kallman[3], Javier Garcia[5], Roberto Mancini[6]

[1]Lawrence Livermore National Laboratory, Livermore, CA, USA
[2]Sandia National Laboratories, Albuquerque, NM, USA
[3]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[4]Los Alamos National Laboratories, Los Alamos, NM, USA
[6] University of Nevada Reno, Reno, NV, USA

The Z-machine at Sandia National Laboratories generates powerful X-ray radiation fluxes. This enables experiments to produce and study macroscopic quantities of matter at extreme conditions. Astronomers use spectra collected with satellite telescopes to construct models for the behavior of accretion powered plasmas around black holes in both active galactic nuclei and X-ray binaries. However, complex models for these radiation dominated non-Local-Thermodynamic-Equilibrium (NLTE) photoionized plasmas are mostly untested with laboratory data. A novel platform developed on the Z-machine for expanding-foil photoionized plasma experiments opens a new regime for benchmark measurements of NLTE photoionized plasmas. The data from these experiments reveal difficulties in modeling both emission intensities and the level of ionization in the plasma. Such data have been a laboratory astrophysics goal for two decades but are even more critical now because of the "Super-Solar" iron abundance problem. Iron abundances inferred from X-ray spectra emitted by photoionized plasma in many accretion disks around black holes appear to contain 5-20 times more iron than the Sun. This contradicts the widely held expectation that most objects in the universe have metallicities that are at most, only slightly larger than Solar. One prevailing theory is that effects of high electron density are not properly accounted for in the models. Reinterpreting astrophysical X-ray spectra with updated high density models resolved some of the discrepancy. However, much of the discrepancy remains along with a key question: do spectral models of photoionized plasmas accurately account for X-ray emission? I will describe my progress in using this dataset to inform the Super-Solar iron abundance problem and discuss the broader potential to evaluate model accuracy.

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*E-mail: cho32@llnl.gov

Production of an opacity table for air

Mark C. Zammit, James Colgan*, Isuru Ariyarathna, Christopher J. Fontes, Jeffery A. Leiding, Amanda J. Neukirch, Rodney W. Whitaker, and Eddy Timmermans

Los Alamos National Laboratory, Los Alamos, NM 87545, USA
*jcolgan@lanl.gov

Opacities are one of the most crucial ingredients in radiation-hydrodynamic simulations used to model a variety of astrophysical phenomena, laser-produced plasmas, and in shock-induced heating studies. For hot plasmas, it is usually only necessary to consider the opacities of atoms and their ions – a task that can still be very challenging for systems where a number of ion stages are populated and for complex ions where many atomic levels may retain population. For cooler plasmas (roughly temperatures in the range of 1 eV), it may be necessary to consider mixtures of atomic and molecular species. This can also be quite challenging, especially for scenarios where ionization and dissociation of molecules can lead to cases where contributions from atoms, molecules, and their ions are all important. Here we describe our recent work in calculating the opacity of air for a range of temperatures and densities. For room temperature cases, the opacity of air is dominated by the diatomic molecule contributions from N2 and O2. At temperatures of a few thousand Kelvin other molecular species, such as NO and NO2, make important contributions. At higher temperatures (approaching tens of thousands of Kelvin), molecular and atomic contributions are both significant. At even higher temperatures, atomic contributions finally start to dominate.

Our approach starts from the LANL Magpie code [1], which computes the equation-of-state of the air components for a given temperature and pressure in local thermodynamic equilibrium. The LANL MOLOP suite [2] is then used to compute the molecular absorption. We use a combination of detailed quantum chemistry (using the MOLPRO code [3]) and RKR methods to compute the potential energy curves and dipole matrix elements for the diatomic molecules of interest. NO2 contributions are provided from work done at Sandia National Laboratories [4]. The atomic contributions are computed using the LANL suite of atomic physics codes [5]. The LANL MOLOP code then assembles the monochromatic opacity of the air mixture and has recently been used to construct tables of air opacities. Examples of such opacities will be shown at the conference.
LANL is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. 89233218NCA000001.

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Ionization and temperature measurements in warm dense copper using x-ray absorption spectroscopy

T. Cordova[1,2†], E. V. Marley[2], D. Chin[3], T. Döppner[2], R. A. London[2], M. K. G. Kruse[2], H. A. Scott[2], F. N. Beg[1], F. Coppari[2], J. Emig[2], S. B. Hansen[4], C. C. Kuranz[5], M. Millot[2], P. Nilson[3], M. P. Springstead[5], P. Sterne[2], and M. J. MacDonald[2]

[1]*University of California San Diego, San Diego, CA, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, CA, USA*
[3]*Laboratory for Laser Energetics, University of Rochester, Rochester, NY, USA*
[4]*Sandia National Laboratories, Albuquerque, NM, USA*
[5]*University of Michigan, Ann Arbor, MI, USA*

Warm dense matter exists at temperatures of order 10 eV and a few times solid density, where the complex balance of collective and quantum effects precludes standard approximations used in plasma physics or condensed matter physics. Understanding ionization in the warm dense matter regime, in particular, is an active area of research requiring additional experimental data to benchmark and improve current predictive capabilities. In this study, we present the experimental results and analysis of K-shell x-ray absorption spectra to infer temperature and ionization state distribution of copper uniformly heated to temperatures 10–30 eV and compressed to densities of 9–30 g/cm^3. The experiments were conducted at the OMEGA laser facility using a buried layer of copper tamped by plastic on both sides. The two sides were then irradiated by a symmetric laser pulses and probed by a laser-generated x-ray source. Experimental results are compared to collisional-radiative models where we find large discrepancies in the predicted x-ray absorption spectra at these conditions. We also explore the role of including density effects in the underlying atomic data used in the collisional-radiative models and compare the results to our experimental data.

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†Corresponding Author Email: tcordova@ucsd.edu

Laboratory Measurement of L-Shell Opacity at GEKKO XII/LFEX High Power Laser Facility

J. Dun[1,2]*, F. Delahaye[3], H. Matsubara[1,2], Y. Karaki[1,2], T. Pikuz[1], A. Ciardi[3,4], R. Takizawa[1], K. F. F. Law[1], Y. Gong[1], M. Koenig[5], and S. Fujioka[1,6]

[1]Institute of Laser Engineering, Osaka University, Osaka, Japan
[2]Graduate School of Science, Osaka University, Osaka, Japan
[3]LERMA, Observatoire de Paris, Paris, France
[4]Laboratoire LULI, Ecole Polytechnique, CNRS, Paris, France
[5]LULI-CNRS, CEA, Paris, France
[6]National Institute for Fusion Science, Gifu, Japan

Opacity represents a fundamental parameter in high-energy-density (HED) physics, which controls the process of radiation energy transfer in a HED plasma. Understanding the atomic process in stellar interior conditions depends on the opacities of mid-atomic-number elements over a wide range of temperatures, which can also help us to understand the efficiency of inertial confinement fusion. However, some of the details of the radiative transfer process are neglected due to the complexity of the atomic process calculation, which leads to inaccurate predictions. For example, one possible explanation of the disagreement between solar models and helioseismology observation is insufficient theoretical opacities. [1] Experimental validation of the opacity models is crucial for astrophysics and the HED science.

Approximately ten years ago, the first measurement of plasma opacity at temperatures above 150 eV and electron densities above $10^{22}/\mathrm{cm}^3$, was achieved by the Z facility at Sandia National Laboratory (SNL). [2] The experiment revealed discrepancies between data and predictions of iron plasmas from different opacity modeling codes in the temperature-density region equivalent to solar convection-radiative boundary condition. The study proposes a hypothesis that the existing opacity models are missing some important physics processes that become significant at stellar interior conditions. [3]

In this paper, we present the work done toward verifying the hypothesis mentioned above and discuss the prospects for future research. A platform for measuring opacity has been developed with the GEKKO XII high-intensity laser facility. The bespoke laser-driven hohlraum can heat the calcium and titanium sample to a HED state while avoiding direct laser heating. The enhanced platform is equipped with the capacity for high-temporal resolution measurement utilizing the LFEX picosecond laser system. The experimental campaign yielded confirmation that the radiation temperature achieved by the laser-driven hohlraums with disparate geometric designs and driven laser energy combinations could reach 100 to 120 eV radiation energy. For the first time, several sets of high-temporal resolution spectra of transmission, sample emission, and backlight emission have been measured, which could be used for opacity calculation.

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*E-mail: u725029c@ecs.osaka-u.ac.jp

Spectroscopic characterization of compressed core conditions in directly-driven magnetized cylindrical implosions

R. Florido[1 *], A. Bordón[1], M. A. Gigosos[2], G. Pérez-Callejo[2], M. Bailly-Grandvaux[3], C. A. Walsh[4], F. Beg[3], R. C. Mancini[5], C. McGuffey[6], J. Saret[3], F. Suzuki-Vidal[7], C. Vlachos[8], J. J. Santos[8]

[1]Departamento de Física, Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain
[2]Departamento de Física Teórica, Atómica y Óptica, Universidad de Valladolid, Valladolid, Spain
[3]Center for Energy Research, University of California San Diego, California, USA
[4]Lawrence Livermore National Laboratory, California, USA
[5]Department of Physics, University of Nevada, Reno, USA
[6]General Atomics, California, USA
[7]First Light Fusion, Oxfordshire, United Kingdom
[8]Centre Lasers Intense et Applications, Universitè de Bordeaux, CNRS, CEA, Bordeaux, France

The application of external magnetic fields in inertial confinement fusion (ICF) implosions has been identified as a method to enhance hot-spot performance, reducing thermal losses and enabling higher fusion yields. To facilitate the investigation of the magnetic-field compression mechanism, a cylindrical geometry is particularly appropriate. This works discusses the use of Ar K-shell spectroscopy to characterize the core conditions in magnetized cylindrical implosion experiments conducted at the OMEGA laser facility. The targets, filled with Ar-doped deuterium, were symmetrically imploded using a 40-beam, 14.5 kJ, 1.5 ns laser drive. Recorded space- and time-integrated Ar K-shell spectra exhibit highly reproducible, distinctive features both with and without an imposed magnetic field. A uniform spectroscopic model was insufficient to replicate the observations; however, a multizone spectroscopic model, combined with a random-search χ^2 minimization procedure, successfully fitted the experimental spectra. The analysis allows to extract intensity-weighted average conditions of the cylindrical imploded core, namely revealing a 50% core temperature rise at half mass density when a 30 T seed B-field was applied. Additionally, the methodology shows potential for deriving a coarse-grained radial profile of core conditions at stagnation, supporting the formation of a hotter central spot in the magnetized scenario. Concurrently, the experimental spectra align well with synthetic spectra obtained by post-processing extended-magnetohydrodynamics simulations, incorporating detailed atomic-kinetics and Stark-broadened line shapes. This provides strong evidence that the attained core conditions at peak compression are consistent with the impact of a 10-kT compressed field.

