White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***6/19/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	S
• Plasma self-organization	
• Statistical mechanics of plasmas	P

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Investigating Warm Dense Matter with Soft X-ray Pulses using Relativistic Surface High Harmonic Generation
Corresponding Author:	Christian Roedel
• Institution:	SLAC National Accelerator Laboratory
• email:	roedel@slac.stanford.edu
Co-Authors:	Frederico Fiuza (SLAC), Siegfried Glenzer (SLAC),

(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)

- ***Describe the research frontier* and importance of the scientific challenge.**

Hydrogen, the simplest element in the universe, can have surprisingly complex properties when it is a warm dense matter (WDM) state. Owing to fundamental questions about the structure and core stability of gas giants in our solar system, properties of warm dense hydrogen have been the subject of intense studies over the past two decades. In these WDM states, strong interparticle forces and quantum degeneracy determine the equations of state (EOS) that govern the thermodynamics and macroscopic structure of many astrophysical objects including the giant gaseous planets and brown dwarfs as well as the implosion of deuterium-tritium-fuel pellets in inertial confinement fusion (ICF). The theoretical description of the EOS of WDM is extremely challenging as these models must tackle a number of important questions such as the existence of plasma phase transitions, metallization, molecular-to-atomic transition, and melting of hydrogen at high pressures. Accordingly, models and simulations require many approximations and computational power. All these complications result in disagreements between various approaches and individual models. Experimental validation of predictions made by theory is thus essential. A precise determination will affect our understanding of the formation and evolution of the solar system and will further affect our ability to achieve inertial confinement fusion in the laboratory. The physical properties of warm dense hydrogen and deuterium are one of the most contested and important science questions in high energy density science [Frontiers2003].

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Since dense plasmas are opaque for optical radiation, extreme ultraviolet (XUV) and soft x-ray sources must be used for investigating WDM and HED plasmas. In the last years, intense XUV and x-ray beams became available at free-electron lasers that advanced research in plasma physics significantly [Vinko2012]. With these developments, plasma diagnostics such as x-ray Thomson scattering are now able to determine plasma parameters with unprecedented precision [Fletcher2015]. For such measurements, however, isochoric heating of hydrogen samples is a prerequisite in order to provide a uniform plasma temperature and density. So far, these conditions can hardly be achieved with optical lasers or x-ray pulses. While optical laser pulses generate highly nonuniform plasmas, x-ray pulses from LCLS do not deplete enough of their pulse energy in low-Z targets like hydrogen. Accordingly, a very limited parameter space of hydrogen plasmas is accessible so far.

Using the XUV free-electron laser FLASH at DESY/Hamburg it was shown that femtosecond XUV pulses with pulse energies of 10-100 μJ are well suited for isochoric heating of micrometer-sized hydrogen plasmas [Fäustlin2012] so that a wide range of temperatures can be reached. In addition, plasma temperatures and densities have been retrieved using XUV pulses and Thomson scattering [Zastrau2014]. Such XUV sources for isochoric heating should be applied in combination with nanosecond lasers for shock compression and x-ray lasers as a plasma diagnostics for measuring the EOS of hydrogen and deuterium over a wide parameter range.

In recent years, intense XUV and soft x-ray pulses have been generated by the relativistic interaction of laser pulses with a solid surface [Dromey2006, Thaury2007]. This process is often described by a relativistically oscillating mirror (ROM) that efficiently converts the laser pulse into XUV and soft x-ray pulses [Tsakiris2006]. In this process, the high frequency radiation is generated due to the relativistic Doppler effect at the time when the surface moves towards the incident laser with relativistic velocity in each laser cycle. Accordingly, a train of attosecond and even zeptosecond pulses can be generated which corresponds to high harmonics in spectral domain [Gordi2004]. For relativistic laser intensities, the generation process can be highly efficient leading to 10-100 μJ per harmonic using Joule-class laser systems [Roedel2012]. These XUV and soft x-ray pulses are suited for the isochoric heating of warm dense hydrogen plasmas and have to be provided with high stability [Bierbach2012] and high repetition rate [Bierbach2015] in order to conduct high precision experiments.

For the envisaged studies, a high power laser system is required that can operate at a repetition rate that should be comparable to state-of-the-art free-electron lasers. Consequently, a 100 TW laser system with a repetition rate in the order of 100 Hz is required. Moreover, relativistic surface high harmonic generation necessitates very high pulse contrast, which means that techniques such as cross-polarized wave, plasma mirrors and nonlinear filtering have to be applied. In order to generate even keV pulses with mJs of pulse energy, ultra-relativistic intensities must be accomplished using a PW-class laser system (1Hz).

