Challenges and opportunities for collaborations in High Energy Density Physics

T.A. Mehlhorn [1]

[1]Sandia National Laboratories, Albuquerque, New Mexico, USA

According to the National Research Council of the National Academy of Sciences „The time is highly opportune … to develop a fundamental understanding of the physics of high energy density plasmas. Recent advances in extending the energy, power and brightness of lasers, particle beams, and Z-pinch generators make it possible to create matter with extremely high energy density in the laboratory. The collective interaction of this matter with itself, particle beams, and radiation fields is a rich, expanding field of physics called high energy density physics. It is a field characterized by extreme states of matter previously unattainable in laboratory experiments" [1].

High energy density physics (HEDP) is defined as an energy density of 10^{11} J/m^3 that is equivalent to a pressure of 1 Mbar. HEDP research is a world wide activity utilizing high power lasers, z-pinches and particle beams. An active collaboration in HEDP physics already exists between German and US researchers including Oliver Boine-Frankenheim, Markus Roth, and Mathias Geissel (Sandia National Labs) and Andreas Tauschwitz, Christoph Niemann and Stefan Neff (Lawrence Berkeley Nat. Lab).

Within the next two decades, new facilities will revolutionize both our understanding and use of plasma physics including the National Ignition Facility at LLNL, ITER, the 26 MA ZR at Sandia, the FIREX1 facility at ILE Osaka, and the SIS 100/200 accelerator at GSI. Sandia performs its HEDP research on a combination of Z and ZBL. The "Z Machine", which is located at Sandia is a pulsed-power accelerator that drives z-pinch loads producing x-ray powers of 100-250 TW and 1-1.8 MJ of radiated x-ray energy. The Z-Beamlet laser (ZBL) is operational and is used on about half of all Z experiments delivering >2 kJ (<2 ns) via a 75-m-length transport tube to Z. ZBL is being upgraded to provide a 2-4 kJ, 1-10 psec short pulse laser for high energy radiography and fast ignitor experiments on Sandia's Z facility beginning in 2007. A stand alone 50-200 J, 0.5 - 10 psec prototype laser system will begin operation in 2004.

GSI likewise has both an accelerator and a laser for HEDP research. The SIS 100 will be a valuable HEDP facility with the highest specific ion deposition capability in the world. It is important to note that higher beam intensites and shorter bunches are critical to HEDP all HEDP research at GSI. The PHELIX, Petawatt High Energy Laser for Heavy Ion Experiments is being constructed at GSI. PHELIX utilized a US/German collaboration: "... related to use of Nova laser parts to build a new Petawatt laser facility at GSI ... 5 transportainers of Nova parts were shipped under the auspices of OFES and the LBNL Heavy-Ion Fusion Program to GSI in November, 2002". PHELIX experiments with the UNILAC beam (1 kJ in 0.5 - 10 ns) are planned in 2004, while a petawatt (PW) capability (500J in 500 fs) is planned for 2005. The SIS 100 coupled with PHELIX will greatly increase the capability and flexibility for high energy density physics at GSI.

An Implementing Agreement between the US-DOE and the German-BMBF on Collaboration in the Field of Dense Plasma Physics already exists. Collaboration may include the following: 1) the study of plasma properties in extreme regimes of density and temperature, 2) the study of energy deposition, x-ray conversion and transport of radiation in dense plasmas, 3) the study of the production and spectroscopy of highly charged ions, 4) research on the interaction of intense laser light with overdense plasmas, 5) experiments on heavy ions; and 6) the development of a database on bunch-compression, focusing, and target plasma interaction physics using intense, multi-Giga-electronvolt heavy-ion beams. A new annex on gas desorption and electron cloud effects in high intensity accelerators has been proposed.

New HEDP collaborations are proposed . The US Heavy Ion Fusion program is interested in leveraging the unique capability at GSI to measure ion stopping powers. Sandia is interested in collaborating in obtaining GSI data in EOS, conductivity and critical points. A theoretical collaboration in exact exchange for density function theory is already in place with R. Redmer (U. Rostock). The controversial deterium EOS is important to both ICF and to Jovian/extrasolar planetary science. Heavy Ions from SIS 100 with innovative targets should create diagnosable warm dense matter (WDM) utilizing volume deposition via "slow" cylindrical isentropic implosion to create „shocklessly imploded" hydrogen with a 50 ns dwell time. GSI has already made a first measurement of electrical conductivity in ion beam heated materials [2]. Sandia is also interested in collaborations in the atomic physics & spectroscopy of dense plasmas. Short pulse, high intensity lasers can both heat and diagnose plasmas. Common research areas of interest in PW laser physics and applications include: 1) ion generation, 2) ion sources, 3) isochoric heating, 4) dE/dx in warm dense matter, and 5) proton deflectometry measurements of transient electromagnetic fields.