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[*] E-mail: ricardo.florido@ulpgc.es

Thoughts about the Iron Opacity Controversy

C.J. Fontes[1 *], C.P. Ballance[2], C.E. Starrett[1], J. Colgan[1], T. Nagayama[3], J.E. Bailey[3]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[2]Queen's University of Belfast, Belfast BT7 1NN, Northern Ireland, UK
[3]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

The controversy concerning the opacity of iron, arising from a discrepancy between helioseismology [1] and revised solar elemental abundances [2], continues to defy explanation. Experiments at the Sandia Z-facility have produced iron, nickel and chromium spectra [3, 4, 5] that have yielded both good and poor agreement with theoretical calculations, adding to the mystery. For example, the bound-free contribution to the opacity agrees well between theory and experiment for nickel and chromium at all measured conditions, while the iron comparisons display good agreement at lower temperatures/densities, but not at higher temperatures/densities. Continuing with a previous study that was presented at the 2023 Atomic Processes in Plasma (APiP) Conference in Vienna, we compare photoionization cross sections generated with the distorted-wave (DW) and R-matrix (RM) methods. At the APiP Conference, good agreement was demonstrated between the DW and RM methods for the case of He-like iron, Fe^{24+}. In this talk, we focus on the Ne-like ion stage, Fe^{16+}, which is predicted to dominate the charge state distribution for iron under the conditions that are present in the Sandia experiments. The DW results are calculated with the Los Alamos Suite of Atomic Physics Codes [6] and the RM results are calculated with the Dirac Atomic R-matrix Codes (DARC) [7]. We consider both the background and resonance contributions to various photoionization cross sections produced with each method, highlighting similarities, differences, and consequences for the corresponding opacities.

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*E-mail: cjf@lanl.gov

Interogating the population kinetics in dense plasmas using X-ray Free Electron Laser resonant photopumping

E. Galtier[1 *], F. Condamine[2], E. Cunningham[1], G. Dyer[1], L. Gournay[3], M. Greenberg[1], P. Heimann[1], D. Khaghani[1], H. J. Lee[1], A. McKelvey[6], B. Nagler[1], Y. Ralchenko[7], O. Renner[2,8], F. B. Rosmej[3,4], J. Seely[9], R. Shepherd[6]

[1]SLAC National Accelerator Laboratory, Menlo Park, USA [2]The Extreme Light Infrastructure ERIC, ELI Beamlines Facility, Dolní Břežany, Czech Republic [3]Sorbonne University, Faculty of Science and Engineering, Paris, France [4]LULI, Ecole Polytechnique, CEA-CNRS-SU, Palaiseau, France [6]Lawrence Livermore National Laboratory, USA [7]National Institute of Standards and Technology, USA [8]Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czech Republic [9]Artep Inc., Maryland, USA

Atomic physics can provide unique information on the detailed processes at play during the evolution of a plasma [1]. However, it suffers critical issues when invetigated in dense plasma conditions, where reabsorption, opacities and/or broadening mechanisms prevent its precise investigation (e.g. [2]). Fifteen years ago, when X-ray Free Electrons Lasers (X-ray FELs) first emerged as user facilities, they allowed breakthrough studies of some key elements of dense plasmas (e.g. opacity [3, 4], continuum lowering [5], population kinetics [6]). Still, because the X-ray pump and the X-ray probe are coupled, the available plasma conditions to be reached are limited in temperature and density space (due to the limited peak intensity an X-ray FEL can reach) as well as time scales (due to the X-ray pulse duration). In this work, we have investigated the population kinetics of a laser-driven modestly-dense copper plasma via X-ray FEL resonant photo-pumping. While we start by presenting on known state-of-the-art full scale analysis of its kinetics, with 3D hydrodynamic simulations coupled to detailed collisional radiative modeling, the emission spectra obtained during this experiment are found to be remarquably similar to fundamental atomic physics spectra obtained from relatively simple atomic physics code only. This work sheds light on the ability to use X-ray FELs to interogate the detailed atomic physics even in the hot and dense plasmas found in fundamental laser/matter interaction or in plasmas relevant to inertial confinement fusion experiments.

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*E-mail: egaltier@slac.stanford.edu

Simulation of K-shell emission spectra of Mg in the interaction of XFEL

Cheng Gao[1] *, Yongqiang Li[1] and Jianmin Yuan[2]

[1]College of Science, National University of Defense Technology, Changsha, Hunan 410073, P.R. China
[2]Institue of Atomic and Molecular Physics, Jilin University, Changchun Jilin 130012, P.R. China

The investigation of x-ray–matter interaction with x-ray free electron laser (XFEL) has attracted considerable attention in the past decade [1], which produces ultrafast ultra-intense x-ray pulses. Research on XFEL-matter interaction is significant for fundamental investigations and applications. In this work, we simulated the emission spectra of Mg in the interaction of XFEL with the photon energy of 1540 eV, duration of 100 fs and peak intensity of ~10^{17} W/cm^2[2]. A time-dependent rate equation is utilized to calculate the temporal evolution of the fine-structure level populations[3-4]. The emission spectra are compared with the experiment and reasonable good agreement is found. The delocalization of high orbtials of highly charged Mg ions in hot dense plasma environment are investigated using an a.b. init. method, in which the plasma screening effects on atomic wavefunctions are considered by introducing an effective screening potential into Hamiltonian. Compared with the commonly used analytic models, better agreement in the K-shell emission spectra of Li-like and He-like Mg are obtained.

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* E-mail: gaocheng@nudt.edu.cn

Ionisation equilibrium in dense carbon and beryllium plasmas

Dirk O. Gericke*

Centre for Fusion, Space and Astrophysics, Department of Physics, University of Warwick,
Coventry CV4 7AL, United Kingdom

Ionisation is central in defining many radiative and transport quantities in dense plasmas. For plasmas with pressures in the Mega- and Gigabar range, models tend to deviate significantly even for light elements which puts large uncertainties on any calculation relying on inputs for the ion charge state. Moreover, the few experimental results available deviate also significantly from often-used models for the ionisation degree. This situation gets even more complicated as the charge state is not well a defined quantity in dense media and one has to be careful when comparing models and experimental results.

This contribution will review the recent experimental results and compare them with predictions from a variety of theoretical approaches. The focus will be on light elements, that is carbon and beryllium, where the degree of K-shell ionisation is the most relevant question. These elements have been probed at the extreme pressures using the National Ignition Facility [1, 2] and large deviations from standard descriptions [3] have been found while the data agree with results from DFT-MD simulations [4]. Both experiments and *ab initio* simulations show also a different trend with increasing density and pressure than the standard models. This deviation can't be explained by a different model for the ionisation potential depression. Details of this comparison as well as details of the extraction of the mean ion charge states from the X-ray scattering data and possible sources of uncertainties will be discussed. One possible source for the different trends in charge state distributions at high pressures can be the distribution of local environments for the ions with allows for an additional spread of the charge states of ions. The significance of these results for astrophysics and inertial confinement fusion will be briefly highlighted at the end.

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*D.Gericke@warwick.ac.uk

Tungsten VUV spectroscopy in WEST tokamak 1-4 keV plasmas

R. Guirlet[1*], C. Desgranges[1], O. Peyrusse[2], N. Saura[3], J. L Schwob[4], P. Mandelbaum[4,5]

[1]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[2]Aix-Marseille Université, CNRS, Laboratoire LP3, UMR7341, 13288 Marseille, France
[3]Aix-Marseille Université, CNRS, Laboratoire PIIM, UMR7345, 13288 Marseille, France
[4]Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem, Israel
[5]Jerusalem College of Engineering, Ramat Beth Hakerem, 91035 Jerusalem, Israel

Since Tungsten (W) was chosen as the plasma-facing material in the future tokamak ITER, several magnetic fusion devices have been equipped partly (JET) or entirely (ASDEX-Upgrade) with W components. Among them, the WEST tokamak has a prominent place because of its capability to sustain 2-5 keV plasma discharges for minutes in a complete W environment.

WEST is equipped with two extreme UV spectrometers, one of which provides a wide variety of measurements thanks to its versatility. It covers the range 5-340 Å with two mobile detectors, each viewing a narrow interval (~20 Å at 15 Å, 60 Å at 310 Å) and a spectral resolution of ~0.2 Å. Its single line of sight can scan the lower half of the plasma with a minimum period of 4 s.

Spectra measured with this spectrometer are very complex due to the large number of spectral structures emitted by W. We have undertaken an extensive work of spectral line assignment using the HULLAC code and the NIST atomic database [1]. W^{25+} to W^{45+} ionisation stages have been identified. From four spectral lines from the higher stages we estimate the W density profile in the core plasma provided the electron temperature is high enough [2].

The strong and broad quasicontinuum (QC) at 45-65 Å has been extensively observed in magnetic fusion devices [3]. It has been attributed to W^{28+}-W^{45+} with additional lines from various ionisation stages. Up to now collisional-radiative modelling has not allowed to reproduce it in a satisfactory way, which suggests that the atomic structure of W or the radiative transitions and their probabilities are not well understood. A semi-statistical approach used in dense plasmas [4] has been applied with encouraging results, concerning both the ionisation degree of W and the quasicontinuum itself.

Given the complexity of this spectral feature, in parallel we have recently started to use artificial intelligence (AI) tools to investigate the relation between the spectral shape of the QC and the thermodynamic profiles of the plasma, in particular the electron temperature. The first step is to establish a relation between the spectrum and the maximum temperature along the line of sight. We have found that the temperature can be predicted with a very satisfactory accuracy ($\pm$ 50 eV) in a boad range (300-3500 eV) if the AI algorithm is trained with plasma discharges performed on the same day. Plasma discharges performed several days from each other do not provide good results, possibly due to the changing vessel status. The next step is to investigate the possibility of extracting the whole temperature distribution from the QC analysis.

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*Email: remy.guirlet@cea.fr

Zeeman Stark line shapes affected by periodic electric fields

I. Hannachi[1,2*], **R. Stamm**[1], **J. Rosato**[1] **and Y. Marandet**[1]

[1]Aix-Marseille Univ. and CNRS, PIIM, 13397 Marseille, France
[2]University of Batna 1, PRIMALAB, Department of Physics, Batna, Algeria

Atoms and ions emitting in a plasma are often subjected to periodic electric fields which can affect the emitted line shapes. Such conditions are typical in non-equilibrium plasmas where ion sound and Langmuir waves are frequently observed. In laboratory settings and magnetic fusion devices, radio frequency waves (rf) are employed for heating and current drive. Spectroscopic measurements of regions heated by the rf field are crucial for enhancing our understanding of wave-plasma coupling [1]. Modeling the effect of periodic electric fields has a long history involving various line shape formalisms, and has often focused on a monochromatic and linearly polarized wave $\vec{E}_w \cos(\omega t + \varphi)$, where φ is a random phase. In this study, we explore the utility of computer simulations in understanding the impact of the particle microfield and a concurrent periodic electric field on line shapes. By solving numerically the Schrödinger equation for a hydrogen emitter, we accurately capture the complex dynamics of our physical system. Several groups employ such computer simulations today, and a recent comparison of the outcomes from their codes has been performed for hydrogen lines in a periodic electric field [2], which will be briefly reviewed and updated here. We will also examine the influence of the magnitude E_w and the frequency ω of the wave, and present the application of the simulation to cases where both the magnetic field and the different electric fields affect the line shape.

