The following draft summary on “Relativistic and Strongly Magnetized Plasmas” is adapted and condensed from a series of whitepapers written by participants of the May 2007 Laboratory Plasma Astrophysics Working Group (LPAWG) meeting (see http://spacibm.rice.edu/~liang/plasmawg/whitepapers). We have identified six major sub-topics representing some of the most promising frontiers at the interface of astrophysical and laboratory plasmas. The six subtopics are ordered according to their scientific merits and readiness for laboratory experiments.

1. Relativistic Collisionless Shocks

1.1 Astrophysics Context: Supersonic collisions of relativistic flows occur frequently in astrophysics and the resulting shock waves are believed to be responsible for the observed radiation of pulsar wind nebula (PWN), Gamma Ray Bursts (GRB), some AGN jets, and production of high-energy cosmic rays. In addition to the dissipation of bulk flow energy, these shocks accelerate nonthermal particles and generate/amplify magnetic fields. Despite recent progress in 3-D computer simulations, the physics of such shocks and the resultant particle acceleration and magnetic field generation are not fully understood. The ability to perform relativistic shock experiments in the laboratory will provide critical important new information on the complex shock physics and cosmic particle acceleration, and allow the calibration of the computer codes.

1.2 Outstanding Questions: (1) What is the shock structure as a function of upstream magnetization, composition (pair vs. e-ion), and field geometry? (2) how do magnetic fields get generated and survive in shocks? (3) What are the mechanisms and efficiencies of electron and ion acceleration? (4) How do relativistic and strongly magnetized shocks differ from nonrelativistic and unmagnetized shocks?

1.3 Laboratory Experiments: Intense lasers are ideal tools for generating relativistic collisionless shocks in the laboratory. A collisionless ambient plasma may be created using the Z-machine at SNL, or long pulse lasers at Omega and NIF, to first heat a sufficiently large volume of hydrogen plasma to multi-keV temperatures so that it becomes collisionless. Then a short pulse laser of intensity $>10^{20}$W.cm^{-2} can be used to deliver a strong shock in this overdense plasma. While the shocks generated by such collisions will only be mildly relativistic ($\leq$0.1c), it can propagate through a large volume of plasma so that it can be studied in detail. Such mildly relativistic shocks are relevant to the afterglow of GRBs and blazar jets and microquasars. Alternatively, multiple short pulse lasers such as the Omega-EP or NIF-ARC system, can create colliding multi-MeV electron/positron jets (cf. Sec.2). Provided that these jets can be generated with sufficient density and column density, so that the interaction region is larger than the plasma skin depth, they may be able to form ultra-relativistic shocks, which are relevant to the emissions of GRB and PWN.

1.4 Future Needs and Strategy: In addition to lasers with intensities $>10^{20}$W.cm^{-2}, magnetized shock experiments will require >10MG pulse magnets. Relativistic shocks also need to be diagnosed on picosecond time scales to measure in-situ temperature, density, magnetic field, pair fraction, particle spectra, and radiation output with high spatial resolution. Computationally, we need to link and merge a variety of multi-physics codes to perform end-to-end simulations of realistic shock experiments, including 3D MHD, PIC, and hybrid codes, plus post-processing codes to model the radiation. DOE supercomputers such as the Roadrunner should be made available to academic groups working on shocks. A national consortium of leading academic theory groups and experimental teams at the laser facilities should be formed to perform laboratory experiments. This project will benefit from close interactions with the NASA community: results of laboratory experiments should be rapidly communicated to astrophysicists analyzing Fermi data.

2. Pair Plasmas

2.1 Astrophysics Context: Relativistic electron-positron (e+e-) pair plasmas are ubiquitous in the high energy universe, from the first few seconds of the Big Bang, to pulsar winds, blazars jets, and GRBs. Transient thermal pair-equilibrium plasmas may also be present around stellar-mass black holes during gamma-ray flares. Because of the unity mass ratio, pair plasmas behave differently from electron-ion plasmas in many respects. Hence it is extremely desirable to study pair plasmas in the laboratory, both for the fundamental physics and for astrophysical applications.

2.2 Outstanding Questions: (1) How do the kinetic physics of pair plasmas, including plasma instabilities and wave-particle interactions, differ from e-ion plasmas? (2) How does macroscopic MHD flows of pair plasma differ from e-ion plasmas? (3) Do pair plasmas radiate differently from e-ion plasmas? (4) Does particle acceleration operate differently in pair plasmas? (5) Can thermal pair-equilibrium plasmas be created in the laboratory? (6) What are the observable manifestations of pair-dominated plasmas besides the annihilation radiation ?