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

XUV and soft x-ray pulses from relativistic plasma surfaces can have a decisive impact for the experimental investigation of warm dense hydrogen and deuterium plasmas over a wide parameter space. These studies may further enable the measurement of the electron-ion equilibration time and the alpha particle stopping in warm dense matter [Edie2013]. Such experiments are essential for the validation of theoretical models of warm dense matter and can advance research in laser fusion.

In addition, the generation of extremely intense XUV and soft x-ray pulses using relativistically oscillating mirrors and PW-class laser systems can result in high frequency radiation of unprecedented peak power [Dromey2009]. Such photon sources have been discussed for testing theories such as nonlinear quantum electrodynamics (NQED) [Bulanov2010]. In this regime of ultra-strong fields, the generation of pairs and vacuum birefringence has been predicted.

The generation of bright XUV and soft x-ray pulses by relativistically oscillating mirrors can lead to further scientific applications. The bright attosecond pulse sources can be used for nonlinear ionization of atomic and molecular systems [Takaha2013]. Due to the broad bandwidth of the generated radiation, applications such as sub-surface imaging [Fuchs2012] and near-edge x-ray absorption spectroscopy [Koning1988] can be applied for the investigation of nanometer structures and materials.

In combination with x-ray free-electron lasers, relativistically oscillating plasma surfaces can further have significant scientific application. When the laser is irradiating the surface in oblique incidence, a plasma grating is formed on ultra-fast time scales. Such plasma gratings can, for instance, be used for the ultrafast switching of x-rays. Moreover, the diffraction pattern of the x-rays will allow the determination of the spatial and temporal structure of the electron motion at the surface. This could lead to a deeper understanding of laser absorption and the attosecond dynamics of laser surface interaction.

References (Maximum 1 page)

[Frontiers] Frontiers in High-Energy-Density Physics: The X Games of Contemporary Science, 2003 (http://www.nap.edu/catalog.php?record_id=10544)

[Vinko2012] Vinko, S. M., et al. "Creation and diagnosis of a solid-density plasma with an X-ray free-electron laser." Nature 482.7383 (2012): 59-62.

[Fletcher2015] Fletcher, L. B., et al. "Ultrabright X-ray laser scattering for dynamic warm dense matter physics." Nature Photonics 9.4 (2015): 274-279.

[Fäustlin2010] Fäustlin, R., et al. "Observation of ultrafast nonequilibrium collective dynamics in warm dense hydrogen." Physical review letters 104.12 (2010): 125002.

[Zastrau2014] Zastrau, U., et al. "Resolving ultrafast heating of dense cryogenic hydrogen." Physical review letters 112.10 (2014): 105002.

[Dromey2006] Dromey, B., et al. "High harmonic generation in the relativistic limit." Nature physics 2.7 (2006): 456-459.

[Thaury2007] Thaury, C., et al. "Plasma mirrors for ultrahigh-intensity optics." Nature Physics 3.6 (2007): 424-429.

[Tsakiris2006] Tsakiris, G. D., et al. "Route to intense single attosecond pulses." New Journal of Physics 8.1 (2006): 19.

[Gordi2004] Gordienko, S., et al. "Relativistic Doppler effect: Universal spectra and zeptosecond pulses." Physical review letters 93.11 (2004): 115002.

[Roedel2012] Rödel, C., et al. "Harmonic generation from relativistic plasma surfaces in ultrasteep plasma density gradients." Physical review letters 109.12 (2012): 125002.

[Bierbach2012] Bierbach, J., et al. "Generation of 10 μW relativistic surface high-harmonic radiation at a repetition rate of 10 Hz." New Journal of Physics 14.6 (2012): 065005.

[Bierbach2015] Bierbach, J., et al. "Long-term operation of surface high-harmonic generation from relativistic oscillating mirrors using a spooling tape." Optics express 23.9 (2015): 12321-12327.

[Edie2013] Edie, D.J., et al. "α-particle stopping and electron-ion energy relaxation in highly compressed ICF fuel." EPJ Web of Conferences 59, 05018 (2013)

[Dromey2009] Dromey, B., et al. "Diffraction-limited performance and focusing of high harmonics from relativistic plasmas." Nature Physics 5.2 (2009): 146-152.

