

WARM DENSE MATTER: ANOTHER APPLICATION FOR PULSED POWER HYDRODYNAMICS*

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Abstract

Pulsed Power Hydrodynamics (PPH) is an application of low-impedance pulsed power, and high magnetic field technology to the study of advanced hydrodynamic problems, instabilities, turbulence, and material properties. PPH can potentially be applied to the study of the properties of warm dense matter (WDM) as well. Exploration of the properties of warm dense matter such as equation of state, viscosity, conductivity is an emerging area of study focused on the behavior of matter at density near solid density (from 10% of solid density to slightly above solid density) and modest temperatures (~ 1 -10 eV). Conditions characteristic of WDM are difficult to obtain, and even more difficult to diagnose. One approach to producing WDM uses laser or particle beam heating of very small quantities of matter on timescales short compared to the subsequent hydrodynamic expansion timescales (isochoric heating) and a vigorous community of researchers are applying these techniques.

Pulsed power hydrodynamic techniques, such as large convergence liner compression of a large volume, modest density, low temperature plasma to densities approaching solid density or through multiple shock compression and heating of normal density material between a massive, high density, energetic liner and a high density central "anvil" are possible ways to reach relevant conditions. Another avenue to WDM conditions is through the explosion and subsequent expansion of a conductor (wire) against a high pressure (density) gas background (isobaric expansion) techniques. However, both techniques demand substantial energy, proper power conditioning and delivery, and an understanding of the hydrodynamic and instability processes that limit each technique.

In this paper we will examine the challenges to pulsed power technology and to pulsed power systems presented by the opportunity to explore this interesting region of parameter space.

Introduction

Pulsed Power Hydrodynamics (PPH), and the underlying pulsed power and megagauss magnetic field technology provide access to extreme conditions of pressure and temperature. The technology, has been applied to the study of hydrodynamics and material properties under extreme conditions over the last decade.

Pulsed power techniques offer access to an energy-rich environment that enables experiments that are larger in scale than laser experiments and generally more precise, flexible, and certainly more easily controlled than are similar high explosively powered hydrodynamic experiments. While the precision and controllability of gas-gun experiments is well established, pulsed power techniques using imploding liner offer access to convergent conditions, difficult to obtain with guns – and essential to many of the highest energy density and to many advanced hydrodynamics investigations[1],[2],[3].

Computational modeling and numerical simulation, is, increasingly, replacing empirical investigation in many fields of high energy density research. Experimental techniques that allow for economical experiments that can be repeated frequently enough to generate useful data sets can provide important opportunities for motivating, developing, and validating extended, or new, computational models that describe material equation-of-state, constitutive properties, and the behavior of materials and systems, at high energy density; and in complex hydrodynamic configurations.

Warm Dense Matter

While theoretical understanding and description of the behavior of condensed matter (in solids at normal density and in compressed solids at temperatures below 1 eV) is a well established, and reasonably advanced, field of study, and while the situation is similar for low and medium density plasmas at elevated temperatures (above 10 eV), there is a intermediate, or transitional state of matter, that is warmer than traditional condensed matter, but cooler and more dense than traditional plasmas. Material in this transitional state cannot be adequately described by traditional plasma, condensed matter or solid state theories. These conditions, called warm-dense matter (WDM), involve densities that range from moderately expanded, that is below normal density, to moderately compressed (a few times normal density) and temperatures that are above the fractional-eV temperatures encountered in single shocks up to 50 eV implying partial, but not complete, ionization. These WDM conditions also imply an opportunity for additional ionization or recombination processes to play a strong role in the behavior of the ensemble as thermodynamic

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conditions change. As the density of a traditional plasma increases, inter-particle potential interactions become significant compared to thermal interactions, and the traditional concepts of Debye shielding begin to break down. The plasma gamma (Γ), which describes the ratio of potential to thermal energy lies between one-tenth and about 50 in the warm-dense matter regime (compared to much lower values in traditional plasmas). For warm-dense matter above normal density, the contribution of electron thermal energy becomes increasingly important until it becomes the dominant physical process for hot matter. Practically, warm-dense matter is found in the core of gas- giant planets, and perhaps, more importantly in the description of any plasma system that begins in the solid state and evolves into a (more traditional) plasma – such as exploding wires and electrically exploded conductors.

