At a meeting of the laboratory plasma astrophysics working group (LPAWG) formed in May 2007, the group tentatively identified five important High Energy Astrophysics (HEA) questions that are most pressing and challenging, that may also benefit from laboratory studies using high energy density (HED) facilities, such as intense lasers and pulse power machines. These five "grand challenge" questions, listed in relative priority, are:

1. What is the role of (e^+, e^-) pairs in the most energetic phenomena of the universe such as gamma-ray bursts, AGN jets and pulsar wind dynamics?
2 . Why are relativistic astrophysical jets so spectacularly collimated and stable over enormous distances?
3. How does tenuous plasma interact with and dissipate ultra-relativistic hydrodynamic or electromagnetic-dominated outflows such as pulsar winds and gamma-ray burst jets?
4. How do shock waves produce high energy cosmic rays?
5. How does magnetic turbulence dissipate energy and accelerate particles in astrophysical plasmas?

The white paper attached below represents work-in-progress drafts by members of the laboratory plasma astrophysics working group (LPAWG) convened in May 2007. The five chapters address the five consensus topics above deemed most worthy of in-depth investigations using laboratory experiments. They are listed here only to provide insights into the five High Energy Astrophysics questions posed by the working group, and only represent the opinion of the individual authors. They are incomplete (e.g. lacking references), and have not been edited or approved by the working group as a whole. These drafts are not to be cited or quoted.

A. Relativistic electron-positron plasmas in the laboratory.
Draft by *Edison Liang* for the LPAWG White Paper. Version 2.0

Though rarely observed in terrestrial laboratories, relativistic electron-positron (e+e-) pair plasmas are supposed to be ubiquitous in the high energy universe, from the first few seconds of the Big Bang, to the winds of pulsars, jets of blazars and gamma-ray bursts (GRBs). The physics and observable manifestations of this exotic state of matter, however, have been relatively unexplored due to the lack of laboratory experiments. This situation is about to change in the coming decade, due to the increasing availability of ultra-intense lasers which are capable of producing copious amount of multi-MeV e+e- pairs in the laboratory with densities exceeding 10^{18} cm^{-3} and magnetic fields exceeding 10^9 G. The creation of such exotic high energy density (HED) plasmas will undoubtedly open up entirely new frontiers in both astrophysics and basic plasma science. Among the many frontiers of laboratory plasma astrophysics, we have identified this area as the most novel and promising for major scientific breakthroughs and discoveries within the next decade. We therefore strongly urge the formation of a coordinated national task force to explore this new frontier, with significant investment by the federal funding agencies. Below we summarize: (a) the astrophysics context (b) outstanding scientific questions (c) experimental approaches (d) technological developments (e) strategy for a national program.

A1. The astrophysics context
Relativistic e+e- plasmas have been postulated as a major, perhaps the dominant, component of matter in pulsar magnetospheres, pulsar winds, blazar jets and GRB outflows. While there is yet no direct observational evidence to confirm the presence of e+e- pairs (e.g. detection of 511 keV

annihilation line), energetic and kinematic arguments strongly support the omnipresence of pair plasmas in the high-energy universe. Their dominance is also built into most popular theoretical models of these objects. For example, the dynamics and radiation output of pulsar wind and wind shocks are sensitive to pair loading. Similarly most GRB scenarios and many blazar models invoke pairs in the outflows. Yet both the microphysics of e+e- plasma kinetics (particle energization, radiation mechanisms, shock structure) and macro-dynamics of e+e-MHD flows have only been explored recently, as computational technology (relativistic MHD and Particle-in-Cell codes) and computer power have reached the necessary capability. However, even with the most advanced supercomputers and algorithms, such numerical simulations are limited to small physical scales, idealized geometries and initial conditions, far from the dynamic range needed to address many critical astrophysical questions. It is therefore extremely desirable to be able to study at least some aspects of relativistic pair plasmas in controlled laboratory experiments, to search for scalable properties and physical laws that may be applicable to astrophysics, and to calibrate the numerical codes.

