Study of Non-LTE Spectra Dependence On Target Mass In Short Pulse Laser Experiments

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Abstract. Backlight sources created from short pulse lasers are useful probes of high energy density plasmas because of their short duration and brightness. Recent work has shown that the production of Kα radiation can be manipulated by the size and geometry of the targets. Empirical relationships suggest that the electron reflux in the target plays an important role in the heating of these targets to create x-ray backlight sources.

Experiments to investigate fast electron transport in thin multilayer targets were performed at the LULI 100 TW laser facility. The targets were composed of V/Cu/Al and varied from 300 to 50 μm in diameter. They were isochorically heated by a 20 J, 300 ps laser pulse that delivered I~2×10^{19} W/cm^2 to form a warm dense plasma. Emission from the rear, unilluminated Al side was observed using both time-resolved and imaging diagnostics. Spectra including the Al-Kα, Al He-like, and Cu-Kα emission from the unirradiated Al side of the target show changes as a function of total mass. The data from targets of different sizes and/or Cu layer thickness are compared and analyzed to better understand the heating of the target and temperature of the plasma

Keywords: non-LTE, x-ray backlight, fast electron transport

Experiments on Interactions of Electrons with Molecular Ions in Fusion and Astrophysical Plasmas

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Abstract. Through beam-beam experiments at the Multicharged Ion Research Facility (MIRF) at Oak Ridge National Laboratory (ORNL) and at the CRYRING heavy ion storage ring at Stockholm University, we are seeking to formulate a more complete picture of electron-impact dissociation of molecular ions. These inelastic collisions play important roles in many low-temperature plasmas. For example, in fusion devices they are important because molecules, molecular ions, and electrons are abundant in the edge and divertor regions and are intrinsically involved in plasma-wall interactions and edge plasma charge, momentum, and energy balance. In astrophysics, the primary gas phase reactions that occur in interstellar clouds are electron-molecular ion and ion-molecule reactions. Electron-impact dissociation of molecular ions is crucial in the chemical dynamics of these cosmic environments and is often the final step in the synthesis of neutral molecules. An electron-ion crossed beams experiment at ORNL investigates the dissociative excitation and dissociative ionization of molecular ions from a few eV up to 100 eV. Taking advantage of a 250-kV acceleration platform at the MIRF, a merged electron-ion beams energy loss apparatus is employed to measure dissociative recombination (DR) down to zero energy. Complementary DR experiments are also performed at CRYRING where chemical branching fractions and fragmentation dynamics are studied. Recent results on the dissociation of molecular ions of importance in fusion and astrophysics will be presented.

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X-ray And EUV Spectroscopy Of Highly Charged Tungsten Ions

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Abstract. The Berlin EBIT has been established by the Max-Planck-Institut für Plasmaphysik to generate atomic physics data in support of research in the field of controlled nuclear fusion, by measuring the radiation from highly charged ions in the x-ray, extreme ultraviolet and visible spectral ranges and providing valuable diagnostics for high temperature plasmas. In future fusion devices, for example ITER, currently being constructed at Cadarache, France, the plasma facing components will be armored with high-Z materials, most likely tungsten, due to the favorable properties of this element. At the same time the tremendous radiation cooling of these high-Z materials impose a thread to fusion and oblique to carefully monitor the radiation. With EBIT a selected ensemble of ions in specific charge states can be produced, stored and excited for spectroscopic investigations. Employing this technique, we have for example resolved the wide structure observed around 5 nm at the ASDEX Upgrade tokamak as originating from E1-transitions into the open 4d shell of tungsten ions in charge states 25+ to 37+ producing a band-like emission pattern. Further these ions emit well separated M1 lines in the EUV range around 65nm suitable for plasma diagnostics. Kr-like to Cr-like tungsten ions (38+ to 50+) show strong soft-x-ray lines in the range 0.5 to 2 and 5 to 15 nm. Lines of even higher charged tungsten ions, up to Ne-like W^{64+}, abundant in the core plasma of present and future fusion test devices, have been investigated with high resolution Bragg-crystal spectroscopy at 0.13 nm.

The Role of Atomic Physics in Understanding Physical Processes in High Energy Astrophysics

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Abstract.
X-ray grating spectra from *Chandra* and *XMM-Newton* have provided new insights into many of the physical processes present in astrophysical sources. For example, (i) many active galactic nuclei (AGN) produce winds or outflows, detectable through X-ray absorption; (ii) active cool stars have coronal pressures several orders of magnitude larger than found on the Sun; (iii) shocks produced by magnetic accretion onto stellar surfaces cool as the material flows down, with density and temperature diagnostics providing tests of the accretion models.

The diagnostics used to determine temperatures, densities, elemental abundances, ionization states, and opacities require extremely accurate atomic data. At the same time, we must have a fairly complete database in order to ensure that the diagnostics are not blended or otherwise compromised. The best spectra are from bright objects with long exposures (days), but the information contained allows us to infer the location(s) of the emitting and absorbing plasmas and understand the physical properties. We will give examples to illustrate the role of atomic physics in our analyses of such spectra and the quality of data required.

Ultrafast X-ray Science at SLAC: Preparing for LCLS

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Abstract. Ultrafast lasers (*t* less than 1 *ps*) can capture the quantum dynamics of single vibration in a crystal lattice or in a molecule, and they have also been used to view the transient molecular-scale transformations of chemical reactions. Hard x-rays (*E* greater than 1 *keV*) can probe the structure of matter on the length scale of a chemical bond. Until recently, only relatively weak sources based on laser-induced plasma radiation were capable of capturing these ultrafast dynamics and also viewing them on the scale of a single chemical bond. The recent Sub-Picosecond Pulse Source experiment at SLAC was the first instrument based on synchrotron radiation from an undulator that could do both. During its two-year run, its 8 *keV*, 80 *fs* x-ray pulses were the brightest ultrafast x-rays ever produced. The planned X-ray free electron laser at SLAC (LCLS) will be far brighter, generating focused x-ray fields as strong as atomic binding fields, comparable to today's highest intensity lasers. These new tools are creating some special opportunities for new science, and also some challenges. I will discuss these, and present recent progress in ultrafast x-ray sources and science.