Understanding the detailed properties of warm-dense matter is a challenging physics problem, in part because the detailed properties of warm-dense matter are, simultaneously, difficult to access experimentally and difficult to model theoretically. By some standards there is no generally accepted theoretical treatment for the interesting regime:

Densities: $1\% < \rho < 2X$ normal density
Temperature: $1 \text{ eV} < T < 50 \text{ eV}$

Tabular EOS data bases such as the widely used Sesame data base from Los Alamos address this region by interpolation between theories in adjacent regions. Figure 1 shows some of the theoretical models that can be successfully applied in adjacent regions, such as the Saha model. The Saha model which adequately

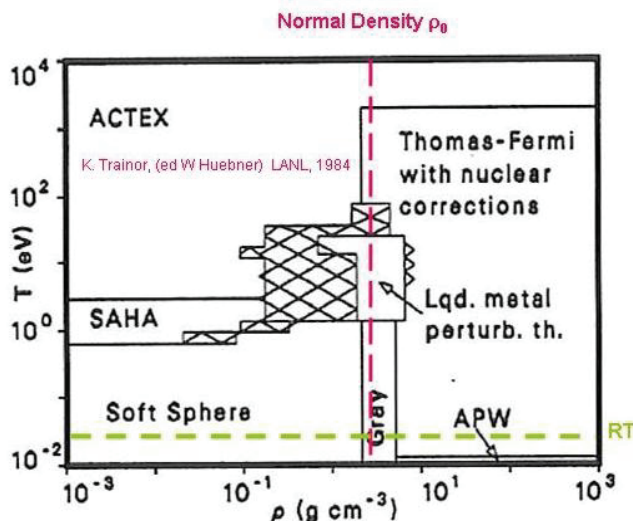


Figure 1. Conditions from 10% normal density to 3-5 times solid density at temperatures of 1-50 eV is termed Warm Dense Matter. No single theoretical treatment describes material behavior in this regime. Tabular treatments frequently interpolate between theories to span WDM parameters. Parameters are for aluminum

describes partially ionized plasmas at temperatures around a few to 10 eV, breaks down at high density where inter-particle collisions (material pressure) begins to significantly influence the ionization state of the material. Thomas Fermi models, adequate at the highest temperatures and pressure, fail to adequately describe the complex physics present at lower temperatures. [4]

Experimental data in this region, even for reference materials such as aluminum is sparse to non-existent owing, in part, to the difficulty of producing the appropriate conditions and equally to the difficulty in diagnosing its behavior.

Experimental Techniques to Produce Warm Dense Matter

In the experimental world of 2007-2009, a variety of experimental venues are being explored, to a greater or less degree, to gain access to limited parts of the WDM parameter space including:

- Isochoric heating by ultra-short pulsed laser, and short pulse particle beams
- Isobaric expansion of ohmically heated wires confined by compressible medium
- Isobaric expansion of ohmically heated wires confined by magnetic fields
- PdV compression of conventional plasma
- Shock compression of a lower density plasma.
- Liner/shock compression of solid density material.

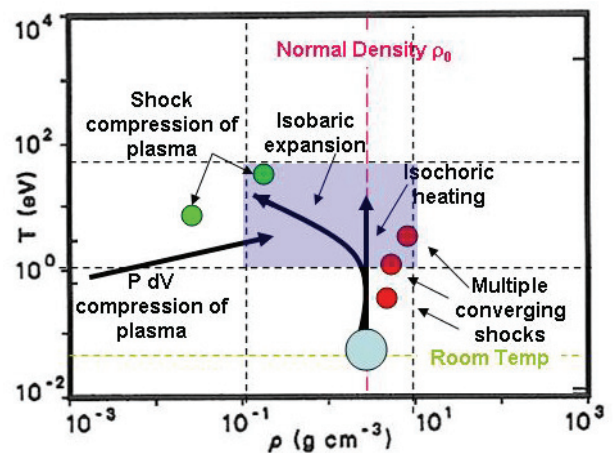


Figure 2. From normal density and temperature, the warm dense matter regime is accessible by rapid heating at constant volume (isochoric), or slower heating with controlled expansion against a confining gas (magnetic field) at nearly constant pressure (isobaric). The regime can possibly be reached by large volume compression of a conventional plasma or by shock heating and compression of a conventional plasma. Multiple shock heating coupled with volumetric compression can be applied to reach compressed states.