2.3 Laboratory Experiments: Ultra-intense lasers (Intensity>$1.4\text{x}10^{18}\lambda^{-2}\text{Wcm}^{-2}$) interacting with overdense targets efficiently couple their energy to multi-MeV electrons. Such electrons can be used to create e+e- pairs in a high-Z target, via the Trident and Bethe-Heitler processes. Recent experiments using the LLNL Titan laser irradiating mm thick Au targets created an estimated 10^{11} pairs, with an estimated in-situ pair density $>10^{16}\text{cm}^{-3}$. Follow-on experiments at OMEGA-EP produced even higher pair yields, and showed that the pairs have a quasi-thermal energy distribution. Future experiments at NIF-ARC should produce much higher pair yield and density.

2.4 *Future Needs and Strategy:* The needs of future pair experiments include: (1) dedicated facilities with multiple kJ-class PW lasers, (2) diagnostic developments for measuring in-situ pair densities and temperature, and positron to ion ratio, (3) techniques for trapping and cooling dense pair plasmas, (4) techniques to accelerate and collimate pairs to form pair jets. Computationally, we need to link 3D plasma codes with particle physics Monte Carlo codes (e.g. CERN-GEANT4) to perform self-consistent end-to-end simulations of pair creation experiments. A coordinated national program to create relativistic pair plasmas and study their astrophysical and terrestrial applications should be formulated. Such a program should involve astrophysicists, positron physicists and laser experimental teams at DOE facilities. 1

3. Relativistic Jets

3.1 Astrophysics Context: Relativistic astrophysical jets are long narrow dynamic structures that emanate from compact objects such as stellar mass black holes, neutron stars, and active galactic nuclei. Despite their widespread occurrence, many aspects of astrophysical jets are not well understood, including: how jets are launched and accelerated, why jets are so narrowly collimated, why jets appear to be extremely stable and straight. Moreover, the relative abundances of ions, pairs and Poynting flux are not known, and their roles in the jet dynamics, dissipation and radiation remain to be understood. Only a few jet parameters can be determined through observations so models of jets are still in a primitive stage. However, new observations from Fermi and other observatories will shed important new light on jets.

3.2 Outstanding Questions: Some of the important questions that may benefit from laboratory jet experiments include: (1) how are jets launched and accelerated? (2) why are jets so well collimated? (3) why are jets so stable? (4) why are jets so straight ? (5) do relativistic jets work differently from non-relativistic jets? (6) what are the differences between magnetic-dominated (Poynting flux) and hydrodynamic jets? (7) how do the multi-scale jet regions interact with each other? (8) how do pair jets differ from e-ion jets? (9) what dissipative and radiation mechanisms are involved in jets?

3.3 Laboratory Experiments: Modern laboratory experiments on magnetized jets use advanced pulsed power magnetic technology and have been underway at Caltech and at Imperial College. Magnetized jet experiments are also planned at Cornell University and at the University of Nevada, Reno. Laboratory experiments on unmagnetized hydrodynamic jets using high energy density laser technology are underway at the University of Rochester and at the Rutherford Appleton Lab. However the detail characterization of most jet parameters has not yet been performed. Relativistic jets of electrons and hybrid electron-pair plasmas have been generated using ultra-intense short pulse lasers. Recent experiments at Omega-EP demonstrated that laser-created positrons can be efficiently accelerated to Lorentz factors > 20 by sheath electric fields to form a relativistic jet.

3.4 Future Needs and Strategy: The conjunction of new experimental facilities that can replicate essential features of astrophysical jets, new computer codes that can solve the complex systems of equations characterizing jets, and new telescopes that can observe jets with higher energy and resolution than ever before, indicates that the next decade is a time of remarkable opportunity for developing an understanding of a phenomenon which has been an enigma for many decades. To take advantage of this opportunity it is proposed that a National Center for Astrophysical Jet Studies be established. This Center would support the experimental, numerical and observational studies now underway at a number of institutions under one roof and would coordinate these efforts by holding regular workshops. The Center, by promoting a synergism of the institutions now working on jets, would greatly accelerate the rate at which the questions listed above become addressed and answered.