Using Laser-driven Shocks to Study the Phase Diagrams Of Low-Z Materials at Mbar Pressures and eV Temperatures*

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Abstract. Accurate phase diagrams for simple molecular fluids and solids (H_2, He, H_2O, SiO_2, and C) and their constituent elements at eV temperatures and pressures up to tens of Mbar are integral to planetary models of the gas giant planets (Jupiter, Saturn, Uranus and Neptune), and the rocky planets. Laboratory experiments at high pressure have, until recently, been limited to around 1 Mbar. These pressures are usually achieved dynamically with explosives and two-stage light-gas guns, or statically with diamond anvil cells. Current and future high energy laser and pulsed power facilities will be able to produce tens of Mbar pressures in these light element materials. This presentation will describe the capabilities available at current high energy laser facilities to achieve these extreme conditions, and focus on several examples including water, silica, diamond-phase-carbon, helium and hydrogen. Under strong shock compression all of these materials become electronic conductors, and are transformed eventually to dense plasmas. The experiments reveal some details of the nature of this transition. To obtain high pressure data closer to planetary isentropes advanced compression techniques are required. We are developing a promising technique to achieve higher density states: precompression of samples in a static diamond anvil cell followed by laser driven shock compression. This technique and results from the first experiments with it will be described.

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Recent developments in the modeling of atomic processes in dense plasmas

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Abstract.
Recent experiments using intense laser pulses on thin targets have produced spectra in which it has been speculated that certain features are due to multiple ionization or recombination events.

To explore this possibility, the rate coefficients for collisional double ionization and its inverse process, four-body recombination, have been added to the collisional rate matrix computed within the Los Alamos plasma kinetics code ATOMIC. The collisional double ionization cross sections are obtained from semi-empirical fits to experimental measurements, and the corresponding four-body recombination rates are derived from detailed-balance considerations.

We have examined emission spectra produced from solving the coupled rate equations, including the double ionization and four-body recombination rate coefficients, for an Ar plasma in which various fractions of hot electrons are present. We find that inclusion of these multiple-electron effects can make appreciable differences to the average ionization stage of the plasma and the resulting emission spectra at moderately high electron densities. Further calculations will be presented at the conference.

Keywords: plasma kinetics, double ionization

Particle Manipulation with Nonadiabatic Ponderomotive Forces

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Abstract. Average, or ponderomotive potentials effectively seen by particles in oscillating fields allow advanced techniques of particle manipulation inaccessible with static potentials. In strongly inhomogeneous fields the ponderomotive force is phase-dependent, and the particle dynamics resembles that of a quantum object in a conservative barrier. Probabilistic transmission through a ponderomotive potential is possible then and can be used for particle beam slicing. Resonant fields can also cool and trap particles exhibiting natural oscillations (e.g., Larmor rotation), as well as transmit them asymmetrically, hence acting as one-way walls. An approximate integral of particle motion is found for this case and a new ponderomotive potential is introduced accordingly.

Modeling Nuclear Fusion with an Ultracold Nonneutral Plasma

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In the hot dense interiors of stars and giant planets, nuclear fusion reactions are predicted to occur at rates that are greatly enhanced compared to those at low densities. The enhancement is caused by plasma screening of the repulsive Coulomb potential between nuclei, which increases the probability of the rare close collisions that are responsible for fusion [1]. This screening enhancement is a small but measurable effect in the Sun [2], but is predicted to be much larger in dense objects such as white dwarf stars and giant planet interiors where the plasma is strongly correlated (i.e. where the Debye screening length is smaller than a mean interparticle spacing). However, such strongly enhanced fusion reaction rates have never been definitively observed in the laboratory. This talk discusses a method for observing the enhancement using an analogy between nuclear energy and cyclotron energy in a cold nonneutral plasma in a strong magnetic field. In such a plasma, the cyclotron frequency is higher than other dynamical frequencies, so the kinetic energy of cyclotron motion is an adiabatic invariant. This energy is not shared with other degrees of freedom except through rare close collisions that break this invariant and couple the cyclotron motion to the other degrees of freedom. Thus, the cyclotron energy of an ion, like nuclear energy, can be considered to be an internal degree of freedom that is released only via rare close collisions. Furthermore, it is shown that the rate of release of cyclotron energy is enhanced through plasma screening by precisely the same factor as that for the release of nuclear energy, because both processes rely on close collisions that are enhanced by plasma screening in the same way [3]. Simulations and experiments measuring large screening enhancements for the first time will be discussed, and the possibility of exciting and studying burn fronts will also be considered.

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Atomic Data For Determining Abundances In Interstellar Clouds

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Abstract. Chemical abundances in interstellar clouds are used to examine processes taking place in this environment, to extract gas density and pressure, and to infer astronomical sources for the synthesis of nuclei. The derivation of abundances from absorption lines at ultraviolet and visible wavelengths relies on knowledge of oscillator strengths. I will discuss our multi-pronged approach involving laboratory measurements, interstellar observations, and theoretical computations for determining oscillator strengths. Results for atoms and ions of carbon, chlorine, magnesium, and phosphorus will be presented. Comparisons with other results will highlight where consensus has been achieved and where further work is needed.