Trajectories in temperature/density of several paths to produce WDM are shown in Figure 2. Additional experiments, fielding of additional diagnostics, improvements in select, existing diagnostics and improved theory and simulation will all be needed to advance the current state of understanding. The pulsed power community, with its energy-rich technology, and its relationship with both the traditional plasma and traditional condensed matter communities can take an important role – in theory, simulation and experiment.

A. Isochoric heating: Isochoric heating techniques employs fast visible lasers, free electron lasers or particle beam sources to rapidly heat material at constant density. In general, the nature of the driver (particle energy or photon frequency) and the target material set the absorption range. The target thickness then emerges from need to efficiently absorb incident energy, but to do so with adequate uniformity (using, for example, 30% of the incident beam energy.) Pulse length (and hence the beam power) requirements are set by need to deliver energy faster than hydrodynamic expansion can allow the target to expand. In general, these criteria imply very fast, very high power sources and place very high time resolution requirements on the diagnostics. Converting beam energy to x-rays introduces cost in conversion efficiency but similarly introduces savings by increasing absorption range and allowing the use of larger targets.[5], [6]

B. Isobaric expansion: Building on techniques pioneered in Russia at the Institute of High Temperature in Moscow[7] and pursued later in the US[8],[9], beginning in 1980's, isobaric (constant pressure) expansion techniques have successfully explored properties at the low temperature edge of the WDM

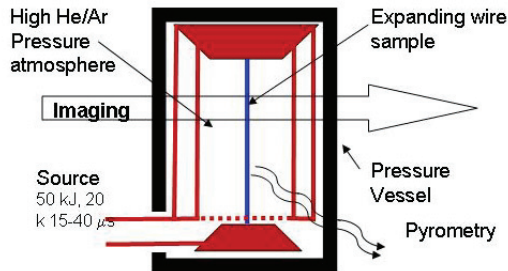


Figure 3. Schematic of an isobaric expansion experiment in high pressure gas. A wire, ohmically heated on 10's of microseconds time-scale, expands against the background, maintaining a nearly constant density profile. Electrical measurements determine conductivity. Simple radiography determines radial expansion, and hence density, while confirming minimal density gradients. Radiometry can determine temperature. A sound speed measurement can be envisioned by launching a laser produced shock across the expanded WDM column.

regime for materials under-going moderate expansion. As shown in Figure 3 in this technique, an ohmically heated wire expands against high pressure (2-400 MPa) gas atmosphere relaxing to a nearly uniform density column at 10-50% solid density. Typically a sub-millimeter diameter wire is exploded with 20-50 KJ of energy at 100-300 KA and 14-50 μsec timescales. Surface breakdown is suppressed by the high pressure atmosphere thereby ensuring that the heating energy is delivered to the bulk of the wire, and the long timescale coupled with small diameter wire helps ensure semi-uniform heating. Electrical measurements record power and energy delivered to the sample, and therefore can be used to deduce average conductivity as well. Radial expansion is measured radiographically or with shadowgraphy. Pyrometric temperature measurements complete the data needed to allow evaluation of thermodynamic properties.

C. Wire Expansion against a Megagauss Field: While vaporizing and slowly expanding a metal column (wire) against a gas background produces a reproducible column of Warm Dense Matter the column is at the lower end of the range of temperatures of interest. More rapid heating, to achieve a higher temperature necessarily produces substantially higher pressures in the column.—Such pressures are too high to support with a gas prefill but can be supported by a magnetic field. A “post” experiment on the Zebra pulser at Univ. of Nevada, Reno initially designed to explore the production and evolution of the surface plasma produced when 4 MG fields are supported on a metal surface, also produces a relatively uniform column of WDM surrounded by a hot corona. Conditional calculations by Garanin and Kuznetsov of VNIIEF suggest that in addition to the hot low density coronal plasma, the interior of the, initially, 1-mm diameter aluminum wire/post relaxes to a region of uniform temperature about 4 eV and 60% of initial solid density as shown in Figure 4. Detailed diagnostics of the coronal plasma, reported by Awe [10], compared with simulations increase confidence in evaluation of underlying column of warm dense matter.

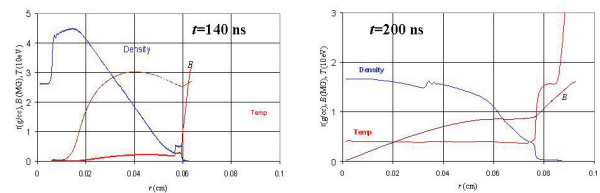


Figure 4. Conditional simulations of a mm diameter post rapidly (100ns) heated by a 1 MA current pulse shows the (delayed but) expected formation of a plasma on the surface as the magnetic field peaks at 3-4 MG. 60 ns later the inner core has relaxed to a nearly uniform density column at half solid density and 4-5 eV.