[Bulanov2010] Bulanov, S. S., et al. "Schwinger limit attainability with extreme power lasers." Physical review letters 105.22 (2010): 220407.

[Takaha2013] Takahashi, E. J., et al. "Attosecond nonlinear optics using gigawatt-scale isolated attosecond pulses." Nature communications 4 (2013).

[Fuchs2012] Fuchs, S., et al. "Optical coherence tomography using broad-bandwidth XUV and soft X-ray radiation." Applied Physics B 106.4 (2012): 789-795.

[Koning1988] Koningsberger, D. C., and Roelof Prins. "X-ray absorption: principles, applications, techniques of EXAFS, SEXAFS, and XANES." (1988).

Figures (maximum 1 page)

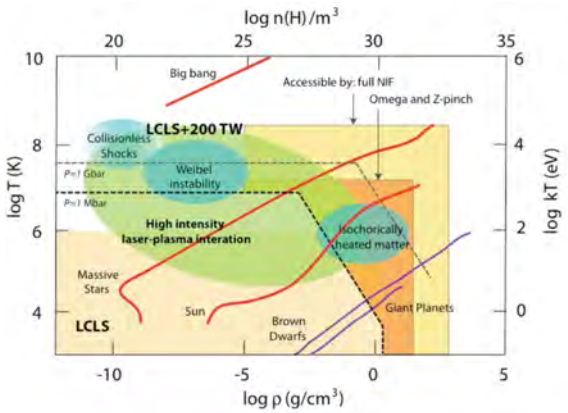

Fig. 1 Scheme of the phase space of hydrogen plasmas: Isochorically heated dense hydrogen plasmas as they are found, e.g., in giant planets, brown dwarfs and stars are accessible using intense soft x-ray pulses.

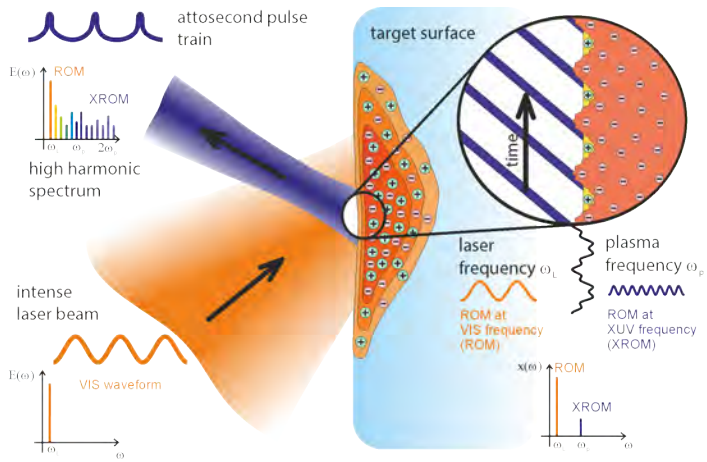

Fig. 2 Attosecond pulse generation using Relativistically Oscillating Mirrors (ROM): While the laser pulse is reflected from the plasma surface, the laser field drives a relativistic oscillation of the plasma surface. The reflected laser field is thus strongly modulated in time domain leading to an attosecond pulse train in specular direction. In spectral domain, high harmonic radiation is generated.

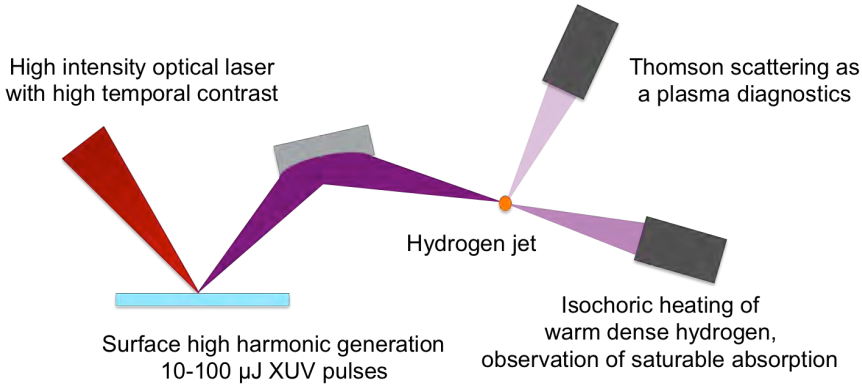

Fig. 3 Schematic of a proposed experiment: Intense soft x-ray pulses are generated at the surface. They are refocused into a jet of deuterium or hydrogen thus enabling isochoric heating of micrometer-sized samples.