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Atomic Processes in Dense Plasmas

Valery S. Lisitsa
Nuclear Fusion Institute, Russian Research Center Kurchatov Institute

Atomic physics in Warm Dense Matter (WDM): background and justification

There is a strong coupling between atoms and plasmas under WDM conditions [1]. In essence photons are radiated in WDM by a compound system "ATOM + PLASMA". The coupling parameter Γ is the ratio of interparticle potential energy to the thermal energy .WDM production is supposed to be done by means of heavy ions beams at GSI. Atomic collisions in dense plasmas are characterized by a collision time $\tau_c \sim \rho_{eff}/v$ and kinetic time $\tau_k \sim [Nv\pi\rho_{eff}^2]^{-1}$. Their ratio is equal to $g=N\rho_{eff}^3$ that is just a number of particles inside the interaction sphere. Binary collisions correspond to $g<<1$ whereas multiparticle collisions in dense plasmas corresponds to $g>>1$. For dipole allowed collision transitions the long range interaction in plasmas can be expressed in terms of plasma electric field F(t). It results in the conception of plasma microfield leading to the atomic state mixing by plasma microfield [2]. Density matrix equations are needed instead of atomic amplitude equations in standard approach [3].

Effects for observations

One of the most important effects is the effect of plasma coupling parameter Γ on microfield distribution and microfield dynamics. Spectral line shapes are of a special interest for atoms in plasma microfield making it possible to determine ion density, microfield dynamic effects (field life-time T_F) due to ion thermal motion and plasma coupling parameter Γ. A cut off of atomic energy levels as a function of plasma density can be observable also. Molecular satellites in far wings of spectral lines (observed in laboratory laser plasmas [4] and white dwarf plasma [5]) can be used for a determination of WDM investigations.

Stopping Power Measurements

A general idea is to observe space resolved spectra generated by a fast projectile in a dense media. Polarization Radiation (PlR) of fast particles in a dense medium is of a special interest. The PlR can be considered as a scattering of the proper electromagnetic field of the fast charged particles in collisions with target atoms [6]. The PlR from fast electrons have been observed for polycristalline Al target. A sharp increase of PlR intensity is proposed for highly charged ions with a charge Z.

The PlR intensity scales as Z^2 that means a sharp increase of the effect. The calculations of PlR for Al and frozen hydrogen targets demonstrate that 1) the quantity of emitted quanta are enough for observation of the effects in experiments with projectile bunches 10^{10} particles; 2) spectra are dependent on the projectile energy E that means a new way for stopping power measurements; 3) spectra are sensitive to the medium structure being a way for WDM structure determination. The results of PlR spectra measurements can be compared with X-ray scattering spectra from PHELIX.

Conclusion

New possibilities of accelerators facilities make it possible to observe a number of effects connected with exotic WDM state. The hydrogen spectra measurements open new possibilities for investigations of nonideal plasma properties in the first turn – statistical and dynamical properties of plasma microfield in the strongly coupled plasmas. New methods of PlR measurements open new possibilities for stopping power measurements in a dense media as well a structure of WDM itself.

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X-ray Scattering from PHELIX Plasmas

David Riley [1] Frank B Rosmej [2]

[1]Queen's University of Belfast, University Road, Belfast BT7 1NN, UK

[2]Universite de Provence et CNRS, UMR 6633, Centre de Saint Jerome, case 232, F-13397 Marseille cedex 20, France

Warm dense matter (WDM) is a regime where neither classical plasma physics nor condensed matter models are applicable. In the former this is because of the effects of strong coupling and degeneracy and the breakdown of the statistical averaging necessary for the Debye screening model. In the latter it is because the temperature at solid density is greater than a small fraction of the Fermi temperature. This regime is generally taken to include densities within a factor of ten of solid density and temperatures ranging from about 1-10eV. The study of WDM is currently of great interest due to its relevance to planetary science and the fact that in this regime, equation of state models disagree- especially off the shock Hugoniot.