D) Shock compression of a lower density /temperature plasma: Under some conditions a lower density plasma can be heated and compressed with a very strong shock to produce a strongly coupled plasma (WDM). One example of such experiments is shown in Figure 5. This elegant, but complex, configuration has been explored using the LANL Trident Laser. In this experiment a short pulse laser beam (200 J, 1.2 ns) rapidly heats a low density foam target to above 1 eV. A second beam (40 J, 1.2 ns) drives a strong shock in the preheated target to both heat and compress the materials and yet a third beam illuminates a back-lighter target to produce x-rays which are used for quantitative radiograph to determine the density of the material after compression. To realistically constrain the models, density measurements made to an accuracy of 1% are needed and temperature measurements (from quantitative spectroscopy) to an accuracy of 10% are needed as well. To date initial temperatures of only 0.44 eV have been achieved, a steady shock has not yet been produced and other stringent requirements on the laser back-lighter have been identified. Clearly, more laser energy is needed for heating and shocking. Against this background, the advantages of the energy rich environments offered by pulsed power become apparent. [6]

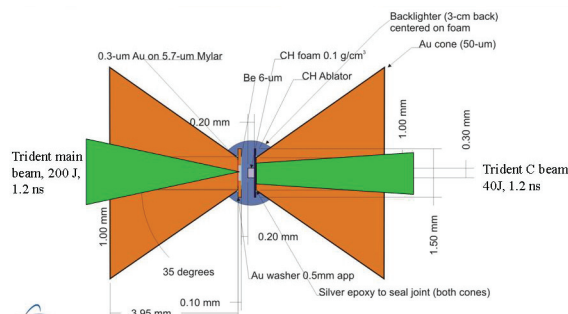


Figure 5. Schematic of a laser heated, shock compressed experiment to reach WDM conditions in modestly expanded material. A fast laser heats a foam target. A second laser pulse launches a shock in the material to compress the initially warm plasma. A third laser beam produces x-rays from a back-lighter target to quantitatively evaluate density. Spectroscopy yields temperature measurements.

E) Liner Implosion Techniques: Magnetically driven liner implosion techniques, compressing initially solid material, can convert many megajoules of liner kinetic energy into internal energy in the target. Over the last several decades, RFNC-VNIIEF initially, and, since 1992, joint VNIIEF/LANL teams have demonstrated techniques to deliver >20 MJ of kinetic energy using an imploding liner with impact velocities approaching 10 km/sec. These parameters require pulsed power sources delivering currents up to 100 MA

and the implementation of precision cylindrical liner implosion techniques.

In the conceptually simplest configuration shown in Figure 6, the liner-impactor stagnates at 2 cm radius against the outer surface of an, annular, centimeter thick target of sample material. To aid in achieving a relatively uniform

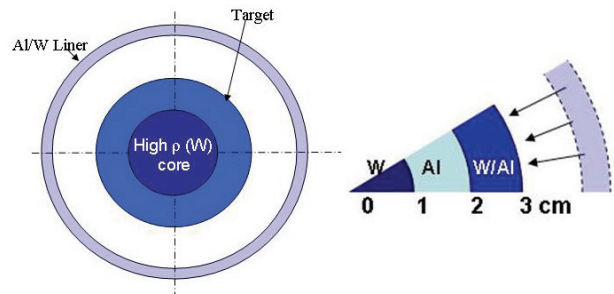


Figure 6. Computationally, a liner impacting an annular, normal density target at 10 km/sec with a high density (tungsten) cylindrical anvil in the center can produce a fairly uniform shell of WDM at densities 2-3 time solid for a matched liner or >4 time solid density for a high density liner. Energy densities of 1-1.5 MJ/cc (>1 eV)

density profile through the target, a 1-cm radius “core” of high density material (eg tungsten) occupies the volume from the center-line to the inner surface of the annular target at radius of 1 cm. The shock launched by the liner’s impact transits the target, but when the shock encounters a large discontinuity in acoustic impedance at the inner surface of the target, the shock reflects from that interface as a compression wave and further compresses the target on its outward radial transit. The same process can occur at the outer surface where the target meets the liner material. If the liner material is matched to the target material, the wave continues outward leaving a relatively uniform compressed target behind. If, on the other hand, the liner is a high density material a compressive shock is again reflected and directed inward, further heating and compressing the target.