X-ray scattering from solid density plasmas*

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With the first experiments on the National Ignition Facility laser, we have begun physics studies that are ultimately aimed at compressing fusion capsules to 1000x solid density and to produce ignition and burn of a deuterium-tritium plasma. For measuring the conditions of relatively cold high-density states of matter such as those occurring during the compression phase of the fusion capsule implosion, we have developed a novel x-ray Compton scattering technique. The proof-of-principle experiment has been performed at the Omega laser facility at LLE, U. Rochester where we have applied Compton scattering in a previously unexplored regime of high-density matter. Spectrally resolved Compton scattering provides information on electron densities, temperature, and velocity distributions at solid densities and beyond. In our experiments, the Compton-downshifted spectral line is broadened by the thermal motion of the electrons in the plasma indicating temperatures of up to T_e = 50 eV at densities of 3 x 10^{23} cm^{-3}. These are the first measurements from dense plasmas close to the Fermi degenerate state that is a fundamental state of matter occurring in many high energy-density laboratory experiments. Since the first demonstration, x-ray scattering has been applied to ionization balance measurements in a broad range of temperatures and densities. In this presentation, we will provide an overview of these ongoing new research activities and will report on new break through measurements of plasmons applying collective x-ray scattering. These data allow accurate measurements of compression and provide new insight in the electronic properties of dense matter. In particular, the role of collisions in dense plasmas may be accurately determined with this novel technique.

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Line spectra and profiles for ultracool substellar objects

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Abstract. The pressures in the line forming regions of cool stellar and substellar objects increase dramatically with lower effective temperatures. This causes strong pressure broadening of the few remaining atomic lines, with damping wings more than 0.5 mu wide, dominating the emitted spectrum. Therefore, there is an essential need for reasonably accurate line profiles for these lines under high-pressure conditions. I will show the results of model atmosphere calculations using detailed line profiles for a number of alkali resonance lines and discuss the need for additional and improved line profile for stellar and planetary atmosphere simulations.

Keywords: line profiles, stellar atmospheres, modeling, radiation transport
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Diagnostic Spectrometers for Tomorrow's X-Ray Sources

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Abstract. A dazzling array of advanced laser, accelerator, and plasma confinement devices are emerging that are producing extreme states of light and matter. Examples of such sources that will produce laboratory x-ray emissions with unprecedented characteristics include megajoule-class and ultrafast, ultraintense petawatt laser-produced plasmas; tabletop high-harmonic-generation x-ray sources; high-brightness zeta-pinch and magnetically confined plasma sources; and coherent x-ray free electron lasers. Characterizing the spectra, time structure, and brightness of x rays emitted by these and other novel sources is a critical component in assessing system performance and progress as well as pursuing the new and unpredictable physical interactions of interest to basic and applied high-energy-density (HED) science. As these technologies mature, increased emphasis will need to be placed on advanced instrumentation and diagnostic metrology, standard reference data, absolute calibrations and traceability of results.

NIST, in collaboration with NRL, is actively designing, fabricating, and fielding absolutely calibrated x-ray spectrometers that have been employed to register spectra from a variety of exotic x-ray sources (electron beam ion trap, electron cyclotron resonance ion source, terawatt pulsed accelerator, laser-produced plasma). These instruments employ a variety of curved-crystal optics, detector technologies, and data acquisition strategies. In anticipation of the trends mentioned above, this talk will focus primarily on the instrumental design considerations that permit acquisition of high-resolution hard x-ray spectra in the HED environment. Recent results are shown from laboratory tests and field use that inform design considerations for diagnostics fielded at tomorrow's x-ray sources.

Probing the Cassiopeia A Supernova Explosion

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X-ray observations of the Cassiopeia A supernova remnant reveal its explosive nucleosynthesis products and thus provide a unique window into the core-collapse explosion that formed the remnant nearly 330 years ago. The synthesis of Fe and other ejecta during the explosion is closely related to asymmetries in the shock wave and the mass and momentum imparted to the nascent neutron star. I will describe how Chandra X-ray observations of Cas A can be interpreted with hydrodynamical and plasma models to infer properties related to the explosion such as the explosion energy, degree of explosion asymmetry and the mass coordinates of the ejecta.

Monochromatic Soft X-Ray Self-Emission Imaging in Dense Z Pinches

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Abstract. The Z machine at Sandia National Laboratories drives 20 MA in 100 ns through a cylindrical array of fine wires which implodes due to the strong **j**x**B** force, generating up to 250 TW of soft x-ray radiation when the z-pinch plasma stagnates on axis. The copious broadband self-emission makes the dynamics of the implosion well suited to diagnosis with soft x-ray imaging and spectroscopy. A monochromatic self-emission imaging instrument has recently been developed on Z which reflects pinhole images from a multilayer mirror onto a 1-ns-gated microchannel plate detector. The multilayer provides narrowband (~10 eV) reflection in the 100-700 eV photon energy range, allowing observation of the soft emission from accreting mass as it assembles into a hot, dense plasma column on the array axis. Data at 277 eV photon energy have been obtained for plasmas ranging from Al to W, and the z-pinch implosion and stagnation will be discussed along with >1 keV self-emission imaging and spectroscopy. Collisional-radiative simulations are currently being pursued in order to link the imaged emissivity to plasma temperature and density profiles and address the role of opacity in interpreting the data.

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New approaches to high-order harmonic generation for coherent soft x-ray generation

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Abstract. The process of high-order harmonic generation (HHG) can be used to generate bright, coherent beams of light in the extreme-ultraviolet and soft x-ray region of the spectrum by upconverting intense femtosecond pulses to very short wavelengths.[1] These high-order harmonics result from ionization of the gas used as a nonlinear medium; thus, a full understanding of the process involves incorporating atomic physics, quantum dynamics, and plasma physics into an already non-trivial nonlinear optics problem.