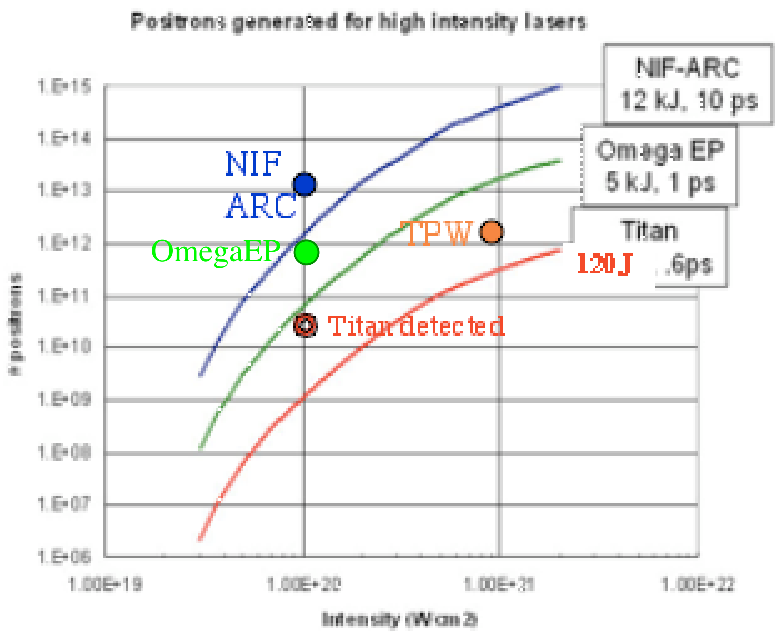
One central question is whether results from laboratory plasmas can be scaled to the astrophysical realm. It turns out that in the relativistic collisionless pair dominated regime, the microphysics is controlled by a small number of dimensionless parameters. They include $\langle\gamma\rangle$ or kT/mc^2, Ω_e/ω_{pe} and $R\omega_{pe}/c$ where R is the characteristic size scale of the plasma or magnetic field. PIC simulations confirm that systems of very different sizes, for which these parameters are identical, exhibit similar microphysical properties and behaviors. Fig. A1 (to be included later) shows one slice of this parameter space and suggests that indeed parameters of laser produced pair plasmas overlap those of many astrophysical phenomena.

A2. Outstanding scientific questions.

Some of the outstanding scientific questions of astrophysical pair plasmas that we would like to address in the laboratory include: (a) how do pairs manifest themselves? (b) how does pair plasma behave differently from e-ion plasma in terms of instabilities, particle acceleration, dissipation, thermalization and other collective behaviors? (c) do pair plasmas radiate differently from e-ion plasmas? (d) how do shocks, turbulence and reconnection in pair plasmas differ from e-ion plasmas? (e) can the BKZS temperature limit for thermal pair equilibrium be tested in the laboratory?

A3. Experimental approach.

Historical approaches to achieving a significant density of positrons in the laboratory rely on collecting and trapping radioactive decay or accelerator-produced e+ in magnetic traps. However, coulomb repulsion limits the density one can achieve with such traps. Also since such trapped e+ are cold, they annihilate rapidly when encountering any e- so it is difficult to produce e+e- plasmas of any significant density. However, recent advances in ultra-intense lasers changed the landscape. Ultra-intense lasers above the intensity of $I_c=1.4\times10^{18}$ Wcm^{-2} couple most of its energy to target electrons with a characteristic temperature of $kT/mc^2 \sim \lambda I^{1/2}$ when λ is wavelength measured in microns and I is measured in units of I_c. Hence for laser intensities > 10^{19} Wcm^{-2} (easily achievable with modern short pulse lasers), most of the laser energy can be converted into relativistic electrons above the pair production threshold. When such electrons collide with high-Z target ions (e.g. Au), they pair-produce via the Trident and Bethe-Heitler processes. In the summer of 2008 a team lead by Hui Chen et al at LLNL using the Titan laser to irradiate mm thick gold targets succeeded in creating copious amounts of pairs, exceeding the previous positron numbers reported by Cowen et al by more than 2 orders of magnitude (Chen et al 2009). The Titan experiments resulted in the most intense and densest MeV positron source ever created on earth. More importantly, the Titan data confirmed that for thick targets (> tens of microns) the positron yield based on the Bethe-Heitler (Heitler 1954) formula is correct to first order. This allows the use of the Bethe-Heitler formula to scale up the positron yield as a function of laser and target parameters. Roughly speaking, the Titan results suggest that a gold target of the optimal thickness (~5 – 10 mm) can produce ≥ 10^{12} e+e- pairs per kJ of laser energy for intensities exceeding 10^{20} Wcm^{-2}, with an in-situ pair density ≥$10^{17}cm^{-3}$ at the target. Scaling from this result we believe that the NIF-ARC beams, focused to intensities ~10^{20} Wcm^{-2}, may be able to produce ≥ $1x10^{13}$ (4 beams, 12 kJ) - $4x10^{13}$ (16 beams, 50 kJ) e+e-pairs, with in-situ pair densities ≥ (1 – 4) x 10^{18} cm^{-3} respectively. Fig.1 shows the estimated positron yield as functions of laser intensity and laser energy based on early design parameters scaling from the results of Cowen et al (1999), compared with the new Titan data. From this we can now estimate the optimum positron yield of the 4 and 16 ARC beams (Fig.1 blue circles), by scaling up from the Titan results.