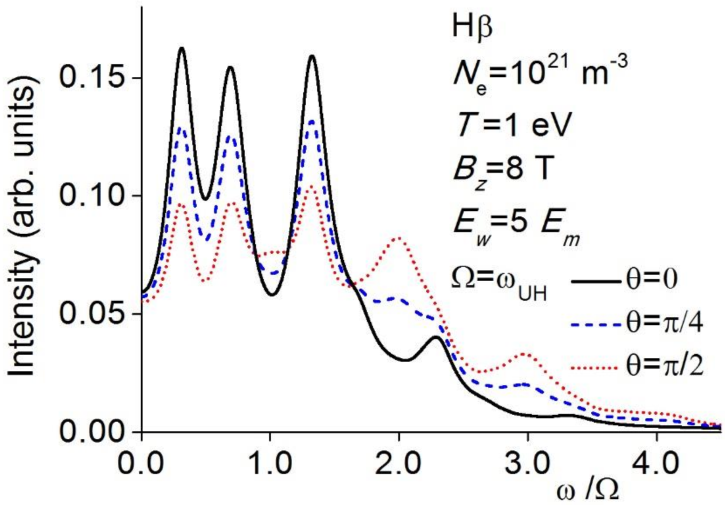

Figure 1. Hβ line observed at different angles with the magnetic field, for a wave magnitude equal to five time the average plasma microfield and an oscillation frequency equal to the upper hybrid frequency.

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* E-mail: ibtissam.hannachi@univ-batna.dz

SALSAA: Statistically Averaged Line Shapes from Average Atom

S. Hansen[1 *], K. Adler[1] and T. Gomez[2]

[1]Sandia National Laboratories, Albuquerque, NM, USA
[2]University of Colorado, CO, USA

We report on an approach to computing ion-Stark contributions to line shapes based on self-consistent data from an average-atom model. The average-atom model uses density functional theory (DFT) to generate Kohn-Sham orbitals for electrons in a self-consistent electron-ion potential within a neutral ion sphere. The free-electron part of the electron distribution is used along with a response function to produce an ion-ion potential that defines a self-consistent radial distribution function and nearest-neighbor distribution for the ions. In traditional approaches to line-broadening, the ion distribution would be used to generate an electric field distribution which, coupled with perturbation theory for the response of bound states to electric microfields, provides the ion-Stark contribution to emission and absorption line broadening. In SALSAA, perturbations in electron binding energies are computed due to changes in the nearest-neighber location and convolved with the self-consistent nearest-neighbor distribution function to generate the ion-Stark contribution to line broadening. This presentation will compare each part of the new method to traditional calculations, showing that the statistical approach can reproduce many of the features of traditional methods with high computational efficiency, enabling self-consistent estimates of ion-Stark line broadening in multi-electron ions.

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[*] E-mail: sbhanse@sandia.gov

Progress on Opacity Measurements at Stellar Interior Conditions Using the National Ignition Facility

R.F. Heeter[1 *], T.S. Perry[2], H.M. Johns[2], Y.P. Opachich[1], M.S. Hohenberger[1], D.P. Aberg[1], P.A. Bradley[2], P.B. Cho[1], J.P. Colgan[2], T.H. Day[2], E.C. Dutra[3], C.J. Fontes[2], E. Gallardo-Diaz[6], J.M. Heinmiller[3], B.A. Hobbs[4], R. Knight[3], D.C. Mayes[4], M.H. Montgomery[4], A.E. Peterson[3,6], R.S. Posadas[1], H.F. Robey[2], E. Smith[2], S. Stoupin[1], T.J. Urbatsch[2], M.S. Wallace[3], L.G. Webster[1], D.E. Winget[4], J.E. Bailey[5], S.B. Hansen[5], G.P. Loisel[5], and T. Nagayama[5]

[1]Lawrence Livermore National Laboratory, Livermore, CA, USA
[2]Los Alamos National Laboratory, Los Alamos, NM, USA
[3]Nevada National Security Sites, Livermore, CA, USA
[4]University of Texas at Austin, Austin, TX, USA
[5]Sandia National Laboratories, Albuquerque, NM, USA
[6]University of Nevada, Reno, NV, USA

There is little spectrally resolved experimental opacity data of plasma at temperatures and densities relevant to the physics of the sun, other stars, and laboratory high-energy-density experiments. Prior and ongoing opacity experiments on the Sandia National Laboratories Z machine have shown up to factor-of-2 discrepancies with theory - a challenging puzzle [1]. Since 2015, an additional set of experiments on the National Ignition Facility (NIF) have begun measuring opacities of iron and other materials at temperatures ~150 eV and density ~7x10^{21} electrons/cm^3 [2], and since 2021 those measurements have been extended to densities above 10^{22} electrons/cm^3. Figure 1 shows preliminary analysis of some NIF iron data, with the higher-density data showing higher opacity than expected theoretically [3]. This presentation summarizes the NIF experiments, efforts to constrain hypotheses for systematic errors, and new capabilities [4]. This data may have implications for modeling the structure of the sun and for determining the age of white dwarf stars.

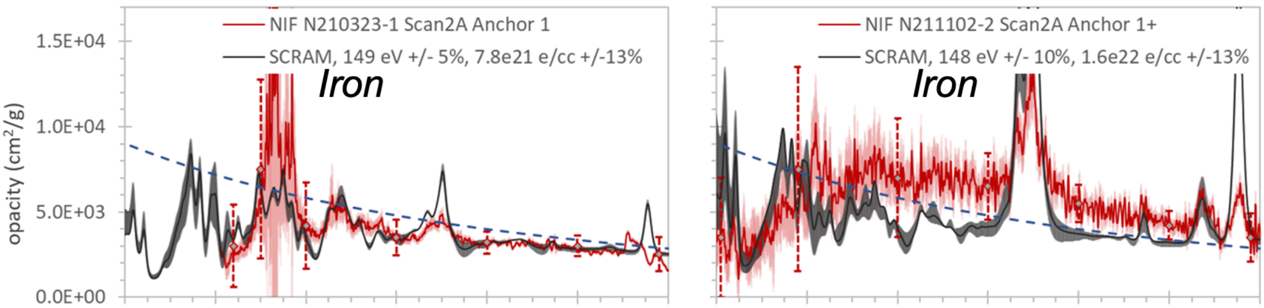

Figure 1. Samples of iron opacity measurements at two different densities, from NIF (Livermore, CA, USA).

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* E-mail: heeter1@llnl.gov

Influence of two-temperature effect on the ionization potential depression in hot dense plasma

Qingbo Luo[1], **Yong hou**[1 *], **Cheng Gao**[1], **and Jianmin Yuan**[1,2]

[1]College of Science, National University of Defense Technology, Changsha Hunan 410073, People's Republic of China;

[2]Institute of Atomic and Molecular Physics, Jilin University, Changchun Jilin 130012, People's Republic of China

The interaction between charged particles in hot dense plasma will cause ionic energy level shift and broadening, resulting in reduction of ionization potential, which alter the electronic structures and physical properties of hot dense plasma, such as opacity and equation of state. The experiment~(O. Ciricosta, et al. Nat. Commun. 7:11713)~on ionization potential depression (IPD) of solid-density Al plasma have indicated that present theoretical models cannot give reasonable desciption of the IPD in hot dense plasma, especially for highly charged ions where the discrepancy between experiment and theory is even greater. The reasonable theoretical methods are needed to describe the effects of dense environments on IPD, and the process of generating hot dense plasmas through the interaction between ultrashort laser pulse and solid-density matter also needs to be carefully considered. Here, the electronic structure is computed by the modified flexible atomic code~(FAC), which has included the correlations of free electrons and other ions by correlaiton functions from the hypernetted chain (HNC) approximation. A self-consistent-field method is used to calculate the electronic structures, and the temperatures for electron and ion in hot dense plasma are considered, seperately. Based on the calculations, the IPD is obtained through two-step model. Considering the interaction of the femeto-second laser on the solid-density Al plasma of Circosta's experiment, we use the two-temperature model to calculate the IPD with increasing the ionic temperature. The theoretical results are good agreement with the experimental results.

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* E-mail: yonghou@nudt.edu.cn

Unveiling preplasma dynamics via collisional processes with nanosecond and sub-picosecond laser pulses

D. Khaghani[1 *], P. Neumayer[2], E. Galtier[1], H. J. Lee[1], G. Dyer[1] and O. Rosmej[2]

[1]SLAC National Accelerator Laboratory, Menlo Park, United States
[2]GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany

We present experimental results from the PHELIX laser facility in Darmstadt, Germany, utilizing both components of the PHELIX laser system: a nanosecond (ns) laser pulse and a 500 fs laser pulse [1]. Our study aimed to understand the interaction dynamics of Cu targets by inducing intentional preplasma formation with the ns laser and heating electrons to a suprathermal distribution with the sub-ps laser.

The experimental method involved recording time-integrated x-ray line emission spectra of highly ionized Cu atoms, focusing on the He-like Rydberg series and Lyman-alpha lines. We explored the impact of different energies in the ns pulse on preplasma formation, the effects of delays between the laser pulses on preplasma expansion dynamics, and the influence of short-pulse laser contrast by varying conditions of the ultrafast optical parametric amplifier (uOPA).

Our results show distinct changes in the x-ray line emission spectrum under different preplasma conditions. The suprathermal electron population generated by the short-pulse interaction serves as a pumping mechanism via collisional ionization in the nanosecond intentional preplasma, revealing the charge state distribution. We interpret these spectral signatures in terms of the plasma dynamics and its transient conditions.

This study enhances our understanding of laser-plasma interactions and provides insights into optimizing experimental conditions for future high-energy density physics research with both optical lasers and XFELs.

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[*] E-mail: khaghani@slac.stanford.edu

Structure of High Velocity Radiative Shocks from optically Thin to Thick

M. Koenig[1], D. Oportus[1], Y. Benkadoum[1], N. Ozaki[2,3], Y. Sakawa[3], K. Maeda[3], Y. Suzuki[3], M. Hanano[3], S. Orlando[4], A. Dearling[5], S. Yakura[6], R. Yamazaki[6], G. Rigon[7], C. Li[7], B. Albertazzi[1]

[1] LULI - CNRS, CEA, Sorbonne Universités, Ecole Polytechnique, Institut Polytechnique de Paris
[2] Graduate School of Engineering, Osaka University
[3] Institute of Laser Engineering, Osaka University
[4] INAF — Osservatorio Astronomico di Palermo
[5] York Plasma Institute, University of York
[6] Department of Physical Sciences, Aoyama Gakuin University
[7] Massachusetts Institute of Technology, Plasma Science and Fusion Center

In astrophysics, many phenomena involving strong radiative shocks (RS) disturb and inject energy into the interstellar medium, affecting the rate of star formation in galaxies. For instance, the compression and disturbance of the interstellar gas caused by shocks from supernova explosions can trigger the collapse of nearby molecular clouds, initiating the formation of new stars. Therefore, the interaction of strong radiative shock waves with other structures is a central problem in astrophysics. Moreover, magnetic fields play an important role additionally to radiation for example in protogalaxies giving rise to globular clusters. It also can stabilize thermal instability with a transverse magnetic field. Recent results of radiative shock (and their interaction with an obstacle) experiments on laser facilities are shown where we have measured many of the variables involved such as shock velocity, radiative precursor length and temperature, ablation of an obstacle by the radiation, shock generated in the obstacle after shock impact. We studied the transition between an optically thin medium (low xenon gas pressure) to optically thick (high xenon gas pressure) and observed a huge difference in the shock and radiative precursor length. In the meanwhile, we performed 2d numerical investigations using FLASH code when an external B field is present as it intervenes in the astropohysical situation. In the case of radiative magnetised shock, we do observe the generation of a magnetosonic wave ahead of the RS for a B field perpendicular to the shock propagation. Discussion on the impact in astrophysics will be presented.