In the past few years we have developed a new technology of "extreme" nonlinear optics that uses rich physics of the HHG process in novel ways. In this talk, I will discuss several recent experimental results. Phase matching of very high-order HHG in a highly-ionized plasma is challenging. Nevertheless, we have demonstrated several techniques for implementing quasi phase matching of HHG, most recently using weak counterpropagating pulses to perturb the nonlinear response of the atoms. [2,3] This represents a coherent control of quantum dynamics on the attosecond time-scale characteristic of electronic processes, and which has no analogy in conventional nonlinear optics. This work is done using a hollow waveguide geometry,[4] which provides near ideal-conditions for such a high-energy density process, and makes it possible to clearly observe coherence in the conversion process. Other recent work shows that pre-ionized discharges can both guide the laser pulses and make it possible to generate higher energy photons by ionizing ions, rather than neutral atoms.[5] By combining these techniques, and incorporating a new concept for phase-matched conversion in highly ionized plasmas, it appear feasible in the near future to generate bright coherent beams of *hard* x-rays using HHG.

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Expansion Dynamics of Ultracold Neutral Plasmas

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Ultracold neutral plasmas [1], formed by photoionizing laser-cooled atoms near the ionization threshold, stretch the boundaries of traditional neutral plasma physics. The electron temperature in these plasmas is from 1-1000K and the ion temperature is around 1 K. The density can be as high as 10^{10} cm^{-3}. Fundamental interest stems from the possibility of creating strongly-coupled plasmas, but recent experimental and theoretical work has focused on the equilibration and expansion dynamics.

Using optical absorption [2] and fluorescence imaging, we study expansion dynamics during the first 30 microseconds after photoionization. Images record the spatial extent of the plasma, while the Doppler broadened absorption spectrum measures the ion velocity spectrally. The expansion is driven by the pressure of the electron gas, so the ion acceleration depends on the electron temperature. Evidence for terminal ion velocity supports predictions of adiabatic cooling of electrons during expansion [3]. Images confirm the self-similar nature of a Gaussian density distribution. The expansion is similar to dynamics of plasmas produced with short-pulse laser irradiation of solid, liquid, foil, and cluster targets. Understanding expansion dynamics is also important for plans to laser cool and trap the plasma.

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* In collaboration with Jose Casto, Priya Gupta, Sampad Laha, and Clayton. E. Simien.

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A New And Much Improved HULLAC

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Abstract. At the APIP'02 in Gatlinburg, Tennessee, we presented the HULLAC code[1] and advertised that we were going to distribute it. However, it was soon realized that it would require considerable effort before a reliable and readable version could be distributed. A lot has been done since. The present version includes the following main improvements:

• A new fitting formula for the cross sections was developed. It is akin to the method of Burgess, Chidichimo and Tully[2], but more compact. It does not depend on the kind of transition (i.e dipolar, forbidden, ...). This cures the plague of many negative cross sections and collision strengths that were obtained with the classical formula of Sampson[3].

• A new algorithm for solving the rate equations of the collisional radiative model was developed. It is based on the factorization of the level populations into population of each ionization stage times the "reduced" population of each level within this ionization stage. A kind of Newton-Raphson algorithm is then set, and solved iteratively.

• The input file was considerably simplified. Dealing with configuration averages (relativistic and non-relativistic), as well as superconfigurations is now possible.

• Most of the code was re-written in a more modern style, including many comments, error corrections, etc... This Fortran version has been tested with many compilers on many platforms. There is no need of anything else than a Fortran compiler.

• We are thankful to the many users whose feedback allowed us to correct many errors. This version is freely distributed for collaboration.

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Radiative Shocks And Plasma Jets As Laboratory Astrophysics Experiments

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Laboratory astrophysics is one of the main applications of high power lasers, especially the new facilities that are building up such as NIF, LMJ and OMEGA EP. At the LULI laboratory we are developing since a few years a program on radiative shocks. Recent results obtained on the new LULI2000 facility will be presented and compared with 2D radiative simulations. In particular a radiative precursor has been observed and fully characterized (density, temperature). Radial radiative losses have been evidenced and will be discussed.

Besides, plasma jets are often observed for Young Stellar Objects (YSO), during their phase of bulk contraction, bipolar outflows (jets) end as emission lobes (bow shocks). The objective of our experiments is to try to generate plasma jets and to characterize them. To this aim, we tried a new target designs in order to generate the plasma jets. The first target was made of a foam filled cone ended with a "nozzle". We did observe a jet-like structure whose time evolution was studied by varying the foam density. High Mach numbers has been measured (5-10) which are similar to some astrophysical objects. An "envelop" density structure of these jets have been observed which is compatible with a self-similar solution of a polytropic expansion of a fluid into vacuum. The second target consists on a V-foil, each side of it generating a hot plasma which collides on the symmetrical axis inducing also a high speed jet. Detailed experimental results will be presented and compared to preliminary 2D simulations.

Discharge Plasmas as EUV Sources for Future Micro Lithography

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Abstract. Future extreme ultraviolet (EUV) lithography will require very high radiation intensities in a narrow wavelength range around 13.5 nm, which is most efficiently emitted as line radiation by highly ionized heavy particles. Currently the most intense EUV sources are based on Xenon or Tin gas discharges. After having investigated the limits of a hollow cathode triggered Xenon pinch discharge a Laser triggered Tin vacuum spark discharge is favored by Philips Extreme UV. Plasma and radiation properties of these highly transient discharges will be compared. Besides simple MHD-models[1] the ADAS software package [2] has been used to generate important atomic and spectral data of the relevant ion stages. To compute excitation and radiation properties, collisional radiative equilibria of individual ion stages are computed. For many lines opacity effects cannot be neglected. In the Xenon discharges the optical depths allow for a treatment based on escape factors. Due to the rapid change of plasma parameters the abundancies of the different ionization stages must be computed dynamically. This requires effective ionization and recombination rates, which can also be supplied by ADAS.

