White Paper for *Frontiers of Plasma Science Panel*

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	"X"
Oral	X
Poster	
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Title:	Extreme chemistry and the properties of warm dense matter
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- ***Research frontier and importance of the scientific challenge.***

Warm dense matter (with pressures >0.1 Mbar, and temperatures of ~1 to a few eV) is ubiquitous in nature, e. g. in the cores of large planets, and also present as a transient state in many laboratory and industrial settings, where energy is focused into materials at high rates, e. g., in processes driven by lasers, electron and ion beams. The properties and kinetics of warm dense matter have been studied for many years and recent advances in technologies to create and diagnose transient states of warm dense matter have seen rapid advancements. Yet, our understanding of the equations of state of warm dense matter is quite limited, as is our ability to steer and control the kinetics of phase transitions and the evolution of warm dense matter.

We see an exciting opportunity to expand our understanding and ability to control matter through advances in forms of extreme chemistry. One intriguing challenge is to first excite a transient warm dense matter state, track and direct its evolution and then quench the material to stabilize novel materials phases. Formation of novel materials phases has been achieved at high pressures and relatively moderate temperatures (e. g. using diamond anvil cells and heating with lasers to a few thousand degrees). Building on recent advancements and enabled by rapidly emerging tools to drive materials into transient warm dense matter states, together with advancements in diagnostics capabilities, modeling and cross fertilization with novel capabilities from fields such as nanotechnology and microfabrication, we believe that important discoveries in the fundamental nature of materials in the warm dense matter regime will become possible in the next five to ten years. This will advance our fundamental understanding of materials and enable the control of the evolution of materials into novel phases, some of which we will be able to stabilize for *ex situ* studies and to take advantage of unique new and tailored properties of materials (e. g. optical, coherence and mechanical properties).

- ***Approach to advancing the frontier and new research tools or capabilities that are required.***

Advancing the frontier of extreme chemistry and our understanding and mastery of warm dense matter requires further refinement and development of tools that enable us to drive materials into transient warm dense matter states, tools to diagnose the evolution of materials through phase transitions, as well as theoretical and computational tools to define experiments and to interpret experimental results. We see the following concrete directions for the advancement of drivers. Please also see the accompanying white papers from LBNL and from J. Barnard et al., LLNL.

Excitation of warm dense matter can be accomplished with intense, short pulses of optical photons, x-rays, electrons or ions, where there are many complementary characteristics in energy deposition profiles, time structure as well as availability that need to be carefully selected for specific experimental studies. Rapidly emerging advances in fs-laser technology have led to photon irradiances well above 10^{20} W/cm^2, allowing experiments in laser-ion acceleration with high repetition rate and high contrast (see accompanying white paper by W. Leemans et al. on the BELLA-i initiative at LBNL). This is exciting as ion pulses formed under these conditions will have multi-MeV/u kinetic energies for heavy ions and well over 100 MeV for protons. With these ion pulses we can heat matter uniformly over target thicknesses of tens of microns, and relatively large, 100 micron-scale areas, driving samples to temperatures of a few tens of eV and Mbar pressures. Heating of materials to warm dense matter states has been demonstrated over ten years ago with intense laser accelerated proton pulses from transverse normal sheet acceleration [1]. Now, pulsed (heavy) ion beams from laser-ion acceleration in novel acceleration regimes such as radiation pressure acceleration [2] are bound to mature into a routine tool for precision studies of warm dense matter and extreme chemistry.

In parallel, advances in accelerator technology have made intense (sub)-ns pulses of ions available at NDCX-II, the neutralized drift compression experiment at Berkeley lab [3]. Here, the benign radiation environment and highly reproducible shots with narrow ion energy spread enable the mapping of warm dense matter properties around 1 eV. Further, the combination of increasingly more reliable drivers with nano-engineered targets (e. g. containing nanocrystals in a selected matrix) and micron-scale patterning can enable systematic studies of materials synthesis under conditions of extreme chemistry.

One example is the formation of nitrogen-vacancy color centers in diamond, which was recently shown to result from ps and nm-scale heating of diamond by swift heavy ions [4], where simulations show a transient temperature spike to 0.5 eV.

- Is it possible to locally drive materials to a warm dense matter state and steer the materials evolution to the formation of novel phases e. g. in semiconductors [4], complex oxides [see e. g. 5] and metal alloys ?

- Can we diagnose these phases *in situ* and can we stabilize them through rapid quenching, enhanced by micro- and nano-structuring of targets?

- Can we steer the flow of energy and the resulting materials kinetics with control over the degree of electronic excitation, direct coupling to the sample lattice through elastic collisions and with selected pressure gradients from structured targets?

- Can we design experiments to simulate astrophysical impact phenomena and states in the core and core-mantel transition regions of planets?

Rapidly evolving diagnostics techniques such as ultra-fast electron diffraction or probe beams derived from laser-plasma interactions can enable multi-scale *in situ* tracking of materials evolution. For warm dense matter states driven by laser – ion acceleration, the high degree of finesse in laser control will allow us to derive high quality probe beams from (multi)-PW drive lasers (see white paper by C. Geddes et al.). This will be an exciting development as near perfect synchronization of e. g. betatron x-rays or proton pulses with the main ion pulse will provide exquisitely precise tools to track the evolution of warm dense matter in a relatively compact setup, complementary to, e. g., x-ray sources based on free electron lasers (FEL) with unmatched brightness, or long pulse lasers with ultra-high energy but often limited beam-time access.

Open access to user facilities with complementary capabilities that provide high quality beams, targetry and diagnostics will enable a vibrant user community to rapidly advance the fields of warm dense matter research and extreme chemistry.

- ***Impact of this research on plasma science and related disciplines and potential for societal benefit.***

The traditional impact areas of warm dense matter research are planetary science, the scientific underpinning of potential future inertial fusion energy, and inertial confinement fusion. While tremendous progress has taken place in the last decade, these remain fascinating frontiers with rapidly evolving opportunities, e. g. in planetary science with the vast expansion of data on exo-planets and associated questions regarding the formation and evolution of planets.

With advancements in driver technology in complementary approaches, including x-ray FELs, long pulse high energy lasers, laser-ion acceleration with (multi)-PW lasers and intense, pulsed ion beams from accelerators [3, 6] we will be able to produce warm dense matter more reliably and in quantities that enable more accurate and precise measurements. Combining advanced drivers with advances in targetry, where we can now take full advantage of micro- and nanofabrication methods that have matured in the last decade, we see great impact potential in the area of extreme chemistry and materials synthesis far from equilibrium.

Progress in our fundamental understanding of warm dense matter and its kinetics will very likely lead to advances in extreme chemistry and the synthesis and stabilization of novel materials phases with high impact potential in areas such as fusion and fission reactor materials, novel detectors, advanced structural materials and materials with tailored optical and coherence properties for applications in diverse fields of basic and applied science and technology.

References

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