* E-mail: michel.koenig@polytechnique.edu

Review of the use of machine-learning methods with spectroscopy in fusion plasmas

M. Koubiti*, **N. Saura and S. Benkadda**

Aix-Marseille Université/CNRS, PIIM Lab., Av. Escadrille Normandie-Niemen, F-13397 Marseille Cedex 20, France

Artificial Intelligence (AI) tools are taking an important place in plasma science [1] and particularly in plasma physics [2-4]. In this context, there is an incrasing actitivity related to the use of Machine Learning in the field of plasma spectroscopy. Combining machine or deep learning methods with plasma spectroscopy have various purposes including real-time inference of plasma dynamics in magnetic fusion devices [5] or the prediction of the plasma parameters [6]. In this paper, we review the various applications of machine-learning and deep-learning algorithms to spectroscopic data in plasmas with a focus on magnetic fusion plasmas without excluding other types of plasmas. We also present our own work related to the use of neural networks such as Convolutional Neural Network (CNN) to theoretical Balmer-α line spectra emitted by hydrogen isotopes for the hydrogen isotopic ratio prediction for Tokamak plasmas [7-8]. The paper will also be an opportunity to discuss the advantages and the drawbacks of the introduction of AI in plasma physics.

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* E-mail: mohammed.koubiti@univ-amu.fr

Toward electron temperature profiles in hot-dense plasmas from x-ray spectral ensembles

B. F. Kraus[1 *], S. P. McPoyle[1], K. Atay[1], E. Kriz[2], R. C. Hollinger[3], S. N. Benjamin[4], S. Malko[1], Lan Gao[1], P. C. Efthimion[1], Shoujun Wang[3], J. King[3], S. Zahedpour Anaraki[3], V. N. Shlyaptsev[3], and J. J. Rocca[3]

[1]Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey, USA
[2]McGill University, Montreal, Quebec, Canada
[3]Colorado State University, Fort Collins, Colorado, USA
[4]Mercer County Community College, West Windsor, New Jersey, USA

High repetition rate laser systems enable new strategies for diagnosing plasma behavior with large datasets. We define an ensemble technique that relies on randomized targeting of x-ray tracer micro-stripes. On each shot, a high-intensity laser pulse is focused on a solid target with Ti tracer stripes embedded in an Al foil, randomly targeting a micro-stripe, a portion of a stripe, or a gap between stripes. High-resolution, time-integrated x-ray spectrometers capture line emission from the portion of the micro-stripe that is heated to sufficiently high electron temperatures. Accumulation of many such cases is used to construct ensemble distributions of x-ray line intensities that encompass all relative offsets of the laser focus to the micro-stripe centers. Synthetic intensity distributions are likewise generated using collisional-radiative modeling. Bayesian fitting of modeled to measured intensity distributions establishes the most likely radial temperature profiles, enabling comparison to hydrodynamic models and calling into question the cylindrical symmetry of these micro-stripe-embedded systems [1]. Ensemble techniques have significant potential for high-energy-density plasma diagnostics, especially with the advent of high repetition rate experiments.

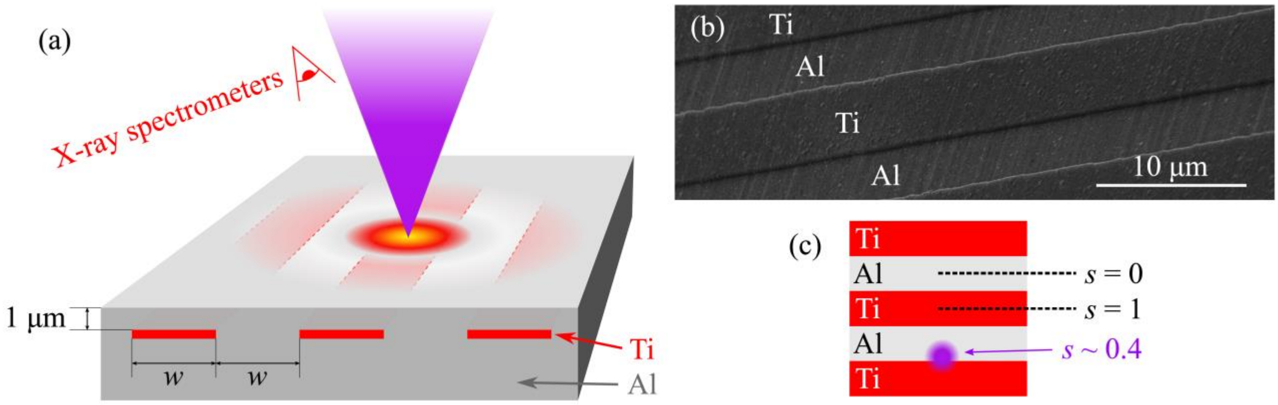

Figure 1. Schematic of micro-stripe layout. (a) A cartoon showing the laser focusing above embedded micro-stripes. (b) An electron microscope image of untamped Ti stripes deposited on Al. (c) An indication of *s*, the relative alignment of the laser focus with a stripe center, which randomly varies between 0 and 1.

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* E-mail: fkraus@pppl.gov

Photon scattering contribution in plasma transmission experiments

Veronika A. Kruse, D. Aberg, C. A. Iglesias

Abstract

The photon scattering contribution in recent transmission experiments at the Sandia Z-Facility [1] is examined using several approaches. First, spectral lines from single photon absorption are compared to resonant scattering estimates at line centers where photon scattering makes the largest contribution. Second, the full Waller-Kramers-Heisenberg expression [2] is applied to a few initial levels producing spectral lines prominent in the experimental spectrum. Finally, a dispersion-type relation [3] is used to compute the total plasma photon scattering cross-section. This last method accounts for all initial levels included in the photon absorption calculation. The numerical results show that photon scattering by bound electrons fails to resolve the extant discrepancies between transmission measurements of Fe and plasma radiation models.

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Radiative cooling of an Al plasma in an AlTi or AlAu mixtures heated by an ultraintense laser pulse

L. Lecherbourg[1,2 *], Ch. Blancard[1,2], S. Baton[3], A. Chaleil[1], P. Cossé[1,2], L. Duthoit[1,3], G. Faussurier[1,2], L. Gremillet[1,2], B. Loupias[1], F. Perez[3], J-.C. Pain[1,2], O. Poujade[1,2], and P. Renaudin[1]

[1]CEA, DAM, DIF, F-91297 Arpajon, France
[2]Univ. Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France
[3]LULI, CNRS, École Polytechnique, CEA, Sorbonne université, 91120 Palaiseau, France

The rapid heating and cooling dynamics of thin solid foils driven by an ultraintense ($\sim 10^{18}$ W/cm^2) picosecond laser pulse has been experimentally studied through time-integrated and time-resolved x-ray emission spectroscopy as well as 2D x-ray imaging. Targets consisted of plastic foils with buried Al, $Al_{42}Ti_{58}$, or $Al_{85}Au_{15}$ layers, with Al as a tracer to infer the plasma conditions. Our measurements indicate that the Al K-shell emission occurs over a shorter duration and from a narrower region in AlTi or AlAu mixtures compared to pure Al samples.

The experimental data are then compared with the 2D hydrodynamic-radiative code TROLL and the atomic physics code SAPHyR. Approximating the heating phase using a simple description of a collisional heating, the simulations reproduced the trends to a good approximation, and pinpoint the importance of radiative cooling in high-Z samples.

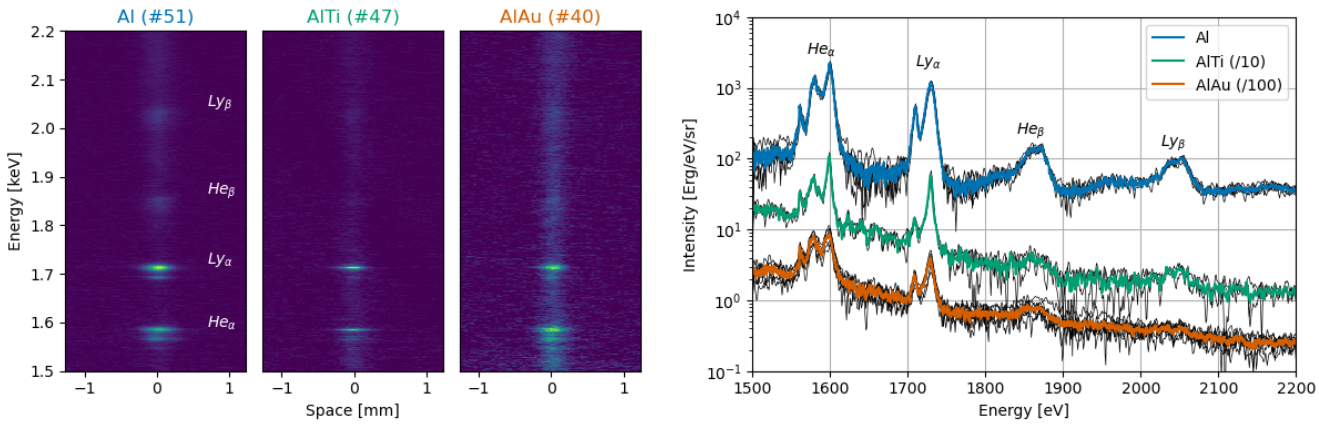

Figure 1. Example of time-integrated and space-integrated high resolution spectra of Al, AlTi and AlAu samples. (left) Raw data, (right) line profiles.

*E-mail: ludovic.lecherbourg@cea.fr

Time-resolved spectroscopy for Z stellar opacity research

G. P. Loisel[1], J. E. Bailey[1], T. Nagayama[1], S. B. Hansen[1], G. S. Dunham[1], P. D. Gard[1], A. P. Colombo[1], A. D. Edens[1], R. Speas[1], Q. Looker[1], M. Kimmel[1], J. Stahoviak[1], J. L. Porter[1], E. C. Harding[1], G. A. Rochau[1], C. J. Fontes[2], C. Blancard[3], Ph. Cossé[3], G. Faussurier[3], F. Gilleron[3], J.-C. Pain[3], D. Aberg[4]

[1]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[3]CEA, DAM-DIF, Arpajon, F-91297, France
[4]Lawrence Livermore National Laboratory, Livermore, California 94550, USA

Time-resolved spectroscopy using a novel hCMOS Ultra-fast X-ray Imager (UXI) is transforming stellar interior opacity measurements at the Sandia Z facility. Calculated opacities disagree with measured opacities [Bailey et al. Nature (2015), Nagayama et al. PRL (2019)], which questions the accuracy of calculated opacities used for the solar interior. The novel time-resolved data help to resolve this dilemma in three unprecedented ways. First, time-resolved measurements of the backlighter history, sample evolution, together with calculated opacities at each time step allows us to assess how temporal integration have affected the published, film-based results. These tests show that the temporal integration cannot explain the reported discrepancy. Second, measurements of the sample temperature and density evolution refine our understanding of the Z opacity platform and enable improved experimental design. Third, Sandia's UXI technology enables measurements of iron opacities at multiple conditions from a single experiment. This not only increases the number of opacity measurements per experiment but also allows to study how opacity changes with conditions from a single experiment. In this presentation, I will summarize the results on sample evolution in Fe experiments as well as progress towards the first extraction of absolute *time-resolved* opacity and remaining challenges to obtain that goal.