Due to very steep gradients (up to a couple orders of magnitude per mm) the plasma of Tin vacuum spark discharges is very complicated. Therefore we shall describe here only some technological aspects of our Tin EUV lamp: The electrode system consists of two rotating wheels. To generate Tin plasmas these wheels are pulled through baths of molten Tin such that a proper Tin film remains on their surfaces. With a Laser pulse Tin is ablated from one of the wheels and explodes rapidly through vacuum towards the other rotating wheel. When the tin plasma reaches the other electrodes it ignites and the high current phase starts, i.e. the capacitor bank is unloaded, the plasma is pinched and EUV is radiated. Besides the good spectral properties of Tin this concept has some other advantages: Erosion of electrodes is no severe problem as the Tin film is regenerative and protects the electrode material. The electrical connections to the rotating electrodes are easily made via the Tin baths. As the liquid Tin cools very effectively the rotating wheels, the concept is scalable to higher powers. The disadvantage, however, is the rather large amount of Tin debris that must be kept away from the optics. Even very thin layers of condensed Tin would severely reduce the reflectivity of the mirrors.

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Important Atomic, Molecular and Radiative Processes in Low Pressure Discharge Lamps

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Fluorescent lamps (FL) are the most efficient low pressure discharges used for lighting. These discharges are filled with a rare gas, typically argon at around 3 torr (400 Pa) pressure, with a few mtorr (0.5-5 Pa) of mercury vapor. At room temperature, mercury has the highest vapor pressure of any of the elements suitable for producing radiation. Under optimum conditions, 70-75% of electrical power in these discharges is converted to ultraviolet (*UV)* radiation by mercury atoms. The *UV* is then converted to visible light by means of a phosphor; the energy difference between the incoming *UV* photon and the outgoing visible photon (the Stokes shift) results in a total conversion efficiency of electrical power to visible light of about 25%. Recent research on low pressure discharges for lighting has focused on two areas; improving the efficiency of existing FL, and efforts to find molecules with radiative transitions in the visible or near UV spectrum which might replace mercury in these lamps The efficiency of producing light in a low pressure discharge depends on the balance between ionization processes, which sustain the plasma, and the excitation of atoms or molecules into radiating states through electron impact excitation and collisions between atoms in excited states. Since radiation emitted at one point in the discharge may be absorbed and re-emitted several times before it finally reaches the wall, radiation transport also plays a significant role in determining the fraction of electrical energy which is converted to radiation. Numerical models have been developed over the last 50 years which have greatly assisted the development of these lamps, but they are hampered by lack of data. This paper will describe the important fundamental processes in low pressure discharge light sources, and discuss the requirements for new and improved atomic and molecular data to support the numerical models.

Measurements of spectral line shapes for studying the particle density and motion in an imploding *z*-pinch plasma

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Spectral broadening of emission lines of singly to five-times ionized oxygen are used to investigate the ion density and flow in the plasma during the implosion phase of a 0.6-μs, 220-kA *z*-pinch experiment. The data are analyzed by comparing the measured line widths to the widths obtained from Stark broadening calculations, for which the electron density and temperature used are experimentally determined in separate studies. It is found that during a substantial fraction of the implosion phase the experimental line widths for ions at the outer boundary of the imploding plasma shell are significantly larger than the calculated widths. It appears that the additional contribution to the experimental spectral widths is due to Doppler broadening that is thus concluded to be larger than expected from assuming that the ion temperature $T_i = T_e$.The ion kinetic energy associated with the ion motion thus inferred is found to be about 20% of the radially-directed kinetic energy.Detailed measurements of the time-dependent distributions of the plasma properties and of the magnetic field allow for using energy balance considerations to examine whether the data can be explained by non-thermal plasma flows at the outer boundary of the imploding shell or by a higher ion temperature.

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Corrugated plasma optical fibres generated in gases of atomic clusters

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Abstract. We report the generation of up to ~ 3cm long periodically modulated plasma waveguides that allow μm-scale control of the instantaneous intensity and phase velocity of a guided ultra-intense femtosecond laser pulse. This is accomplished by focusing an auxiliary spatially modulated laser pulse onto cryogenically cooled cluster jets. We can control the depth and period of the waveguide axial modulations, as well as the plasma ionization stage, electron density and guided spot size. The method is highly tunable and extremely stable, with controllable modulation periods as short as 70 μm and as long as 3 mm. Single-mode propagation at >10^{17} W/cm^2 in these guides has been demonstrated using argon, nitrogen, neon, and hydrogen clusters. A high degree of waveguide uniformity and shot-to-shot consistency is attained. We review several applications of our new device . Efficient direct electron acceleration by a radially polarized laser pulse can be achieved by quasi-phase matching in an axially modulated plasma waveguide [1]. High-harmonic generation could be quasi-phase matched [2] at extremely high orders. Finally, recent calculations [3] show that these channels could convert multi-millijoule femtosecond laser pulses into terahertz radiation with high efficiency.

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Laser Wakefield Acceleration: A path to creating 100 GeV electron beams on a tabletop

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The extraordinary ability of space-charge waves in plasmas to accelerate charged particles at gradients that are orders of magnitude greater than in current accelerators has been well documented. We show here that 100TW to 2000TW class lasers can excite large amplitude wakefields and be stably self-guided in very underdense plasmas to produce 1 to 10 GeV mono-energetic, self-injected electron beams with nCs of charge. For such powers the plasma wakes can be excited by the nearly complete blowout, i.e., expulsion, of plasma electrons by the radiation pressure of a short pulse laser. We also show that these wakefields are ideal for accelerating externally injected beams of electrons. The proposed regime is distinct from the "bubble regime" in that it advocates using lower densities and wider spot sizes while keeping the intensity relatively constant in order to increase the output electron beam energy and keep the efficiency high. We discuss what laser parameters would be needed to generate 100 GeV beams with more than a nC of charge in a single stage in this LWFA regime. Our theoretical results are verified by three-dimensional particle-in-cell simulations.

