White Paper for *Frontiers of Plasma Science Panel*

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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	P
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	Pump-probe studies of Warm Dense Matter and High Energy Density Plasma using ultrashort THz/optical/X-ray radiations
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(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.**

Ultrafast pump-probe studies have been used to gain fundamental understanding of Warm Dense Matter (WDM) and High Energy Density Plasma (HEDP) by pumping and probing these important matter states using different methods [1-3]. In the past, the majority of the studies have used optical pumping and probing [1]. But with the availability of XUV and X-ray free electron lasers, studies using XUV/X-ray probing and pumping are now possible [4]. After decades of being referred to as the terahertz (THz) gap, THz radiation is now routinely used in spectroscopic and imaging applications. However, only one study [5] has been reported using THz radiation to investigate the properties of WDM/HEDP. Recently, very high optical-to-terahertz energy conversion efficiencies of >1 % have been reported using lasers with wavelengths at above 1 micron [6-9] and around 0.1% using a Ti:Sapphire laser with wavelength at 0.8 micron [10]. In addition, laser based THz sources using semiconductor crystals [7], organic crystals [9] and plasmas [11] can cover a wide spectral range from a fraction of a THz to above ten THz. These sub-picosecond THz pulses typically consist of a single cycle of electric field. One application of THz radiations in WDM/HEDP is use them to obtain electrical and the related thermal

conductivities which are very important parameters. For example it is speculated that the uncertainty in thermal conductivity in the WDM regime could lead to the observed hydrodynamic mixing in ignition experiments at NIF being significantly larger than predicted by model calculations [15, 16]. Currently, there are uncertainties in electric conductivity in the WDM regime. As shown in Figure 1, there can be large discrepancies in dc electrical conductivity calculations among models. THz probing can measure electrical conductivity near dc value and can provide the much needed data for benchmarking dc conductivity calculations. In addition, the THz probing can be used to study the dynamics of ionic system in WDM/HEDP. Finally, high intensity THz radiation may be generated using PW class laser systems. High intensity THz radiation as pump potentially may be applied to excite directly the motions of ionic systems, which is distinctly different from optical pumping which excite electrons. For example a solid density polyimide WDM with ion temperatures of few eV potentially may be created by depositing the THz radiation in the ionic system directly. The ability to excite ionic system directly could lead to a lot of interesting physics

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

Figure 2 is a schematic diagram which illustrates the setups for the generation of ultrafast THz radiation and for obtaining electrical conductivity of Warm Dense Gold near dc value. The data can provide the much needed data for benchmarking dc conductivity calculations. Unprecedented high quality dc conductivity data can be obtained by using a laser system with high repetition rate. The temporal profile of the dc electrical conductivity at a given excitation energy density is constructed from multiple laser shots with different time delays between the pump and the probe beams. The error bar of the data at a given recording time can be significant reduced when large number of shots is taken.

Optical lasers and XUV/X-ray free electron lasers have already significantly advanced the fundamental understanding of WDM/HEDP. The high x-ray brightness properties of LCLS allow high-precision x-ray measurements that provide time resolved measurements of structure evolution, densities and temperatures of optical or x-ray created WDM/HEDP. These studies can take advantage of the multiple-color probing capabilities of the upcoming LCLS-II to resolve the evolution of the properties during pump excitation. LCLS-II's 10 – 25 keV hard X-rays allow the investigation of the dynamics of inner core electrons of high-Z WDM/HEDP. The current 200 TW laser and the proposed PW laser at the MEC can also be used to generate sub-10-fs betatron x-ray for pump-probing studies of WDM/HEDP [18]. Combining the THz technique with the ultrashort optical and x-ray techniques will provide a "dream" set of pump-probe tools for scientists and it will lead to important scientific discoveries in years to come.

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

The proposed ultrashort THz pump-probe technique for investigating WDM and HEDP can be implemented at SLAC and other similar facilities in the world . When it is combined with the optical and

x-ray techniques at LCLS/LCLS-II-PW they will provide a comprehensive pump-probe experimental platform using ultrashort electromagnetic waves from a large frequency range from THz to X-ray for advancing our fundamental understanding of WDM/HEDP. The knowledge gained will significantly impact many scientific and technological areas including better understanding of our Universe and providing detailed scientific knowledge for fusion energy technologies.