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* E-mail: gploise@sandia.gov

A Comparison of Plasma Conditions Inferred from Optical Thomson Scattering Measurements and X-ray Spectroscopy

E.V. Marley[1 *], G. Swadling[1], C.Bruulsema[1], E. R. Toro[2], J. Katz[3], E. Folsom[1]

[1]Lawrence Livermore National Laboratory
[2]Stanford University, Department of Mechanical Engineering
[3]Laboratory For Laser Energetics University of Rochester

The K-shell emission of low- and mid-Z elements are commonly used in HED plasma experiments to infer the plasma conditions. A study has been done utilizing simultaneous x-ray spectroscopy and Optical Thomson Scattering (OTS) measurements to compare the electron temperature inferred from the ion acoustic wave (IAW) feature and from fitting the measured x-ray spectra with atomic kinetics codes. A buried layer platform was used to create uniform non-local thermodynamic equilibrium plasmas (ne $\sim$ few $10^{21}/\mathrm{cm}^3$, Te $\sim$0.8 — 1.2 keV) for this study. The target was a 250 μm diameter, 200 nm thick dot buried between two 1000 μm diameter, 5 μm thick beryllium foils. Lasers heat the target from both sides for 3ns. The density was inferred using both the electron plasma wave EPW feature as well as the size of the emitting volume measured with time resolved x-ray imaging. Two different target materials were used for the study: titanium and copper. The K-shell emission of the titanium and the K- and L-shell emission of the copper were measured time resolved. The comparison of the plasma conditions inferred from fitting the x-ray spectra with different atomic kinetic codes and the OTS measurements will be discussed.

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*E-mail: marley2@llnl.gov

Population Kinetics for Laser Plasma Interactions

B.E. Marré [1*], A. Huebl [2], M. Bussman [1,3], U. Schramm [1], R. Widera [1], T. Cowan [1], T. Kluge [1]

[1]HZDR, Dresden, Germany [2]Berkley National Lab, Berkley, USA [3]CASUS, Görlitz, Germany

Standard atomic physics models in Particle-In-Cell(PIC) simulations either neglect excited states, predict atomic state populations in post processing only, or assume quasi-thermal plasma conditions.

This is no longer sufficient for high-intensity laser plasma interactions such as direct-drive ICF and laser plasma accelerators, due to their non-equilibrium, transient and non-thermal plasma conditions, which are now accessible in XFEL experiments at HIBEF (EuropeanXFEL), SACLA (Japan) or at MEC (LCLS/SLAC).

To remedy this, we have developed FLYonPIC, a extension of the PIC code PIConGPU, to self-consistently and time-dependent model atomic population kinetics inline in PIC-Simulations, in transient plasmas and without assuming equilibrium or steady state temperatures.

This new approach to atomic physics modeling will be useful in predicting plasma emission prediction, plasma condition probing with XFELs and better understanding of isochoric heating processes, all relying on an accurate prediction of atomic state populations inside transient plasmas.

I will show comparisons of FLYonPIC-PIConGPU, SCFLY, and ground state only PIC simulations for different plasma conditions relevant to ICF and laser plasma accelerators.

*E-mail: b.marre@hzdr.de

Oxygen opacity experiments for stellar interiors at Z and NIF

D.C. Mayes[1 *], J.E. Bailey[2], P.A. Bradley[3], G.S. Dunham[2], C.J. Fontes[3], T.A. Gomez[4], S.B. Hansen[2], R.F. Heeter[5], B.A. Hobbs[1], M. Hohenberger[5], H.M. Johns[3], G.P. Loisel[2], T. Nagayama[2], Y.P. Opachich[5], T.S. Perry[3]

[1] University of Texas at Austin, Austin, TX, USA
[2] Sandia National Laboratories, Albuquerque, NM, USA
[3] Los Alamos National Laboratory, Los Alamos, NM, USA
[4] University of Colorado Boulder, Boulder, CO, USA
[5] Lawrence Livermore National Laboratory, Livermore, CA, USA

Much of what we know about the universe is rooted in our understanding of the Sun. However, ongoing disagreement between solar models and helioseismic measurements of the interior structure of the Sun raises concerns about the accuracy of stellar models. One hypothesis that could help resolve this discrepancy is that the opacities of matter at solar interior conditions are higher than models predict. Experiments on the Z Machine and at NIF investigate this by measuring iron and oxygen opacities at conditions near the solar convection zone base (CZB). The published iron measurements [1] are higher than model predictions, supporting this hypothesis. This talk will focus on the progress of the oxygen opacity experiments at each facility. Oxygen is the largest contributor to the opacity at the solar CZB and no experimental benchmark in this regime exists to date. We will discuss our methods for characterizing the opacity and plasma conditions and show preliminary oxygen measurements from both Z and NIF.

This work was supported by the Wootton Center for Astrophysical Plasma Properties under NNSA Stewardship Science Academic Alliances award number DE-NA0004149. Experimental time was provided by the Z Fundamental Science Program of SNL and the NIF Discovery Science Program of LLNL. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525, and LLNL is operated under DOE NNSA contract DE-AC52-07NA27344.

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* E-mail: dmayes@utexas.edu

Understanding the effects of preheat from the Au M-band and L-band hohlraum radiation on EOS experiments

Joseph Nilsen*, Rich London, Damian Swift, and Amy Lazicki

Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

In this talk we look at the effect of the Au M-band and L-band hohlraum radiation on preheating the EOS sample in experiments done at the NIF laser facility. In particular we examine EOS experiments that were done using a Mach Stem shock wave created by putting a plastic CH cone inside the hohlraum with the EOS sample outside the hohlraum at the base of the cone, as shown in Fig. 1. The EOS sample consisted of Au and CH steps. The experiments measured the shock breakout times from the steps and used impedance matching of Au vs CH to determine a point on the Hugoniot for Au. The experiments were able to create planar shocks at pressures above 500 Mbar in the Au.

In this talk we show the importance of preheat effects from the Au M-band and L-band hohlraum radiation and how we were able to mitigate some of these effects by doping the plastic cone with Ge. The preheat causes the Au sample to heat and undergo hydrodynamic motion before the main Mach Stem shock arrives and it is important to minimize and understand the effect of the preheat on the interpretation of the experimental results. Unlike EOS experiments on lower-Z materials the effect of the L-band radiation is very important and more difficult to eliminate.

The preheat is a general issue for EOS experiments that needs to be understood and is not unique to the Mach Stem platform.

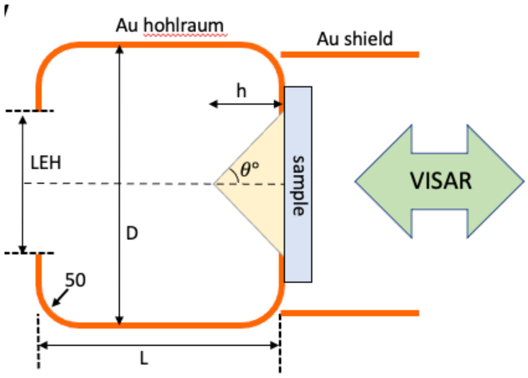

Figure 1. Mach Stem geometry for EOS experiments [1].

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* E-mail: nilsen1@llnl.gov

The Opacity Project: R-Matrix Opacities for Laboratory and Astrophysical Plasma Sources

Anil Pradhan[1] *

[1]The Ohio State University, Columbus, Ohio, USA 32210

The Opacity Project (OP) was initiated in 1983 and aimed to employ the state-of-the-art atomic physics based on the powerful R-matrix method to compute stellar opacities[1, 2]. However, hitherto computational and theoretical issues related to its implementation have proved to be intractable. Simpler approximations based on atomic structure and distorted wave methods were used in the OP work, akin to other existing opacity models. The primary difference is that the R-matrix method accounts more precisely for electron correlation, configuration interaction, and channel coupling effects. That, for example, gives rise to autoionization resonances in bound-free photoionization cross sections in an *ab initio* manner [2, 3]. This presentation describes recent developments reported in a series of papers on R-matrix calculations for opacities (RMOP I-IV: [4, 5, 6, 7]), including (i) large-scale atomic calculations for iron ions of heretofore unprecedented complexity, and (ii) a new treatment of plasma effects on resonances in photoionization cross sections with collisional electron impact, Stark ion microfield, and thermal Doppler broadening mechanisms. Generally, these physical effects are likely to manifest themselves for atomic processes in high-energy-density (HED) environments such as stellar interiors. In addition to atomic-plasma issues, the OP-RMOP works employ the Mihalas-Hummer-Däppen equation-of-state (EOS), and it is important to ascertain its precise behavior which may also affect opacities via atomic ionization states and level populations as function of temperature and density [8]. An exemplar of astrophysical applications is the "solar problem" which depends on an accurate determination of opacities. Similarly, laboratory measurements of opacities (viz. [9]) are also addressed. The interface of EOS, atomic data, and opacities is important for HED plasmas [8], and might constitute a topic of detailed discussion for the RPHDM workshop.

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*E-mail: pradhan.1@osu.edu

Ultrahigh Resolution X-ray Thomson Scattering Measurements at the European XFEL

T. Gawne[1,2], Z. A. Moldabekov[1,2], O. S. Humphries[3], K. Appel[3], C. Baehtz[2], V. Bouffetier[3], E. Brambrink[3], A. Cangi[1,2], S. Göde[3], Z. Konôpková[3], M. Makita[3], M. Mishchenko[3], M. Nakatsutsumi[3], K. Ramakrishna[1,2], L. Randolph[3], S. Schwalbe[1,2], J. Vorberger[2], L. Wollenweber[3], U. Zastrau[3], T. Dornheim[1,2], T. R. Preston[3*]

[1]Center for Advanced Systems Understanding (CASUS), D-02826 Goerlitz, Germany
[2]Helmholtz-Zentrum Dresden-Rossendorf (HZDR), D-01328 Dresden, Germany
[3]European XFEL, D-22869 Schenefeld, Germany

Using an ultrahigh resolution ($\Delta E \sim 0.1$ eV) setup to measure electronic features in x-ray Thomson scattering (XRTS) experiments at the European XFEL in Germany, we have studied the collective plasmon excitation in aluminum at ambient conditions, which we can measure very accurately even at low momentum transfers. As a result, we can resolve previously reported discrepancies between *ab initio* time-dependent density functional theory simulations and experimental observations. The demonstrated capability for high-resolution XRTS measurements will be a game changer for the diagnosis of experiments with matter under extreme densities, temperatures, and pressures, and unlock the full potential of state-of-the-art x-ray free electron laser (XFEL) facilities to study planetary interior conditions, to understand inertial confinement fusion applications, and for material science and discovery.