Based on simple hydrodynamic simulations an aluminum liner impacting the target at 10 km/sec (approximately 2 MJ of kinetic energy per centimeter of liner height) compresses a (matched) Al target to 8 gr/cc (~3X normal density) and energy densities approaching 140 kJ/gr (>1MJ/cc) and maintains these conditions for several hundred nanoseconds. On the other hand, if the liner-impactor is tungsten, and the impact velocity is 10 km/sec (or about 14 MJ/cm), the multiple shock process compresses the Al sample between the tungsten liner and the tungsten core, reaching densities of 10 gr/cc (>4X normal) in the aluminum target and 150 kJ/gr (1.5MJ/cc). Temperature in the compressed target from one to a few eV are estimated, but while the energy density is relative clear, the ionization state in the WDM regime is

uncertain, hence number of particles (ions plus ionized electron) is uncertain that the distribution of the internal energy, and hence its interpretation as “temperature” is subject to the EOS model.

It is apparent from these elementary considerations that WDM conditions with $\rho > \rho_0$ can be produced with precision liner implosions. For a specified set of impact conditions: impact at a radius of 2 cm, velocity at impact of 10 km/sec and impactor thickness of 1 cm, a range of initial liner geometries (radii and thickness) can be employed. For acceleration with a simplified, step-function, constant current drive, larger initial radii with appropriately thinner initial liner thickness, implies three related conditions: longer implosion time, lower required current and lower peak accelerations as shown in Figure 7. Taken together these conditions imply that larger initial radii are to be preferred.

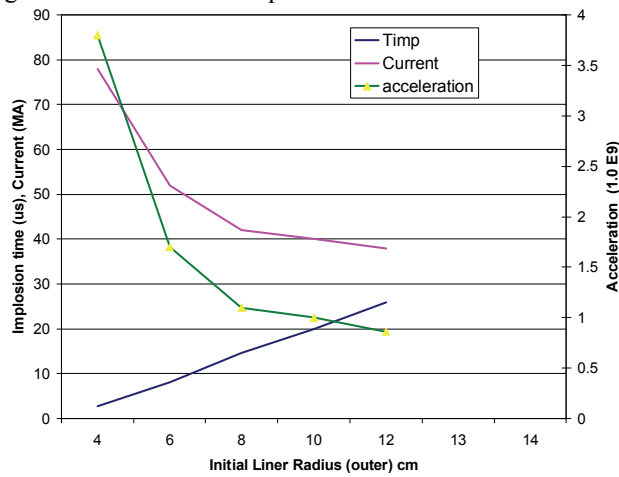


Figure 7: For specified impact conditions increasing initial radius requires lower driving current, longer time implosion time and results in lower acceleration.

However at current densities above 1 MA/cm (magnetic pressure of 62 KBar) a fluid, (melted) layer is assured at the metal/field interface, and for acceleration directed from the field containing region into the metal (implosion) that fluid/field interface is unstable in the Rayleigh Taylor (RT) mode with an Atwood number:

$$N_a = (r_2 - r_1) / (r_2 + r_1) = 1.$$

The well-known, time dependent growth of a single-wavelength periodic perturbation with wavelength $\lambda = 2\pi/k$ and initial amplitude A_0 , at a stratified interface undergoing constant acceleration, g , with uniform density, inviscid, fluids on each side is:

$$A(t) = A_0 e^{\sqrt{Na} k g t} = A_0 e^{\sqrt{2\pi Na} k g / \lambda t}$$

But under constant acceleration, the distance that the material (and the interface) travels, $S = \frac{1}{2} g t^2$ implies that:

$$\sqrt{gt} = \sqrt{2S}, \text{ and}$$

$$A(t) = A_0 e^{2\sqrt{Na} \sqrt{S/\lambda}}$$

Hence, large wave numbers, short wavelength, perturbations grow fastest. More detailed analysis shows that dissipative mechanisms, surface tension, material strength, or fluid viscosity preferentially reduce the short wavelength growth-rates and, indeed, for sufficiently short wavelengths, $\lambda < \lambda_c$, growth ceases.[11] Thus the longer wavelengths can grow to the largest amplitudes and wavelengths comparable to the liner thickness are generally the most disruptive.