References (Maximum 1 page)

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Figures (maximum 1 page)

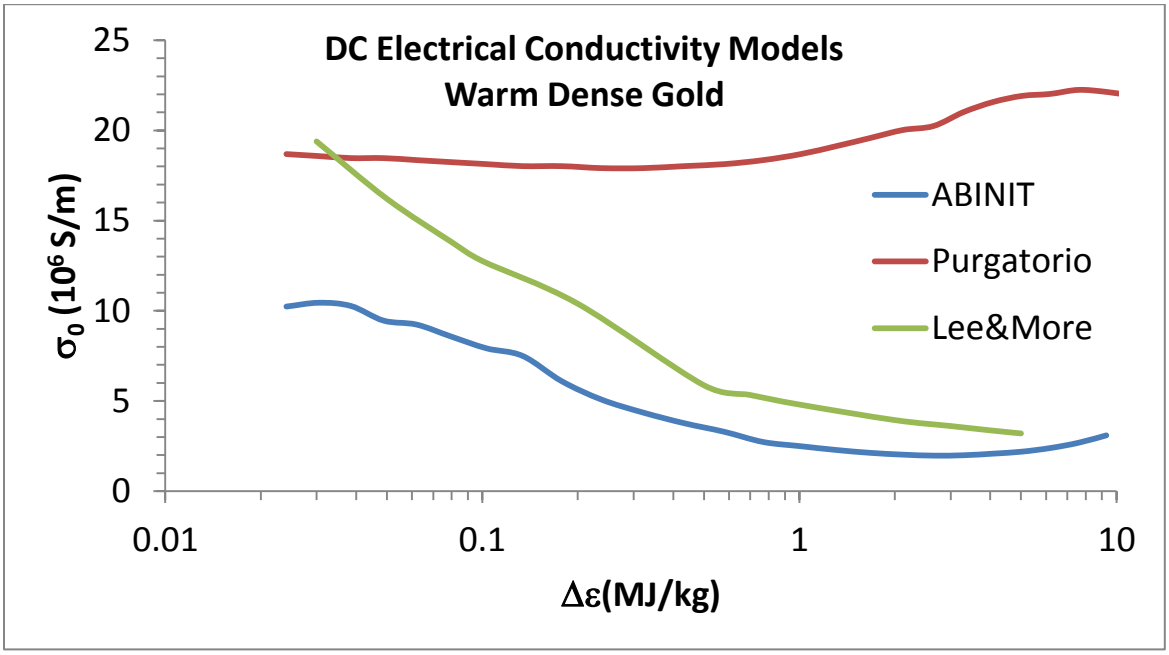

Figure 1. DC electrical conductivity of ultrashort laser generated solid density Warm Dense Gold [1] from various model calculations (blue line: ABINIT [12], red line: Purgatorio [13], green line: Lee & More [14]). Significant disagreements exist among models. THz probing will provide the much needed data for benchmarking these and other dc conductivity calculations.

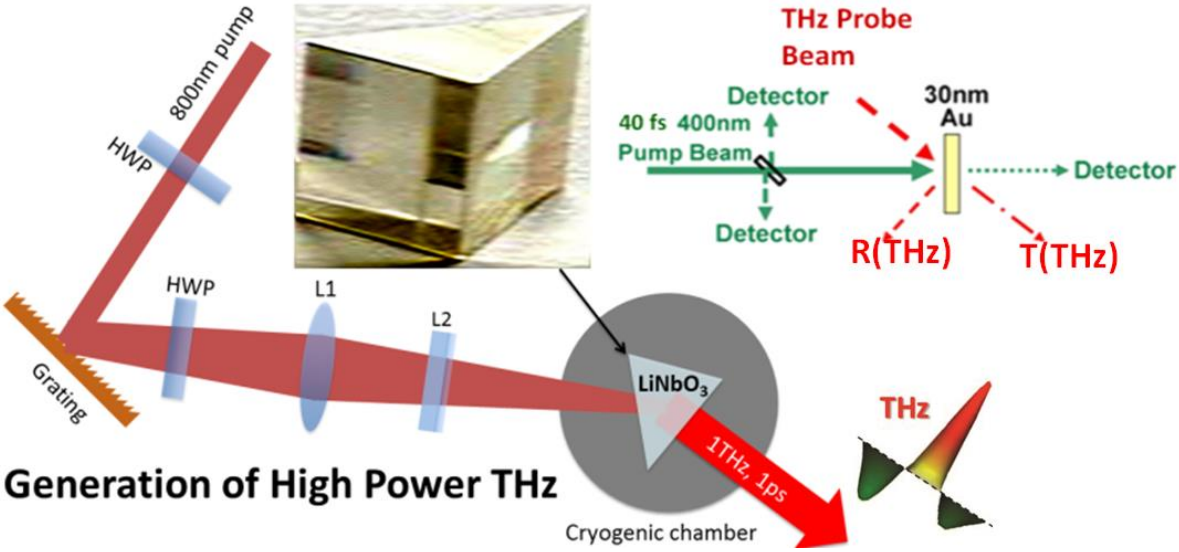

Figure 2. Schematic diagram illustrating the setups for the generation of high power THz radiation and for obtaining dc electrical conductivity of ultrashort laser generated solid density Warm Dense Gold.