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doi.org/10.1103/PhysRevB.109.L241112

*E-mail: thomas.preston@xfel.eu

Diagnosing surface heating in relativistic laser plasma interactions using GISAXS

S.V.Rahul[1], M. Banjafar[1], L. Randolph[2], T.Preston[1], M.Makita[1], J.P. Schwinkendorf[1], O.Oezturk[3], T.Yabuuchi[5], K. Miyanishi[5], M. Nishiuchi[6], M. Ota[7], L.Huang[4], T.Kluge[4], C.Gutt[3], M.Nakatsutsumi[1]

[1] European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany
[2] Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Straße, 52428 Jülich, Germany
[3] Universität Siegen D-57068 Siegen, Germany
[4] HZDR, Bautzner Landstraße 400, 01328 Dresden, Germany
[5] SACLA, 1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan
[6] National Institutes for Quantum and Radiological Science and Technology, 4-9-1 Anagawa, Inage-ku, Chiba-shi 263-8555, Japan
[7] National Institute of Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5202, Japan

High field surface plasmons have recently attracted attention in producing the ultracompact sources electron accelerators and intense XUV sources via High order Harmonic Generation[1]. While these sources allow a diagnosis of the far field of the surface plasmons, an understanding of their transport and the consequent heating in the near field remains challenging. Propagating in a nm thin skin layer on the solid density plasma surface, these surface plasmons present the peculiar problem of requiring a probe with nm depth sensitivity in the solid density region - thus ruling out optical and proton imaging techniques.

Here, we present our results employing Hard X-ray Free Electron Lasers to probe sub-relativistic intensity laser driven solid density plasma surfaces. We irradiate Hard X-ray pulses at Grazing Incidence and monitor the Small Angle X-ray Scattering (GISAXS). This method, previously developed by us for laser ablation studies[2], allows us to obtain sensitivity to nm electron density fluctuations, with a picosecond resolution. We measure the dynamics of electron density correlations due to target neutralization inside a multilayered solid target, at several distances away from the laser irradiation spot. We infer the speed of the lateral heating front to be >0.77c. Finally, we present preliminary measurements of the surface heating due to resonantly generated surface plasmons.

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[*] E-mail: sripati.rahul@xfel.eu

NLTE-12, Benford's Law for Atomic Databases and All That

Yuri Ralchenko*

National Institute of Standards and Technology, Gaithersburg MD20899, USA

This talk will cover two topics. First, an overview of the 12th non-LTE Code Comparison Workshop that was held in Valladolid, Spain (Oct 2023) will be presented. This meeting was attended by more than 20 researchers who submitted case calculations with 14 different collisional-radiative (CR) codes. The proposed cases included (i) CR and photoionization kinetics and the L-shell emission of Fe for typical astrophysical conditions, (ii) CR kinetics and K-shell emission of Kr in dense plasmas of NIF imploded capsule experiments, and (iii) ionization balance and spectra of Au in hot laser-produced plasmas. We will present comparisons of the submitted data, main conclusions of the meeting, and future plans.

The second part of the talk (in collaboration with J.-C. Pain) will address applications of Benford's law to atomic spectra and opacity databases [1]. This intriguing, and yet not fully understood, law of anomalous numbers states that the significant digits of data follow a logarithmic distribution favoring the smallest values. We will discuss the compliance with this law of the atomic databases focusing on (i) line energies, oscillator strengths, and Einstein coefficients from the NIST Atomic Spectra Database [2] and (ii) radiative opacities from the NIST-LANL Lanthanide Actinide Opacity Database [3].

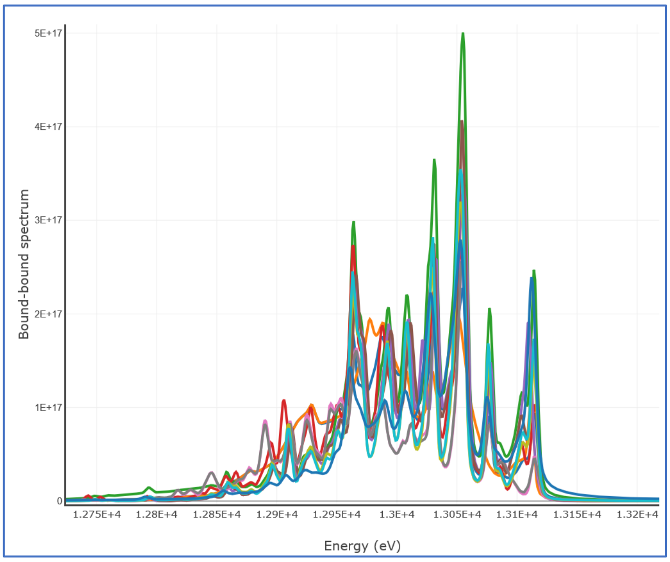

Figure 1. NLTE-12: Comparison of the bound-bound Kr spectra at 2000 eV and 3×10^{24} cm^{-3}.

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* E-mail: yuri.ralchenko@nist.gov

Scattering of ultrashort X-ray pulses in optically dense plasma: account for pulse duration and propagation effects

F.B. Rosmej[1,2*], V.A. Astapenko[3] and V.S. Lisitsa[3,4]

[1] Sorbonne University SU, Faculty of Science and Engineering, Paris, France
[2] Ecole Polytechnique, LULI, Palaiseau, France
[3]Moscow Institute of Physics and Technology MIPT, Dolgoprudnyi, Russia
[4]National Research Center "Kurchatov Institute", Moscow, Russia

Scattering of electromagnetic radiation in media is an important experimental tool to obtain information about the properties and state of matter. Recent advances in generating ultrashort laser pulses (USP) open perspectives of sub-femtosecond scattering processes. For ultra-short electromagnetic fields the scattering differs considerably from the standard long-pulse theory. One of the interesting properties is associated with the interaction of ultrashort pulses with dense matter: here, the short pulse propagation is characterized by possible resonance processes in the optically dense medium due to the large width of the frequency spectrum.

We consider a semi-analytical approach [1] that overcomes the failure of Fermi's Golden Rule in the description of the ultra-short photoprocess but maintains the possibility to employ cross sections (note, that the complex numerical solution of the time-dependent Schrodinger equation makes it difficult to employ measured cross sections). A central element of this approach is the probability induced by USP during all time of pulse action:

$$W(\tau) = \frac{c}{(2\pi)^2} \int_0^\infty \frac{\sigma(\omega)}{\hbar\omega} |E(\omega,\tau)|^2 \, d\omega \cdot \tag{1}$$

$\sigma(\omega)$ is the cross section of the photoprocess and $E(\omega,\tau)$ is the Fourier transform of electric field strength in the pulse, τ is the pulse duration. This approach has been used [2] for the study of femtosecond X-ray pulse driven resonance scattering on ions in plasmas. It was shown particularly that the dependence of the scattering probability on the pulse duration can be nonlinear for certain values of pulse parameters even if the radiation intensity is small (1^{st} order perturbation theory). The approach was generalized to account for the dependence on the pulse propagation length in optically dense hydrogen plasmas [3].

In the present work we account for the absorption of USP in optically dense hot plasmas employing the integral expression for the scattering probability:

$$W_{scat}(\tau, z) = \frac{c}{(2\pi)^2} \int_0^\infty \frac{\sigma_{scat}(\omega)}{\hbar\omega} |E(\omega,\tau)|^2 \exp[-N\sigma_{abs}(\omega) z] \, d\omega \cdot \tag{2}$$

$\sigma_{scat}(\omega)$ and $\sigma_{abs}(\omega)$ are the scattering and absorption cross sections, respectively, N is the density of the scattering ions, z is the propagation length of the USP in the plasma. This expression allows to consider two new fundamental parameters in dense plasmas: (i) the ratio of the spectral resonance line width and the width corresponding to the pulse duration, (ii) the optical thickness of the medium.

Numerical calculations of the scattering probability (2) have been carried out for femtosecond USP resonance scattering on highly charged ions in hot dense plasmas with account for the fine structure splitting of the ionic energy levels and the Doppler effect. The dependencies of the scattering probability on pulse duration and propagation length were analyzed for different ionic charges at temperatures of about 100 eV and densities 10^{21}-10^{23} cm^{-3}. We also examine the influence of the pulse duration τ and plasma length z on the spectrum of the USP scattering probability for various ions. The analysis allows to explore the main features of USP scattering in dense hot plasmas.

* E-mail corresponding author: frank.rosmej@sorbonne-universite.fr

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Recent advances on laser-plasma based soft x-ray lasers

Stephane Sebban[1], Adeline Kabacinski[1], Eduardo Oliva[2], Fabien Tissandier[1], Michaela Kozlova [3,4], Jean-Philippe Goddet[1], Igor Andriyash[1], Cédric Thaury[1], Philippe Zeitoun[1] and Julien Gautier[1]

[1]Laboratoire d'Optique Appliquée, ENSTA-Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

[2]Instituto de Fusion Nuclear "Guillermo Velarde" and Departamento de Ingenier ́ıa Energética, E.T.S.I. Industriales, Universidad Politécnica de Madrid, Spain

[3]ELI Beamlines Project, Institute of Physics CAS, Praha 8, Czech Republic

[4]Institute of Plasma Physics CAS, Praha 8, Czech Republic

Intense and short soft X-ray light pulses offer unprecedented possibilities for studying ultrafast phenomena in matter at the nanometer scale. Plasma-based soft X-ray lasers (SXRLs) have the avantage of being compact sources. We report recent achievement aiming to demonstrate the control and reduction of duration of a seeded collisional soft X- ray laser induced by the anticipated interruption of the gain lifetime at high densities [1]. By controlling the peak intensity velocity of an ultrashort beam by spatio-temporal couplings we improve the performances of a SXRL, which intrinsically suffers from the group velocity (v_g) mismatch between the infrared pump beam used to generate the plasma amplifier and the XUV seed. The energy extraction was measured to raise from 19 to 59% when the pump v_g ranges from 0.55c to 1.05c. We also demonstrate that the SXRL pulse duration is governed by the pump beam velocity and can be maintained constant along its propagation, resulting in energetic pulses as short as 350 fs [2]. The measurements, in good agreement with simulations from a 3D Maxwell-Bloch code, have been performed thanks to an original method allowing to recover the temporal profile of any kind of soft X-ray laser pulse in single-shot operation.