This work was done in collaboration with W. Lu, M. Tzoufras, F.S. Tsung, C. Huang, C. Joshi, L.O. Silva, and J. Vieira, and R.A. Fonseca.

Plasma Astrophysics – Cosmology and the Growth of Cosmic Structure

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I will present some of the ways that x-ray spectroscopy can be utilized to determine cosmological parameters focusing on 5 methods : the gas fraction in clusters, the use of the Sunyaev-Zeldovich effect, the detection of resonance scattering in clusters , the use of resonance absorption and emission in background sources and the growth of structure. All of these techniques except the S-Z effect rely heavily on high resolution x-ray spectroscopy and require the next generation of x-ray spectroscopic missions such as Constellation-X. The promise of these techniques is great and they have the potential for precision cosmology with errors similar to those of other precision techniques such as type Ia supernova.

If time permits I will also talk about how we can learn about how active galaxies strongly influence the growth of cosmic structure and how broad band high resolution x-ray spectra are necessary to measure the effects of AGN and how much energy they input into the universe and the role of new atomic physics calculations in interpreting these results.

Theoretical and experimental studies on high-average power EUV light sources by laser produced plasmas

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Extreme ultraviolet (EUV) radiation from laser-produced plasma has recently attracted particular attention for use in mass-production of the next generation semiconductor devices of node-size below 35 nm. It is expected to generate over 180 W at 13.5 nm within a 2% bandwidth at repetition rates of 7-10 kHz. Since 2003 a new project of MEXT (Japan Ministry of Education, Science, Culture, and Sport) has started to provide experimental and theoretical databases for clean and efficient EUV generation, and technical guidelines to build-up an EUV-source system for practical use in industry. The key materials for 13.5 nm EUV are lithium, xenon, and tin, mostly due to their potentials for high conversion efficiency. Comprehensive experimental databases are provided for a wide range of parameters of lasers and targets. These experimental data are utilized in the industry as well as used to benchmark the radiation hydrodynamic code, including equation-of-state solvers and advanced atomic kinetic models, dedicated for EUV plasma predictions.

The atomic models are benchmarked with spectroscopic measurements not only for laser produced plasma (LPP), but also for magnetically confined plasma, discharge produced plasma (DPP), and EUV emissions arising from the charge exchange for uniquely ionized ions colliding with rare gas target [1]. In particular, the charge exchange measurement enables us to make precise comparison of the synthetic spectra for individual ions. Moreover, opacity measurement for Sn plasma was made using laser generated thermal x-ray [2].

In the presentation, present status of LPP EUV source studies will be discussed.

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Kim Memorial Lecture

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Dr. Kim made internationally recognized contributions in many areas of atomic physics research and applications. He joined NIST in 1983 after 17 years at the Argonne National Laboratory following his Ph.D. work at the University of Chicago. Much of his early work at Argonne and especially at NIST was the elucidation and detailed analysis of the structure of highly charged ions. He developed a sophisticated, fully relativistic atomic structure theory that accurately predicts atomic energy levels, transition wavelengths, lifetimes, and transition probabilities for a large number of ions. This information has been vital to model the properties of the hot interior of fusion research plasmas, where atomic ions must be described with relativistic atomic structure calculations. In recent years, Dr. Kim worked on the precise calculation of ionization and excitation cross sections of numerous atoms, ions and molecules that are important in fusion research and in plasma processing for manufacturing semiconductor chips. Dr. Kim greatly advanced the state-of-the art of calculations for these cross sections through development and implementation of highly innovative methods, including his Binary-Encounter-Bethe (BEB) theory and a scaled plane wave Born theory. His methods, using closed quantum mechanical formulas and no adjustable parameters, avoid tedious large-scale computations with main-frame computers. His calculations reproduce the results of benchmark experiments as well as large-scale calculations requiring hours of computer time. In this presentation, I will emphasize this recent work and show its power and generality.

Simultaneous COLTRIMS And X-Ray Spectroscopic Studies Relevant To Cometary, Planetary, And Heliospheric X-Ray Emission

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Abstract. X-ray and extreme ultraviolet (EUV) emission has been observed from over 20 comets since first observed in 1996. Charge exchange between highly charged solar wind (SW) minor heavy ions and cometary neutrals is now recognized as the primary mechanism responsible for the observed emission. In the SW charge exchange (SWCX) mechanism, electrons are captured from cometary neutrals by the SW ions into excited states of the resulting ions; which may then decay radiatively and in the process emit X-ray and/or EUV radiation. SWCX has also been suggested as contributing to the soft X-ray background of the heliosphere, and the first definite detection of SWCX induced X-ray emission from the exosphere of planet Mars has been recently reported. To gain better insight into the relevant atomic processes, we have performed highly differential laboratory studies by means of simultaneous cold-target recoil ion momentum (COLTRIMS) and X-ray spectroscopic measurements. The measurements involved the triple-coincident detection of X-rays, scattered projectile, and target recoil ions. In addition to the X-ray energy and the final projectile and recoil ions' charge states, the measurements provide the collision *Q*-value and therefore are state-selective. Ne^{10+}, Ne^{9+}, and O^{7+} projectile ions collided with He, Ne, Ar, CO, and CO_2 neutrals. The measurements provide unequivocal evidence for a significant contribution by multiple-electron capture processes to cometary X-ray emission, and strongly suggest that models based solely on single-electron capture (SEC) are bound to yield erroneous conclusions on the solar wind composition and velocities and on cometary atmospheres. In addition, state-selective H-like and He-like X-ray spectra resulting from SEC have been obtained. These spectra allow for critically testing theoretical predictions on the angular momentum distributions, and in the case of the He-like spectra, predictions on the spin multiplicity. Comparisons with some theoretical calculations will be presented.