4. Beam Dissipation and Weibel Instability

4.1 Astrophysics Context: Violent astrophysical phenomena often produce very energetic relativistic outflows. They include pulsar winds (PW), gamma-ray bursts (GRBs), relativistic jets in AGNs and microquasars. Pulsar winds are the most relativistic outflows whose Lorentz factors may be as high as 10^{6-7}. The outflows are observed because they produce radiation throughout the entire electromagnetic spectrum. For this to happen, kinetic energy of an outflow must be converted into the internal energy of the radiating electrons and likely magnetic fields. The energy dissipation may occur in collisionless shocks, current sheets, reconnection and boundary (shear) layers. Theory and computer modeling indicate that Weibel-like instability (a current filamentation instability) likely play an important role when relativistic flows or beams interact with an unmagnetized ambient plasma. Weibel instability also has important laboratory applications. Although the theory of Weibel instability dates back to 1959, there has been relatively few experiments to test Weibel instability of relativistic beams.

4.2 Outstanding Questions: (1) how do growth and saturation of Weibel instability depend on the beam size, density, composition, temperature and Lorentz factor? (2) when is Weibel stabilized by transverse temperature, density gradient and flow-aligned guide fields? (3) what is the asymptotic structure of magnetic turbulence and wakes created by Weibel? (4) how does Weibel-generated magnetic fields accelerate nonthermal particles? (5) what is the radiation output from Weibel-unstable electron beams (e.g. jitter radiation)? (6) when Weibel is suppressed, how do beams dissipate via classical 2-stream instability?

4.3 Laboratory Experiments: The mononenergetic and intense beams accelerated by laser wakefields (LWFA) offer the opportunity to study Weibel-like and other instabilities of these beams when they propagate into a second plasma or an extension of the original plasma, as well as to use these beams to probe the magnetic fields left behind by a prior pulse of laser or beam energy. The radiation intensity in GRBs is $\sim 10^{19}$ W/cm^2 (for the isotropic emission energy $\sim 10^{53}$ erg and the emission radius $\sim 10^{13}$ cm), which is very similar to that provided in a number of Petawatt (PW)-scale laser facilities presently in operation. Other plasma parameters are also very similar (the field and the density at internal GRBs shocks are $B\sim 0.1$ MG, $n\sim 10^{15\text{-}16}$ cm^{-3}, compare with $B\sim$(few × 0.1) MG, $n\sim 10^{17\text{-}18}$ cm^{-3} in typical laser plasmas), so one can readily probe this astrophysical phenomenon in a lab experiment!

PW lasers can also produce intense multi-MeV hot electron/positron jets and tens of MeV proton jets via direct irradiation of solid targets. When these jets run into a sufficiently dense plasma, their interaction and anomalous dissipation may allow us to study a whole range of beam-plasma instabilities, and study their effects on collisionless dissipation, diffusive particle acceleration, EM turbulence generation and radiation.

Alternatively, we can pass the laser beam through long underdense gas targets to generate quasi-monoenergetic electron beams with energies up to GeVs, and then use these "cold" beams to interact with dense plasma to study the Weibel instability. Since Weibel behaves very differently depending on the beam temperature, density and current size, these two different approaches are complementary to each other, allowing us to study Weibel over a much broader range of physical conditions. Another dimension of beam-plasma interactions can be investigated by taking advantage of the Z-machine or long pulse NIF lasers. With a total combined energy of > MJ, the Z or long pulse NIF lasers can be used to preheat a sufficiently large volume of dense (say > 10^{21}/cm^3) plasma to multi-keV temperatures, making it collisionless despite being overdense. This will allow us to investigate, for the first time, beam-plasma interactions in both overdense and underdense, and collisionless as well as collisional regimes. Such a large dynamic range of plasma regimes is unique to the HED facilities.

4.4 Future Needs and Strategy: In addition to HED facilities to create the relativistic electron beams and heat the plasma, the most critical need for studying relativistic Weibel instability is diagnostic development. Weibel instability may be probed indirectly using the jitter radiation emitted by the hot electrons passing through the self-generated turbulent magnetic field. A more direct approach is to image the transition radiation emitted when the electron/positron filaments emerge from a target. The magnetic fields created by Weibel may be probed using deflection of proton beams created by another intense laser. Computationally, 3D PIC simulations of Weibel need to be extended to much larger domains in space and time to replicate realistic laboratory conditions, not to mention astrophysical settings. This will require larger supercomputers and faster, memory-efficient algorithms, as well as smarter graphics/visualization software.