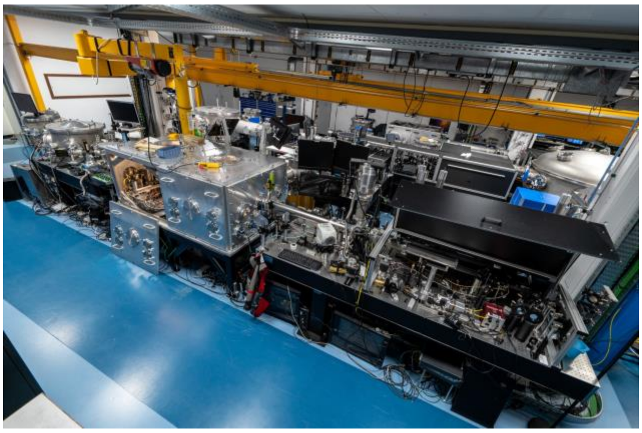

Figure 1. Soft X-ray laser beamline at LOA (Palaiseau, France)

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* E-mail: stephane.sebban@ensta.fr

High resolution, sub-picosecond x-ray spectroscopy of buried layers heated with high intensity, short pulse lasers*+

R. Shepherd[1], Hai Le[1], M. J. MacDonald[1], G. V. Brown[1], E. Magee[1], P. Beiersdorfer[1], H. Scott[1], L. Hobbs[2], C. R. D. Brown[2], M. Hill[2#], M. Martin[1], M. Foord[1], M. Patel[1], R. London[1], S. Pitt[2], D. Hoarty[2]

[1]Lawrence Livermore National Laboratory, Livermore, Ca., 94551, USA
[2]Atomic Weapons Establishment, Aldermaston, Reading, RG7 4PR,UK

Short pulse, laser (SPL) heated matter has opened an avenue to studying matter at conditions previously unobtainable. While SPLs can generate matter at extreme densities and temperatures, characterization of the heated matter can be extremely challenging. The conditions are extremely dynamic in nature, requirement a careful monitoring of the plasma evolution.

High temporal and spectral resolution spectroscopy can play an important role in understanding the heating dynamics of buried layers. At the onset of heating, the laser deposits energy into non-thermal electrons at the laser-target interaction plane. Some fraction of the non-thermals escapes the target, producing a charge imbalance and a return current. The spectral features during this heating phase result from thermal and non-thermal electron distributions. Temporally resolving the Li-like satellites along with the He_{α} complex provides an avenue for studying the plasma temperature as it transitions from a relatively low temperature to a high temperature. We look at the impact of the non-thermal electrons on the sulfur He_{α} and Li-like dielectronic complex using the LLNL sub-picosecond, high resolution-STreaked Orion High REsolution treX (STOHREX). The targets were 50 μm diameter "dots", made from 160nm of FeS and 60 nm KCl, tamped by 3 μm of parylene. The experiments were performed at the Orion laser facility using ~700 fs, 532 nm, 150 J focused to a 100 μm spot. The impact of non-thermal electrons on the inferred temperature rise is studied using recent adaptations to the Cretin code to account for non-Maxwellian electron distributions on spectral features. The preliminary results will be presented along with spectroscopic modeling.

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#Current address, Lawrence Livermore National Laboratory,
+ Email: shepherd1@llnl.gov

Line shifts induced by plasma screening in x-ray heated matter

M. Šmíd

[1] Helmholtz Zentrum Dresden Rossendorf, HZDR, Dresden, Germany

The electronic structure of ions in dense plasma is influenced by changes in the microscopic electric fields, a phenomenon referred to as plasma screening. In our study, we have experimentally measured plasma screening by observing energy shifts in bound-bound transitions induced by an x-ray free electron laser (XFEL). This was achieved by identifying the specific electronic configurations corresponding to the Kα, Kβ, and Kγ lines of copper heated to roughly 100 ev. Our findings provide a foundation for refining plasma screening models, incorporating related effects such as ionization potential depression and continuum lowering, thereby enhancing our understanding of atomic physics within the Warm Dense Matter regime.

* E-mail: m.smid@hzdr.de

Detailed line-shape modeling for diagnostics of high-energy-density plasmas

E. Stambulchik*

Weizmann Institute of Science, Rehovot 7610001, Israel

Radiation of mid-Z tracer species is widely used for diagnosing high-energy-density plasmas. In particular, the Stark broadening of K-shell transitions is a ubiquitous tool for inferring the electron density. Almost universally, it is a single quantity – the line width – that is used for the analysis. Here, however, we explore finer details of line profiles, including the shift, that may allow for determining the plasma density alternatively and for probing the atomic composition of the tracer ion environment. The calculations were carried out using computer simulations [1], recently extended [2] to treat the radiator–plasma interaction beyond the standard multipole approximation.

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*E-mail: evgeny.stambulchik@weizmann.ac.il

Opacity Model with Self-Consistent Plasma Effect

C. E. Starrett[1] and C. J. Fontes[1]

[1]Los Alamos National Laboratory, U.S.A

In warm and hot dense matter, the high density and elevated temperature introduce non-perturbative plasma effects into the electronic structure. These effects influence the measured opacity in complicated ways, and are hard to model. Techniques, like diagnosis of plasma conditions from line shapes, and the modeling of physical systems like stars, require an ability to accurately predict the opacity of these dense plasmas. We have developed a variational model that includes plasma effects in a self-consistent way. It does this in part by including all electrons, bound and free, and not making a hard distinction between them [1,2]. We present calculations of the opacity in dense conditions relevant to the solar interior. Comparisons with a state-of-the-art traditional approach reveal some important differences.

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* E-mail: starrett@lanl.gov

Full-potential treatment for multiple-scattering calculation of hot dense plasma opacity

H. B. Tran Tan[1] *, C. J. Fontes[1], and C. E. Starrett[1]

[1]Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA

The calculation of the optical properties of hot dense plasmas with a model that has self-consistent plasma physics is a grand challenge for high-energy density science. It is generally hoped that the development of such a model will reconcile discrepancies between theory and experiments such as the irons opacity problem [1, 2, 3]. Recently, an electronic structure model that uses multiple scattering to solve the Kohn-Sham density functional theory equations has been successfully applied to dense plasmas [4, 5]. A prominent advantage of this approach has over other state-of-the-art methods is that it does not use pseudopotentials; instead, the core electronic states are computed self-consistently. Results from this multiple scattering theory formalism are in good agreement with those obtained with other methods.

The existing implementation of the multiple scattering method is, however, not complete. For example, single-site scattering is treated by first averaging over the true three-dimensional potential then solving the scattering problem in this spherically symmetric average potential. It is expected that the asymmetry of the true potential, arising from the highly disordered nature of a plasma, will have appreciable effects on the plasma's properties such as its equation of state and opacity. Our work seeks to address this issue. We approach the full-potential scattering problem using the Siegert-states formalism [6, 7, 8], which accurately reproduces bound states, while yielding discrete complex-energy free states in contrast to the usual real-energy continuum. Siegert states are thus very convenient for the computation of physical quantities involving summations over complete sets of states. Indeed, the usefulness of Siegert states in the average-atom model has been recently demonstrated [9]. In this poster, we explain how Siegert states may be used for a full treatment of three-dimensional plasma potentials.

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*E-mail: bao@lanl.gov

Zeeman Splitting Observed and Simulated in Laser-Produced Magnetized Blast Waves

A. Triantafyllidis[1*], J. -R. Marquès[1], S. Ferri[2], A. Callisti[2], Y. Benkadoum[1], A. Ciardi[3], A. Dearling[4], N. Ozaki[5,6], Y. De León[1], J. Beard[7], P. Renaudin [8], M. Koenig[1], B. Albertazzi[1]

[1]LULI - CNRS, CEA, Sorbonne Universités, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
[2]Aix Marseille Université, CNRS, PIIM, F-13013 Marseille, France
[3]Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, LERMA, 75005 Paris, France
[4]York Plasma Institute, Department of Physics, University of York, YO10 5DD
[5]Institute of Laser Engineering, Osaka University, 2-6 Yamada-Oka, Suita, Osaka, 565-0871 Japan
[6]Graduate School of Engineering, Osaka University, Osaka, 565-0871, Japan
[7]Laboratoire National des Champs magnétiques Intenses (LNCMI), UPR 3228, CNRS-Université Joseph Fourier (UJF)-Université Paul Sabatier (UPS)-Institut National des Sciences Appliquées (INSA), F-31400 Toulouse, France
[8]CEA, DAM, DIF, Arpajon 91297, France

Magnetic fields are ubiquitous in the Universe and play a critical role in laboratory experiments, fundamentally influencing plasma behavior. For example, they can smooth out discontinuities in blast waves, alter the geometry of supernova remnants from spherical to barrel-shaped, and inhibit heat transport [1, 2]. Investigating these systems requires accurate determination of the plasma's parameters (density and temperature), the magnetic fields' strength and orientation, as well as whether it has been influenced by the plasma (compression or diffusion).

The recent advent of apparatuses capable of generating strong magnetic fields coupled with high-energy laser facilities [3] necessitates the development of advanced experimental platforms and numerical codes for magnetic field diagnostics. Even though multiple diagnostics already exist, all face significant limitations; B-dot probes disturb the plasma, proton deflectometry requires an extra, high-intensity laser beam, and polarimetry is not sensitive enough for certain systems.

To address this need, we developed an optical, time-resolved, high-dispersion spectrometer (resolution of ~0.1 nm) and performed measurements on laser-produced blast waves at the LULI2000 facility. Utilizing a pulsed-power system, we generated well-characterized magnetic fields of up to 20 T, both perpendicular and parallel to the blast waves' propagation. We collected the emitted spectra of multiple intense radiative transitions of nitrogen (2s22p(2P0)3l - 2s22p(2P0)3l') and used line-shape modeling to extract the parameters of the plasma; from the distinct signatures of the Zeeman and Stark effects on spectral lines, we inferred the average magnitude of the magnetic field inside the plasma and its density while its temperature was calculated from line intensity ratios and Doppler broadening. Our experimental results were extensively compared with spectra simulated using the Stark-Zeeman line-shape code PPPB, developed at PIIM [4], to examine if the magnetic field was compressed by the plasma.

Here, we present the first clear observation of Zeeman splitting in a homogenous, low-temperature, diffuse plasma (5-20 eV, ~10^{18} cm^{-3}) and show an excellent agreement between the experiment and the PPPB simulations for all magnetic field strengths and orientations. These results reveal that the external magnetic field diffuses into the post-shock region and demonstrate the capabilities of PPPB to accurately interpret our data, allowing for the establishment of a novel experimental platform for benchmarking atomic physics codes.

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* E-mail: angelos.triantafyllidis@polytechnique.edu

Probing dense plasmas with high harmonics

P. Velarde[1 *], L. Ansia[1,2], and A.G de la Varga[1]

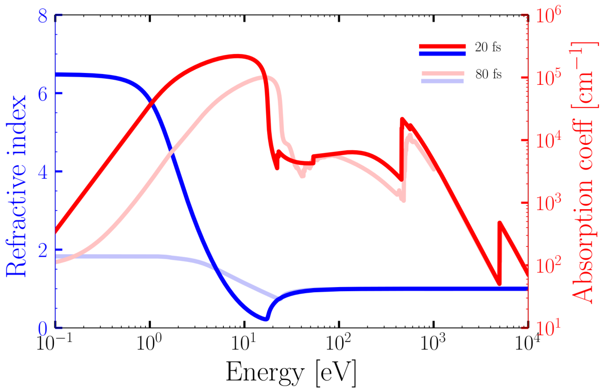
[1]Instituto de Fusión Nuclear, Universidad Politécnica de Madrid, José Gutiérrez Abascal 2, 28006 Madrid, Spain.

[2] GoLP/Instituto de Plasmas e Fusão Nuclear, Universidade de Lisboa, 1049-001 Lisboa, Portugal.

The advent of X-ray free electrons laser opened up new opportunities in the study of warm dense matter. With intensities previously achievable only by infrared and visible lasers, XFELs facilitate the creation of matter with precisely better defined properties, such as temperature and density. Recently, there has been a particular focus on the generation of dense plasmas from mid-Z materials, especially transition metals.