X-ray absorption of dense plasmas created by an ultra-short laser pulse

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When a sub-picosecond laser pulse irradiates a very thin foil with moderate intensities, impulse heating followed by a rapid heat conduction produces a high-density, moderate-temperature plasma before any hydrodynamic expansion occurs. Short-pulse x-ray sources of a few picosecond duration emitting in the sub-5-keV range have been generated by irradiating high-Z materials with a sub-picosecond laser pulse. This offers the possibility to use point-projection time-resolved absorption spectroscopy for the study of spectral opacities of dense plasmas.

Quantitative data of transmission spectra in the warm dense matter regime have been measured using the 100-TW LULI facility. The 1s-2p and 1s-3p absorption lines of Al and 2s-3p absorption lines of Br were measured for densities up to 1 g/cm^3 and temperatures varying from 5 to 30 eV. Our experiment allows one to investigate a higher-density plasma regime than that commonly accessible by using volumetrically radiatively heated foils. The space-resolved electron temperature at the peak of the main laser pulse was deduced from the Fourier Domain Interferometry diagnostic system. Temperature and density, obtained for a specific delay, were inferred by lagrangian hydrodynamic simulations.

In the warm dense regime studied, the Al plasma is weakly ionized and density effects are not negligible. The continuum lowering modifies the ionization balance and pressure ionization tends to delocalize atomic orbitals. In the spectral range studied, many 1s-np absorption lines merge in the K-shell photoionization. Therefore, our experimental data allow us to test the accuracy of approximations that have been proposed to account for density effects in spectral opacity calculations. To interpret the absorption spectrum in terms of spectral opacities, it is necessary to (i) infer the density and temperature of the layer during the absorption measurement, (ii) take into account the temporal and longitudinal gradients in the analysis, (iii) check that non-equilibrium effects due to time-dependent population kinetics are negligible at the time of the x-ray probe. All three of these points will be presented and discussed.

Compact high repetition rate soft x-ray lasers: a doorway to high intensity coherent soft x-ray science on a table-top

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Recent advances in high repetition rate soft x-ray lasers allow the generation of very high brightness soft x-ray beams using table-top set ups. The peak spectral brightness of some of these new lasers operating in the 25-100 eV photon energy region surpasses by several orders of magnitude that of third generation synchrotrons, enabling new applications. These advances include the demonstration of 5 Hz repetition rate table-top soft x-ray lasers that operate in the gain-saturation regime to produce intense beams at wavelengths ranging from 13.2 to 32.6 nm, and the observation of lasing at wavelengths down to 10.9 nm [1]. The results were obtained by collisional electron impact excitation of highly ionized atoms in dense plasmas efficiently heated with picosecond optical laser pulses of only 1 J energy. Further improvement in the brightness of these compact sources can be obtained seeding the soft x-ray amplifiers with high harmonic pulses. We have conducted a table-top experiment in which we demonstrated the saturated amplification of high harmonic seed pulses in a dense transient collisional soft x-ray laser amplifier medium created by heating a solid titanium target [3]. Amplification of the seed pulses in the 32.6 nm line of Ne-like Ti generated laser pulses of sub-picosecond duration that were measured to approach full spatial coherence. The peak spectral brightness is estimated to be ~ 2×10^{26} photons/(s mm^2 mrad^2 0.01% bandwidth). The scheme is scalable to produce extremely bright lasers at very short wavelength with full temporal and spatial coherence.

These new compact laser-pumped lasers in combination with desk-top size soft x-ray lasers excited by fast electrical discharges are allowing the implementation of table-top experiments with intense soft x-ray light. These include the demonstration of broad area imaging with resolution down to 38 nm, diagnostics of dense plasmas by soft x-ray laser interferometry, nanoscale ablation of materials, single photon ionization spectroscopy of molecules and nanoclusters. Work supported by the National Science Foundation ERC for Extreme Ultraviolet Science and Technology under NSF Award EEC-0310717 and by the US Department of Energy.

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Recombination and Ionization Data Needs for Cosmic Atomic Plasmas

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Abstract. Cosmic atomic plasmas can be divided into two broad classes: electron-ionized and photoionized. Electron-ionized plasmas are formed in objects such as the sun and other stars, supernova remnants, galaxies, and the intercluster medium in clusters of galaxies. Photoionized plasmas are formed in objects such as planetary nebulae, H II regions, X-ray binaries, and active galactic nuclei. Understanding the spectral and thermal properties of these objects requires an accurate knowledge of the ionization level of the gas. This in turn depends on a reliable understanding of the underlying recombination and ionization processes which determine the ionization balance. Here I will review some of the various atomic collision processes which determine the charge state distribution in a cosmic atomic plasma. I will also discuss some of the recent theoretical and experimental advances in generating the needed atomic data. I will close by describing the relevant atomic data needs for the near future.

This work was funded in part by the NASA Astronomy and Physics Research and Analysis program, the NASA Solar and Helospheric Physics Supporting Research and Technology program, and the NSF Astronomy and Astrophysics Research program.

Plasma-wall interaction: How atomic processes influence the performance of fusion plasmas

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Abstract. Plasma edge physics is one of the major challenges in fusion plasmas. The need for power and particle exhaust for any reactor inspired a lot of theoretical and experimental work. Understanding this physics requires a multi-scale ansatz bringing together also several physics and numerical models.

