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.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	S
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• Plasma self-organization	
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	"X"
Oral	X
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Title:	To measure and model the properties of warm dense matter
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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.**

Warm dense matter (WDM) lives literally at the frontier of plasma science. Bridging the gap between plasma and condensed matter, WDM shares properties of both. Indeed its density is similar to that of the solid, yet its temperature is on the order of 1 eV. WDM, making up the core of giant planets, is key to understanding the formation of gaseous giants[1,2] and Mega-Earths[3] as well as the dynamics of planetary collisions[4]. It is a transitional state during the compression of inertial fusion targets driven by x-ray. Yet, the quantum properties of WDM and how they are expressed at the macroscopic level are mostly unknown.

This scientific no-man's land results from little experimental data and inadequate physical models available. Indeed there exist enormous challenges in unraveling the properties of WDM. The experimental challenges in measuring WDM properties rest with:

- the difficulty in producing uniform WDM samples;
- the presence of other physical states inside WDM samples;
- the requirement of using bright and intense x-ray sources to penetrate and diagnose WDM.

A plethora of theoretical challenges impedes rapid advances in modeling WDM. For instance:

- well established theories such as plasma and condensed matter physics do not apply to WDM;
- perturbation theory fails to capture the non-adiabatic nature of WDM produced in the laboratory;
- even if the very nature of WDM can be fully captured by quantum mechanical theory, only macroscopic methods can be used in practice to model the evolution of large systems.

These challenges clearly show the wealth of exciting discoveries awaiting scientists working in WDM research, a field truly at the frontier of plasma science. Despite the many hurdles awaiting physicists, this white paper condenses the experimental and theoretical challenges previously listed into two distinct grand challenges:

1. *Can we design a robust, experimental research platform capable of generating high quality WDM samples and diagnose them with great precision?*
2. *Is it possible to develop macroscopic theories capable of capturing the microscopic, quantum nature of WDM and incorporate these theories into numerical simulations that can predict the static and dynamic behavior of large systems?*

The rest of this white paper identifies the present shortcomings in WDM research. It then discusses the near term and long term tasks required to address these shortcomings. Finally, it describes the necessary upgrades in existing facilities as well as diagnostics developments.

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

At the moment, most WDM samples are generated by heavy ion beams[5] (HIB), high power lasers[6] (HPL) or coherent light sources[7] (CLS). These techniques produce samples with sub-millimeter dimensions. They are difficult to diagnose due to limitations imposed by the geometrical size of the sample and the intensity of bright x-ray sources. The restrictive temporal, geometrical and/or spectral resolution of x-ray detectors remains the major bottleneck. Indeed the primary diagnostic of WDM is x-ray Thomson scattering[8], which requires both large, homogeneous samples, to maximize photon scattering, homogeneous samples, to make meaningful scattering measurements, and high detector sensitivity, to capture the few scattered photons. On the theory side, the most successful theoretical models rely on density functional theory[9] (DFT) or classical molecular dynamics[10] (CMD). However these theories are still bound to the microscopic realm and cannot be applied directly to larger, more complex systems.

The near-term tasks should leverage the existing facilities to improve the resolution and sensitivity of x-ray detectors, allowing the recording of scattered/absorbed x-ray spectrum with a much higher degree of precision. This task can be achieved with the present experimental platforms. While the interpretation of measurements may not allow for a detailed understanding of WDM properties, x-ray probing (e.g. Thomson scattering) techniques should gained in precision and resolution from the improvement of x-ray spectrometers and detectors. Concurrently, new research platforms should be developed to generate WDM. Standard experimental techniques (HPL, CLS) have reached their maximal capacity at producing small (sub-millimeter) WDM samples. Developing similar yet more energetic platforms to produce truly large (millimeter) WDM sample will prove to be costly. Near term research should focus on finding new experimental approaches to the production of WDM. For instance, numerical simulations have shown that large WDM samples can be generated by a pulsed-power machine (PPM) such as Z[11], using a plasma closing switch[12]. This scheme prevents the expansion of the sample (detrimental to the generation of a pure WDM state) by initially imposing a 10 MegaGauss magnetic field on the sample surface as the current starts to flow inside it. This scheme promotes compression only. Driving the sample directly with a PPM (i.e. without the plasma closing switch scheme) creates local expansion of the material, filling WDM with pockets of mixed states[13]. On the theoretical side, the near term tasks should focus on developing new theories and numerical techniques that can capture the nature of WDM at the macroscopic level (e.g. resistivity, heat conductivity, opacity). Rather than relying on computer power to

solve DFT or CMD on larger geometrical scales, theorists should devise techniques to incorporate the properties of WDM into MHD models. Since MHD conserve mass, momentum and energy, it seems possible to expand MHD theories into a new set of models able to capture WDM behavior, which also conserve mass, momentum and energy. A concrete example is the Desjarlais[14] modification of the Lee-More resistivity model[15], which improved the predictive capability of numerical codes.

The long term tasks would incorporate the x-ray sources, improved diagnostics as well as the new experimental platform into an existing (or brand new) facility. Ultimately the best platform to produce large WDM samples may not be the best platform to produce the intense x-ray source required to study WDM. This would require the merging of two facilities into one single entity devoted to the study of WDM. Since HPL or CLS are more expensive to build than HIB or PPM, it may be necessary to build a new HIB or PPM facility next to a HPL or CLS facility. This entity, dedicated to high energy density plasma (HEDP) research, would also be able to produce and diagnose WDM using techniques discussed in the near term tasks. Based on new and improve experimental measurements theorists should be able to determine which models capture best the properties of WDM.

As WDM research is still in its infancy, it is difficult to produce an exhaustive list of required upgrades to existing facilities. However, based on the discussion summarized in this white paper, increasing the energy of existing HPL and CLS is necessary to palliate the difficulties inherent to x-ray production and detection. If it can be demonstrated that large PPM can be used to produce WDM samples, this new addition to the WDM experimental portfolio will be transformational when coupled to a high intensity laser, which would allow x-ray Thomson scattering or proton radiography to probe WDM in great details. The development of warm (in the 50 keV range), bright x-ray sources will greatly improve Thomson scattering signals. In this area, both HPL and CLS can really shine. The development of other methods to produce warm x-ray sources should be undertaken. Finally, x-ray detector arrays with improved resolution and sensitivity have to be developed. Image plates[16] are a promising technology[17] which should be further pursued. Yet image plate measurements are time-integrated and parasitic x-ray burst can be recorded, de facto polluting the desired x-ray spectrum. An essential task in diagnostics improvement would focus on developing highly sensitive (i.e. active gain) time gated, high resolution x-ray detector. This improvement would alleviate many intensity requirements on bright x-ray sources.

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

The research in WDM will develop our knowledge of matter under extreme conditions, one of the last frontiers in modern physics. The experimental techniques to produce large size WDM, to accurately diagnose WDM and the physical models to capture the properties of WDM are yet to be developed. The research on WDM will reach far beyond its border:

1. The efficient, high energy density drivers required to produce WDM can be used to generate HEDP or to develop inertial fusion energy.
2. High resolution, high gain gated x-ray detectors are essential to WDM studies but are also indispensable to high energy physics or medicine.
3. The innovative physical models and numerical algorithms capable of predicting the properties of WDM will yield new physical paradigms which can find applications in statistical mechanics or solve other types of multi-body problems.

Ultimately, a more accurate grasps at the properties of WDM will help astrophysicists in understanding of the formation and evolution of exo-planets especially if WDM systems can be simulated using macroscopic models.

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