Titan data suggests that NIF-ARC can easily exceed 10^{13} e+

Figure. A1 *The measured Titan e+ yield (red circle) exceeded the original design estimates (red curve) by a factor of ~ 20. Hence new estimates for NIF-ARC (blue circle: 4 beams,12kJ) should also be scaled by a factor of 20 from the blue curves. The blue circles show that ARC can easily produce more than 10^{13} positrons in each shot at 10^{20} Wcm^{-2} intensity.*

Even higher pair density may be achievable in principle using double-sided irradiation. Other proposed schemes involve using circularly polarized lasers, pre-compressing the high-Z target, and separating the laser target from the high-Z converter, etc. We note that in order for the pair cloud to constitute a "plasma" it should be much larger than the skin depth. For an assumed pair cloud of size ~10 microns, this is satisfied if the initial pair density is $n > 10^{17}$ cm^{-3}. We also note that for laser intensities exceeding 10^{30} $W.cm^{-2}$, pairs can be produced directly by vacuum breakdown. However, that kind of laser intensity is still far off in the distant future. In addition to creating pairs, intense laser-target interactions also produce ultra-strong fields that can exceed 10^9 G. The relation between strong field generation and pair production have not yet been studied, but it is conceivable that some created pairs will be imbedded in strong fields. We also note that the ratio $\Omega_e/\omega_{pe} \sim 30\ (B/10^9G)(n/10^{20}cm^{-3})^{-1/2}$. So the created pair plasma can in principle be used to study magnetic-dominated outflows.

Once strongly magnetized pair plasmas are successfully created in the laboratory, they can be used to study at least some aspects of major astrophysics problems, from collisionless shocks to magnetized e+e- jets, as well as many basic plasma physics questions. Each astrophysical problem may require a different experimental setup and a different set of diagnostics.

A4. Technological developments:

What is critically needed for future experiments include: (1) dedicated facilities with multiple PW-class lasers, especially in a head-on configuration, and (2) diagnostic developments for probing strongly magnetized pair plasmas. Examples of the types of instruments required are diagnostics to detect positron and electron numbers, spectra, angular distribution, and particle distribution function; magnetic field strengths, extents, orientations, and fluctuations; and (collisionless) shock existence, strength, extent, and velocity.

On the theory side, what is urgently needed is end-to-end 3D simulations of a complete experimental setup for pair production, using realistic laser profiles and material properties. The PIC simulations of laser target interactions need to be fully coupled to the pair production and annihilation processes, using the CERN GEANT4 code, so that newly created pairs are also subject to laser-generated electromagnetic interactions. For thick targets, both lasers and pairs must be transported through the high-Z target self-consistently, taking into account collisions, ionization and absorption. Current code capabilities will need to be upgraded to address many complex physics issues. Scaling issues will need to be addressed using simulations with a broad range of physical scales.

A5. Strategy for a National Program

We have identified the physics and astrophysics of relativistic magnetized pair plasmas as an important and challenging frontier, ripe for laboratory experiments. To overcome the daunting challenges of such experiments, we clearly need a coordinated national program involving both academia and the DOE/NNSA laboratories with access to HED facilities. One way to make progress in this field is to form a national center involving all major players in this field. Such a center can be modeled after the DOE ASCI centers and NSF PFC centers, but with major participation and contributions by the DOE/NNSA laboratories. Initial experiments can begin at the regional facilities such as Austin, TX, Ann Arbor, MI, Reno, NV, Lincoln, NB, etc. Follow-on experiments can then progress to use the Jupiter (LLNL), Z-PW (SNL) and Omega-EP (Rochester) lasers, before performing large scale experiments on the NIF-ARC. Diagnostic developments and computer simulations should go hand-in-hand with increasing laser power.