5. Ultrastrong Magnetic Fields

5.1 Astrophysics Context: Neutron star magnetic fields can exceed 100TG, while white dwarf fields may exceed 100MG. Current ultra-intense lasers are capable of generating transient fields approaching a GigaG, which overlaps with magnetic white dwarfs and accreting neutron stars identified as millisecond pulsars. The study of laboratory plasmas with strong fields in this range may demonstrate for the first time that the conditions appropriate to the atmospheres of these magnetic neutron stars and magnetic white dwarfs can be produced in a terrestrial laboratory. Measurements of such a plasma may enable the study of highly dynamical phenomena such as the "photon bubble" instability. They may also permit probes of non-linear regimes of the Zeeman effect in hydrogenic atoms, as well as "guiding center drift atoms" where the strong field changes electron orbits into ExB drift orbits. Laboratory insights may spawn new observational diagnostic of neutron stars and magnetic white dwarfs. Theories of anisotropic radiation and particle transport in such objects may be meaningfully tested in the laboratory.

5.2 Outstanding Questions: (1) how do strong fields alter the atomic structure, ionization, collision and radiative properties? (2) can radiation and particle transport in strongly magnetized stellar atmospheres be replicated in laboratory experiments? (3) can novel astrophysical phenomena such as the "photon-bubble" instability in accreting neutron stars be tested in the laboratory? (4) can the atmospheres of strongly magnetized white dwarfs be modeled using laboratory experiments?

5.3 Laboratory Experiments: To replicate radiation-dominated neutron star accretion columns in the laboratory we require radiation temperatures of the order of 1 keV at densities of order 10^{-3} g/cc and magnetic field strengths from 0.1-1Gigagauss, which would be required to prevent transverse expansion of photon bubbles and confine the plasma to flow in one direction. In 1992, it was first proposed that ultra-strong fields can be generated by relativistic laser interactions ($>10^{18}$ W/cm^2) due to currents produced by supra-thermal electrons accelerated in the evanescent region of the laser wave which propagate deep into the interior of the plasma. This magnetic field is in the azimuthal direction about the laser axis of propagation and the peak field extends for about an anomalous skin depth into the plasma. Later calculations predicted the generation of fields up to 250MG in the overdense plasma for moderately relativistic interactions. The strongest magnetic fields (>Gigagauss) have been predicted to exist in this overdense region of plasma near the critical surface during the actual time of the interaction of the picosecond laser pulse with the high density plasma. Such fields cannot be measured with conventional techniques such as Faraday rotation. These fields are produced by the extreme ponderomotive force of the focused laser light which displaces electrons in the interaction region from the background ions. This effect can also greatly change the propagation and energy of fast electrons generated during the interaction and can also affect the location where such electrons deposit their energy.

5.4 Future Needs and Strategy: Since experimental work is presently behind theory in this field, precise magnetic field measurements are most critical to identify the important mechanisms and to verify predictions. To date the highest measured laboratory magnetic fields (up to 0.7 Gigagauss) have been inferred by laser plasma interactions at 10^{20}W/cm^2 using polarization measurements of scattered radiation. With intensities up to 10^{23}W/cm^2 becoming available with present lasers, magnetic fields greater than several Gigagauss should be generated, which should allow a more systematic study of high magnetic field physics. Observations of the dynamics and the spatial extent of these magnetic fields may result in a new diagnostic for studying the propagation of supra-thermal electrons in overdense plasmas. The use of charged particle probe beams (e.g. protons) may allow the strength and dynamics of the magnetic fields to be measured with high resolution.

To examine the "photon bubble" instability requires the co-location of a nanosecond high energy laser system with a PW-level short pulse laser to produce the large B-fields, plus another high power short pulse laser to generate a particle probe beam. Several facilities which are capable of such experiments are presently in operation (OMEGA-EP, HERCULES, Texas Petawatt) and many others are under construction. After the completion of an experiment design phase such work could be begun in short order. DOE should strongly support such experiments.