The plasma edge of fusion experiments is characterized by atomic and molecular processes. Hydrogenic ions and neutrals hit material walls with energies from several eV up to 1000s of eV. They saturate the wall materials and due to physical or chemical processes neutrals are released from the wall, both atomic and molecular. They determine via interaction with the plasma strongly its properties. These processes can be beneficial for a fusion experiment by using radiation losses to minimize the power load problem of target plates, but also can create severe problems if the dilution of the plasma gets too large or condensation radiation instabilities can be created.

A complete physics model for the plasma-wall interaction processes alone is already rather challenging (and still missing): it requires e.g. inclusion of collision cascades, chemical formation of molecules, diffusion in strongly 3D systems. A full description needs a multi-scale model combining quite different numerical techniques like molecular dynamics, binary collisions, kinetic Monte Carlo and mixed conduction/convection equations in strongly anisotropic systems.

X-Ray Measurements Using a Microcalorimeter on an Electron Beam Ion Trap

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ABSTRACT

The X-ray telescopes and spectrometers flown on Chandra and XMM-Newton are returning exciting new data from a wide variety of cosmic sources such as stellar coronae, supernova remnants, galaxies, clusters of galaxies, active galactic nuclei and X-ray binaries. To achieve the best scientific interpretation of the data from these and future spectroscopic missions and related ground-based observations, theoretical calculations and plasma models must be verified or modified by the results obtained from measurements in the laboratory. Such measurements are the focus of several laboratory astrophysics programs that use an electron beam ion trap (EBIT) to simulate astrophysical plasma conditions. Here we describe our recent spectroscopic measurements using a microcalorimeter on the EBIT at the National Institute of Standards (NIST).

Lithium Polarization Spectroscopy: Making Precision Plasma Current Measurements in the DIII-D National Fusion Facility*

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Abstract. Due to several favorable atomic properties (including a simple spectral structure, the existence of a visible resonance line, large excitation cross section, and ease of beam formation), beams of atomic lithium have been used for many years to diagnose various plasma parameters. Using techniques of active (beam-based) spectroscopy, lithium beams can provide localized measurements of plasma density, ion temperature and impurity concentration, plasma fluctuations, and intrinsic magnetic fields. In this paper we present recent results on polarization spectroscopy from the LIBEAM diagnostic, a 30 keV, multi-mA lithium beam system deployed on the DIII-D National Fusion Facility tokamak. In particular, by utilizing the Zeeman splitting and known polarization characteristics of the collisionally excited 670.8 nm Li resonance line we are able to measure accurately the spatio-temporal dependence of the edge current density, a parameter of basic importance to the stability of high performance tokamaks. We discuss the basic atomic beam performance, spectral line-shape filtering, and polarization analysis requirements that were necessary to attain such measurements. Observations made under a variety of plasma conditions have demonstrated the close relationship between the edge current and plasma pressure, as expected from neoclassical theory.

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Development of Compton radiography using high-Z backlighters produced by ultra-intense lasers

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Abstract

High-energy K-alpha backlighters will be valuable for radiography experiments at the National Ignition Facility (NIF), and in for radiography of imploded inertial confinement fusion cores using Compton scattering to observe cold, dense plasma. Key considerations are the available backlight brightness, and the backlight size. To quantify these parameters we have characterized the emission from low- and high-Z planar foils irradiated by intense picosecond and femtosecond laser pulses from the TITAN laser facility at Lawrence Livermore National Laboratory. Spectra generated by a sequence of elements from Mo to Au, spanning the x-ray energy range from 17 to 69 keV, have been recorded using a Charged Coupled Device (CCD) in single hit regime and a Dual Crystal Spectrometer (DCS). High-resolution point-projection 2D radiographs have also been recorded on Fuji BaFBr:Eu2 image plates using calibrated resolution grids. We discuss the results in light of the requirements for applications at NIF.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48

A theoretical survey of formation of anti-hydrogen atoms in a Penning trap

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Keywords: magnetized plasma, antimatter
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Hot anti-hydrogen atoms are created at CERN, by ATRAP[1] and ATHENA[2] experiments, by bringing together positrons and anti-protons in a magnetic Penning trap. Most of these atoms are created in exotic, highly excited states, such that the magnetic forces on positrons are greater than the Coulomb attraction of anti-protons. This paper presents an overlook of the recent progress made toward theoretical understanding of the complicated dynamics which leads to the formation and detection of anti-hydrogen atoms. There is no formal difference between the plasmas described here and normal, electron-proton, matter plasmas, except the reversed sign of electrical charges. The next generation of experiments need to bring the anti-hydrogen atoms to the ground state and to cool them to sub-milliKelvin temperature. Only then, high resolution spectroscopy can expose differences between matter and anti-matter due to CPT violations. Suggestions are made for possible pathways toward this goal.

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Inference of Mix from Experimental Data and Theoretical Mix Models

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Abstract. The mixing between fuel and shell materials in Inertial Confinement Fusion implosion cores is a topic of great interest. Mixing due to hydrodynamic instabilities can affect implosion dynamics and could also go so far as to prevent ignition. We have demonstrated that it is possible to extract information on mixing directly from experimental data using spectroscopic arguments. In order to compare this data-driven analysis to a theoretical framework, two independent mix models, Youngs' phenomenological model and the Haan saturation model, have been implemented in conjunction with a series of clean hydrodynamic simulations that model the experiments. The first tests of these methods were carried out based on a set of indirect drive implosions at the OMEGA laser. We now focus on direct drive experiments, and endeavor to approach the problem from another perspective. In the current work, we use Youngs' and Haan's mix models in conjunction with hydrodynamic simulations in order to design experimental platforms that exhibit measurably different levels of mix. Once the experiments are completed based on these designs, the results of a data-driven mix analysis will be compared to the levels of mix predicted by the simulations. In this way, we aim to increase our confidence in the methods used to extract mixing information from the experimental data, as well as to study sensitivities and the range of validity of the mix models.