The most significant source of initial perturbations are the departures from perfect smoothness and cylindricity introduced by fabrication. For modern high precision fabrication roughness, waviness and overall deviation from cylindricity, distortion can be described by:

Roughness: $A_0 = 0.1 \mu$, $\lambda = 25-100 \mu$

Waviness: $A_0 = \sim 2 \mu$, $\lambda = 1-3 \text{ mm}$

Distortion: $A_0 = 2-5 \mu$, $\lambda = 5+ \text{ mm}$

Realistically, liners are not imploded with constant currents, but generally are driven by waveforms characterized by a sinusoid or at least by risetime and peak value (followed by a fall time, perhaps significantly different than the rise time). Therefore the acceleration history, and hence the growth history of perturbations is more complicated. One example of perturbation growth history is shown in Figure 8 where perturbation amplitude is plotted as a function of time for a liner implosion driven by a sinusoidal current of 75 MA amplitude and about 7 microsecond quarter period. The liner initial radius is 7.6 cm, the thickness is 4.2 mm so that the liner has thickened to 10 mm when the inner surface arrives at 2 cm radius at approximately 10 km/second. The initial perturbation is amplitude is 0.25μ and the wavelength is 1 mm. By 5 microseconds, the amplitude of the perturbation has grown to about 1 mm, the liner is about 4.4 mm thick and the interface has moved 0.3 cm. However, in the next half-microsecond, if the growth is not inhibited by some dissipative mechanism it will grow to cm amplitudes, destroying the liner integrity before the liner can arrive at the target. The fact that experimental measurements show less growth suggests that dissipative mechanisms, such as strength in the unmelted part of the liner play a significant role in controlling the behavior, and give some hope of success in designing WDM experiments based on liner implosions.

The liner implosion approach to producing WDM environments is a good example of the application of the energy-rich aspects of pulsed power/high magnetic fields to problems in hydrodynamics and material properties. The practicality of such approaches depends, in part, on the maturity of the technology which produces very large

currents, and which uses those currents to produce very large amounts of implosion kinetic energy. Some examples from experiments over the last decade illustrate the status of the technology including the Ranchero system [12], the joint LANL/VNIIEF High Energy Liner (HEL-1) [13], and the joint LANL/VNIIEF ALT 1 and 2 experiments. [14]

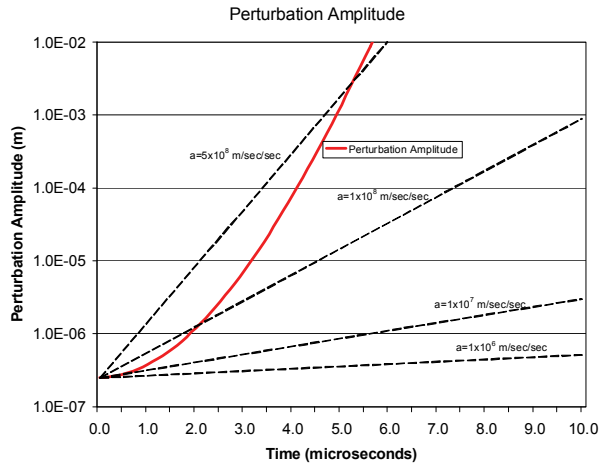


Figure 8 Time history of the growth of a 0.25 micron, 1 mm perturbation in a 7.6 cm radius 4.2mm thick liner imploded with a 75 MA sinusoidal current with quarter period of about 7 microseconds.

Summary

The pulsed-power community has, at its disposal, the energy-rich technology that can be applied to provide access to the elusive and challenging regime of Warm Dense Matter, producing the needed environments in macroscopic quantities; with high precision; good reproducibility; and to do so economically enough to provide useful data sets.

Once created, however WDM remains difficult to diagnose and creative efforts to refine, and indeed invent new diagnostics and new experimental approaches will be a significant issue – and a scientific challenge worthy of the community.

For Strongly Coupled plasmas: isobaric expansion techniques confined by high pressure gas environment give access to moderately expanded material at ~ 1 eV. Magnetic “Post” techniques permit access to similar densities at $T = \text{few eV}$.

For Compressed, Condensed Matter: Simple converging shock techniques can produce compressed densities of a few times solid density and internal energies of 10’s to 100 kJ/gram (100’s kJ to MJ per cubic centimeter), and temperatures of several eV.

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