These experiments are typically complemented by collisional radiative models (CRMs), which have proven to be useful tools for understanding the temporal evolution of the sample. Recently, the non-thermal CRM BigBarT [1, 2, 3, 4] code has been extended to simulate arbitrary materials while maintaining a self-consistent approach for evolving non-thermal electron distributions and incorporating degeneracy effects. Additionally, time-dependent indexes of refraction have been derived using the Kronig-Kramers relations, allowing for the investigation of electromagnetic wave propagation in the plasmas.

The dielectric function is used to calculate the polarisation using the Havriliak–Negami method. This polarisation is used to calculate the propagation of a harmonic HHG beam in a target which has been isochorically heated by the XFEL. For this calculation, Maxwell's equations are solved numerically with a Godunov method with adaptive mesh, which allows to simulate the complete physical system during the whole HHG pulse. The phase differences of the outgoing HHG beam can be measured on a wavefront detector and the spatial variation of the sheet electron density can be derived. We present the results of simulations of this approach to measure density profiles in dense plasmas with HHG beams.



Refractive index and absorption coefficient for Ti illuminated by a XFEL pulse of I=1.6x10^{16} W/cm^2, FWHM=25 fs and hν=5.2 keV.

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*E-mail: pedro.velarde@upm.es

XFEL induced k-shell fluorescence in the solid to plasma regime

G .O. Williams[1 *], L. Ansia[1], M. Makita[2], P. Estrela[1], M. Hussain[1], T. Preston[2], J. Chalupsky[3], V. Hajkova[3] , T. Burian[3], M. Nakatsutsumi[2] J. Kaa[2], Z. Konopkova[2], J. C. P. Koliyadu[2], N. Kujala[2], K. Appel[2], V. Vozda[3], L. Juha[3], H.-K. Chung[4], P. Vagovic[5], H. Scott[6], P. Velarde[7], U. Zastrau[2], M. Fajardo[1].

[1] GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal

[2] European XFEL, Holzkoppel 4, 22869 Schenefeld, Germany

[3] Department of Radiation and Chemical Physics, Institute of Physics, Czech Academy of Sciences, Na Slovance 1999/2, 182 21 Prague, Czech Republic

[4] National Fusion Research Institute, Daejeon 34133, Republic of Korea

[5] Center for Free-Electron Laser Science CFEL, Deutsches ElektronenSynchrotron DESY, 22607 Hamburg, Germany

[6] Lawrence Livermore National Laboratory, Livermore, California 94550, USA

[7] Instituto de Fusión Nuclear, Universidad Politécnica de Madrid, José Gutiérrez Abascal 2, 28006 Madrid, Spain

High intensity XFELs have allowed uniform heating of solids on the micron scale and unique plasma diagnosis through x-ray spectroscopy and scattering. Here, we present results of XFEL heating and simultaneous fluorescence spectroscopy on mid-Z elements. The k-alpha and k-beta emission spectra are measured at several intensities and photon energies. The main features of the spectra are discussed and compared with models. We highlight the importance of features that persist from the solid-state to the plasma regime, that are important in the analysis of spectra in the warm dense regime, with temperatures near and below the Fermi temperature.

*E-mail: gareth.williams@tecnico.ulisboa.pt

Quantum coherence and inner-shell x-ray lasing in XFEL generated NLTE hot and dense plasmas

J. Yuan[1] *, J. Zeng[2] , Y. J. Li[3] , J. Liu[4] , C. Gao[4] , and Y. Q. Li[4]

[1]Institue of atomic and molecular physics, Jilin University, Changchun 130012, China
[2] College of Science, Zhejiang University of Technology, Hangzhou 310023, China
[3] Gradaute School of China Academy of Engineering Physics, Beijing 100193, China
[4] College of Science, National University of Defense Technology, Changsha 410073, China

High bright x-ray free electron laser (XFEL) with photon energy of hundreds to thousands eV can directly ionize the inner shell electrons of atoms, inducing sequential ionization processes such as Auger decay, electron impact excitation, ionization, and electron attachment. Dozens of electrons can be ionized from complex atoms within a few femtoseconds to tens of femtoseconds, resulting in a non-equilibrium plasma containing dozens of ionization stage of ions with exotic electronic configurations and hundreds of eV temperature free electrons [1]. Based on the classical rate equation and the quantum density matrix evolution equation, we have studied the ionization kinetics process and dynamics of gas/solid target [2] and possible atomic x-ray lasing [3,4] on the basis of detailed level accounting model. Based on finite difference and Monte Carlo numerical methods, the numerical calculation program can simulate the evolution process of rate equation containing tens of millions of atomic energy levels, as well as the time-dependent evolution process of density matrix containing thousands of quantum states. The results will demonstrate the precise atomic kinetics and the impact of quantum effects on ionic stage and energy level population evolutions.

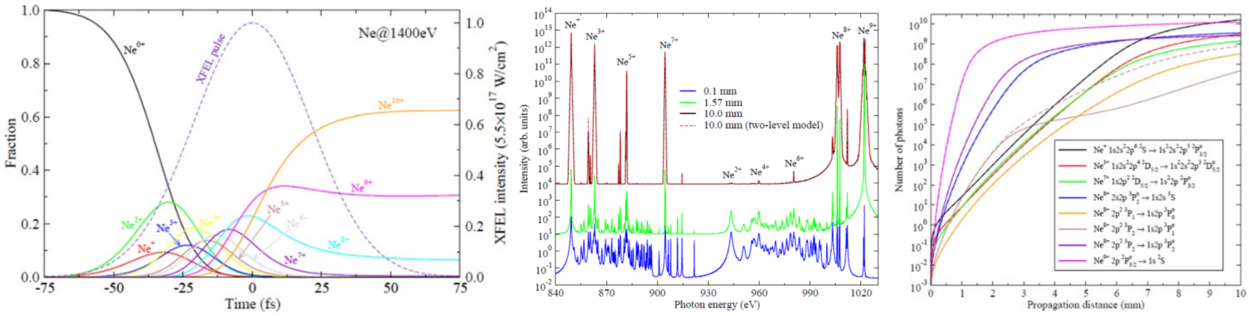

Figure 1. XFEL photoionization pumped Ne atom inner shell lasing amplification. (left) Evolution of different charged Ne ions populations with time, (middle) spectral distribution of emitted x-rays propagating at different distances in a medium, and (right) gain curves of some selected transitions.

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* E-mail: yuanjianmin@jlu.edu.cn

X-ray Imaging and Ionization dynamics in ultra-relativistic laser plasmas revelaled with an X-ray Free Electron Laser

Mikhail Mishchenko[1], Motoaki Nakatsutsumi[1], Erik Brambrink[1], Toma Toncian[2], Dominik Kraus[2], Irene Prencipe[2], Thomas Kluge[2], Thomas Cowan[2], Lingen Huang[2], Michal Smid[2], Alejandro Garcia[2], Hauke Höppner[2], Oliver Humphries[1,2], Eyal Kroupp[3], Evgeny Stambulchik[3], Ingo Uschmann[4], Robert Lötzsch[4], Paul B Neumayer[5], Byoung-ick Cho[6] and Ulf Zastrau[1] *

[1] *European XFEL GmbH, Germany*
[2] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Germany*
[3] *Weizmann Institute of Science, Israel*
[4] *Friedrich-Schiller-Universität Jena, Germany*
[5] *GSI Helmholtzzentrum für Schwerionenforschung, Germany*
[6] *Gwangju Institute of Science and Technology, South Korea*

We present time-resolved resonant X-ray measurements of the micron-spatially resolved opacity, together with emission spectroscopy from laser-irradiated Cu foils. This study overcomes the limitations of earlier time-integrated observations of the characteristic K-lines and bremsstrahlung. The abundance of highly charged Cu ions is used as a marker for electron temperatures in the few 100 eV range during the first picoseconds after interaction.

We observe electron cooling inside the bulk within the first picosecond. The ionized region is limited spatially to a spot corresponding to the laser focal size and localized to the laser-irradiated side of the Cu foil. Despite the consistency of our experimental X-ray emission and opacity data in indicating a rapid plasma cooling and recombination, two-dimensional PIC simulations on the other hand predict a quasi-static temperature on this timescale. We find that the PIC simulations can only reproduce our experimental observations for a very narrow intensity and preplasma parameter space.

Moreover, the experimental data enables the assessment of enhancements to PIC codes with respect to the treatment of energy dissipation in three dimensions, atomic physics, and radiation transport.

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* E-mail: ulf.zastrau@xfel.eu

Distinct transient structural rearrangement of ionized water revealed by XFEL X-ray pump X-ray probe experiment.

B. Ziaja[1,2*]

in collaboration with: M. Stransky, T.J. Lane, A. Gorel, S. Boutet, I. Schlichting, A.P. Mancuso, Z. Jurek.

[1] Center for Free-Electron Laser Science CFEL, DESY, Hamburg, Germany
[2] Institute of Nuclear Physics, PAN, Kraków, Poland

Using X-ray free electron laser (XFEL) radiation to conduct an X-ray pump X-ray probe experiment, we studied strongly ionized water as part of our ongoing work on radiation damage [1]. After irradiance with a pump pulse with a nominal fluence of ~5×10^5 J/cm2 , we observed for pump-probe delays of 75 fs and longer an unexpected structural rearrangement, exhibiting a characteristic length scale of ~9 Å. Simulations suggest that the experiment probes a superposition of ionized water in two distinct regimes. In the first, fluences expected at the X-ray focus create nearly completely ionized water, which as a result becomes effectively transparent to the probe [2]. In the second regime, out of focus pump radiation produces O^{1+} and O^{2+} ions, which rearrange due to Coulombic repulsion over 10s of fs. Importantly, structural changes in the low fluence regime have implications for the design of two-pulse X-ray experiments that aim to study unperturbed liquid samples. Our simulations account for two key observations in the experimental data: the decrease in ambient water signal and an increase in low-angle X-ray scattering. They cannot, however, account for the experimentally observed 9 Å feature. A satisfactory account of this feature presents a new challenge for theory.

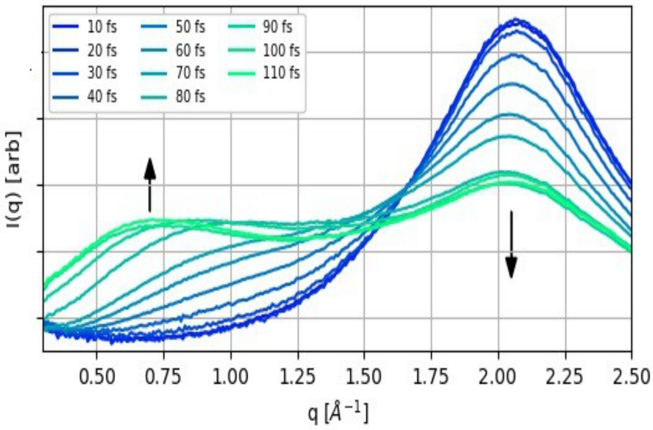

Figure 1. X-ray pump X-ray probe experiment reveals a new structural change in ionized water.

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* E-mail: ziaja@mail.desy.de