6. Turbulence and Reconnection in Relativistic Plasmas

6.1 Astrophysics Context: Many astrophysical plasmas exist in a strongly turbulent state, where the local properties such as density and electromagnetic fields experience quasi-random fluctuations. These fluctuations are typically driven by large scale forces, like motion of macroscopic bodies or plasma elements. Dissipation of turbulent motion leads to plasma heating, generation of magnetic field and, most importantly, acceleration of particles to super-thermal energies. Astrophysical turbulence provides a way for the macroscopic energy to be dissipated into kinetic energy of particle motion, which in turn produces a wide range of observable radiation. Thus the interpretation of many astrophysical observations, especially those related to high energy astrophysics, requires understanding of turbulent processes. Classical examples of astrophysical turbulence applications include, (i) plasma heating and particle acceleration in Solar flares; (ii) heating and acceleration of the Solar wind; (iii) angular momentum transport in accretion disk around pre-main sequence stars and compact objects; (iv) numerous turbulence-related processes in the interstellar medium, like support of molecular clouds against gravitational collapse and, inversely, seeding of collapsing proto-stellar clouds; (v) acceleration of cosmic rays, both protons and electrons, in galactic supernova remnants, clusters of galaxies and jets of Active Galactic Nuclei; (vi) heating of intercluster medium in clusters of galaxies. Though these environments are very different in terms of plasma parameters, the turbulent processes can be generally grouped into several categories: MHD (collisional) turbulence; Whistler/Hall turbulence: Shock-and-reconnection-generated turbulence; Turbulence in collisionless high beta plasmas; Turbulence in strongly magnetized plasmas (sigma >1). The new features we are adding to this list are relativistic plasma temperatures, relativistic flow speeds and pairs.

6.2 Outstanding Questions: (1) Whistler/Hall turbulence. As the turbulent cascade propagates to smaller scales, the typical frequencies of fluctuating electromagnetic field may become high enough so that ions stop responding to them. Alternatively, in neutron star crusts, ions may be fixed in an ion lattice. What are the spectra and anisotropic properties of the turbulence in this case? (2) Turbulence in collisionless high beta plasmas. In many astrophysical applications binary collision times are much longer than plasma dynamical time scales and the cyclotrons and plasma oscillations periods (plasma in clusters of galaxies are, perhaps, the best example of such regime). How does dissipation proceed on kinetic scales? (3) There is a new plasma turbulence regime which takes place in a number of astrophysical setting (e.g.corona of magnetars, AGN and GRB jets): turbulence in strongly magnetized plasmas, where energy density of magnetic field exceeds plasma energy density, including rest mass. What are the spectra and anisotropic properties of turbulence in this case? Virtually in all of these turbulence types the key questions are the same: what are the spectra and anisotropic properties of the fluctuating quantities on different scales, and what are the spectra of particles accelerated, presumably, by Fermi-type mechanism. Beside Fermi acceleration in a turbulent medium, there are alternative ways to produce non-thermal population of high energy particles, such as DC-electric field generated in current sheets and reconnection sites. This is an especially promising route in a magnetic-dominated plasma, where most of the energy is stored in magnetic field. This leads to the next topic: (4) How do current sheet dissipation and reconnection proceed in relativistic plasmas?

6.3 Laboratory Experiments: If we inject relativistic electron/positron or MeV proton jets generated by intense lasers into a plasma with a steep density gradient, or if we can create multiple relativistic *colliding shocks* using multiple laser beams, they may be able to generate sufficient plasma turbulence to address some of the questions above. Furthermore, if we can also create magnetic fields of *opposite polarities* in the ambient plasma prior to the jet/shock interactions, the MHD turbulence created by the jet-jet/jet-plasma interactions may induce or enhance current sheet dissipation and magnetic reconnection. This will help to address one of the outstanding issues in MHD turbulence, namely, whether it can dissipate and nonthermally heat electrons/positrons/ions by enhancing the current sheet dissipation and magnetic reconnection. The physics of current sheet dissipation and reconnection in relativistic and /or pair plasmas is important to black hole accretion, the pulsar wind “sigma problem”, gamma-ray bursts and many other astrophysical phenomena.

6.4 Future Needs and Strategy: Multiple intense lasers will be needed to create the colliding shocks or particle beams capable of generating turbulence in a relativistic plasma. At present only NIF at LLNL may possess such capability, if the proposed short pulse ARC beams are completed. In addition to the lasers, pulsed magnets of > 10 MG fields will be needed to create intense current sheets. Diagnosis of the magnetic field, particles and waves generated by the turbulence will be major challenges. New diagnostic technologies will be needed before meaningful measurements can be made. Computationally, the big gap between MHD and PIC simulations will need to be bridged before we can confidently explore the complete cascade range from the MHD to the kinetic scale. 3D reconnection simulations have recently reached a threshold where electron-positron plasmas can be meaningfully studied with sufficient mode numbers for both the kink and tearing instabilities. However, realistic electron-ion simulations in 3D reconnection is still in its infancy and must await even faster and larger supercomputers. To study particle acceleration in turbulence and reconnection, new algorithm must be developed to keep track of particle data only for the most energetic particles.