Making samples of WDM suitable for study in the laboratory is difficult. Laser-plasma generated samples tend to suffer from steep density and temperature gradients and are short lived (~ns). The ion beam facility at GSI offers the chance to make large uniform samples with scale times of ~100ns. We propose to make use of such samples and probe them with 1ns pulses of X-ray line radiation generated by the PHELIX laser. The diagnostic is X-ray Thompson scatter. This techniqe has only recently been developed [1]. We intend to use the ~1kJ available to generate $\sim 10^{15}$ photons [2] of Ti He-alpha ($1s^2$-$1s2p\ ^1P$) line radiation at 4.75keV. This is generated along with Li-like satellites to form a line array of ~50eV spectral width. Kozyreva *et. al.* [3] have shown that a cylindrical frozen hydrogen sample can be heated with heavy ions to create a uniform plasma with density ~0.05g/cc at ~0.6eV with a length of ~1mm and diameter ~0.6mm. Given that the equation of sate for dense hydrogen continues to be a matter for debate, [4] this presents an interesting potential sample for X-ray scattering. Figure 1, shows a schematic of the proposed experiment. We can consider how many X-rays are likely to be scattered. The X-ray source sample (Ti foil) can be placed within 5mm of the sample. A pinhole system can be used to restrict the probe to a fixed diameter of the target. Assuming this is done and the probe subtends ~0.3mm on the target we can estimate that $\sim 10^{12}$ photons probe the target. The scatter cross-section depends on the scatter angle chosen but is $\sim 4\times 10^{-26}$ cm^2/sr. As an aside, we should state that the angle of scatter determines if the scatter is in the collective or non-collective mode. In the former we sample fluctuations on a longer spatial scale than the Debye length and expect to see a plasmon feature in the scatter spectrum, in the latter we probe shorter spatial scales and expect to see a spectrum reflecting the Doppler shifts due to thermal motion of the electrons. Give the size of the plasma we expect to see at least 10^8 photons/sr scattered. With a spatially resolving imaging crystal we can achieve a throughput of 10^{-4} sr and thus capture 10^4 photons per data shot. Given the high detection efficiency of modern CCD X-ray detectors, this is enough to make a spectrum. The expected spectra should differ from optical spectra in that the Compton shift of scattered photons (0-90eV) is noticeable and the spectrum is not symmetric since the structure factors on either side of the central wavelength are related by $S(-\omega,k)\sim e^{-h\omega/kT}S(\omega,k)$. This is not important, in the optical case ($h\omega<<kT$) but is for X-rays and collective scatter would yield a single plasmon peak shifted by the plasma frequency plus Compton shift from the incident wavelength. Theoretical work on X-ray Thomson scatter spectra, looking at the effects of strong coupling and degeneracy has been started [5] and is expected to be stimulated further by the availability of data from interesting samples such as dense hot hydrogen.

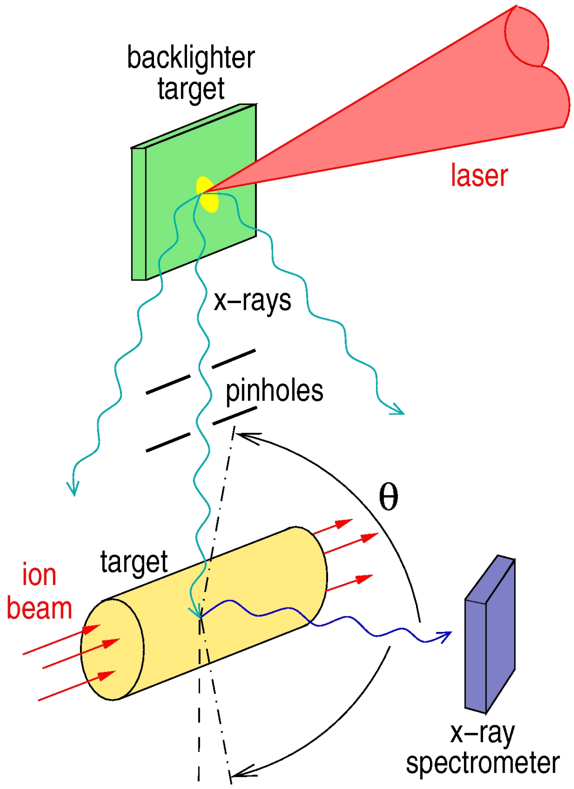

Figure 1. Schematic of the proposed X-ray scattering experiment using ion-beam generated samples and laser-plasma x-rays as a probe.

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