B. Astrophysical Jets.
Draft by *Paul Bellan* for the LPAWG White Paper. Version 2.0

Astrophysical jets are exceedingly long narrow bi-directional dynamic structures that emanate from localized objects such as young stars, binary black holes and neutron stars, and active galactic nuclei. They have been observed in various forms for nearly a century but were not predicted before they were observed because they are too bizarre. However, they exist in many contexts and seem to play important roles in stellar, black hole, and galactic evolution. Despite their widespread occurrence, many aspects of astrophysical jets are not well understood and theories abound. Examples of what is not understood include: the mechanisms by which jets are formed and launched, why jets are so extremely narrow (collimated), why jets appear to be extremely stable and often extremely straight. Moreover, the relative abundances of ions, electrons and Poynting flux, and their roles in controlling the jet dynamics are not known. Only a few jet parameters can be determined through observations so models of jets are now rather weakly constrained by observations.

Because of their inherently non-localized and non-spherical structure, jets cannot be characterized by a simple one-dimensional model of the sort so often used as a first attempt when investigating a new phenomenon. Furthermore, because the launching region is orders of magnitude smaller than the characteristic length scale of the jet, multi-scale analysis is definitely required. For example, the central engine of jets is believed to be magnetically dominated, but at large distances hydrodynamic models seem to be able to reproduce jet structures. The conversion from magnetohydrodynamically-dominated processes to hydrodynamically-dominated processes is not clear.

Recent developments offer exciting new opportunities for advancing understanding of what makes jets work. These developments are (i) advanced technology laboratory experiments involving topology, boundary conditions, and governing physics analogous to astrophysical jets, and (ii) advanced 3D numerical simulations that solve the complex set of coupled partial differential equations believed to characterize jets. These experimental and numerical approaches can be cross-checked with each other to develop a robust jet model characterizing physics that is now too complex to be understood. The experiments have already begun to provide detailed information on the launching and collimation mechanisms and are expected to soon provide information on why jets are so remarkably stable. In principle, this information could be reconciled with numerical models and so benchmark the numerical models, but no funding exists for conducting such a comparison.

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 being 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.

Specific questions that can be addressed by the experiments and numerical simulations include:

1. how are jets launched
2. why are jets so collimated
3. why are jets so stable
4. why are jets so straight (some jets are as straight as an arrow for a megaparsec!)
5. do relativistic jets work differently from non-relativistic ones
6. what is the relationship between magnetic and non-magnetic behavior
7. how do the multi-scale regions interact with each other
8. what dissipative mechanisms are involved
9. how can experiments and numerical simulations be related to observations
10. what role do jets play in stellar, black hole, and galactic physics.

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 resolution than ever before indicates that the next few years is a time of remarkable opportunity for developing an understanding of a phenomenon which has been an enigma for nearly a century.

In order to take advantage of this opportunity it is proposed that a Center for Astrophysical Jet Studies be established with funding at the rate of $3 million per year. This Center would support the experimental, numerical and observational studies now underway at a number of institutions 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. In addition to the Center and to take further advantage of the new opportunities to address and answer the questions listed above, it is proposed that Astrophysical Jet Studies be made an NSF/DOE topical focus area with dedicated funding of $4 million per year.

C. Relativistic outflows and instabilities.

Draft by *Karl Krushelnick and Mikhail Medvedev* for the LPAWG White Paper. Version 2.0.

Background

Violent astrophysical phenomena, which are quite common in astrophysics, often produce very energetic relativistic outflows. They include gamma-ray bursts (GRBs), relativistic jets [Fig. A2] in active galactic nuclei (AGN), jets from quasars and micro-quasars, pulsar winds, and perhaps some supernova explosions associated with GRBs. The diversity of plasma conditions in them is enormous. Pulsar winds are likely the most relativistic outflows whose Lorentz factors may be as high as 10^6. AGN and quasar jets are steady-state collimated outflows from accretion disks around central galactic black holes, while micro-quasars represent their downscaled version with stellar mass black holes in binary systems. The Lorentz factors of such jets range from a few to about 20 or so. GRBs are thought to be produced during collapse of massive stars and are likely to generate jets as well whose Lorentz factors are estimated to be between 100 and 1000. The composition of the outflows likely varies as well: pulsar winds are likely relativistic electron-positron plasmas, whereas plasmas in GRBs and jets are thought to have an electron-ion composition, though it can be magnetic field dominated too. One should bear in mind however that little is known *for sure* in the field.

The outflows are observed because they produce radiation throughout the entire electromagnetic spectrum. For this to happen, kinetic energy of an outflow shall be converted into thermal energy of the radiating electrons and, in some cases (e.g., GRBs), into the magnetic field too. The energy dissipation in the outflows happens either in collisionless shocks or via reconnection, depending on their magnetization factor. Theory and computer modeling [Fig. A3] indicate that the Weibel-like instability (i.e., a current filamentation instability) is responsible for the collisionless shock formation in GRBs and jets, as well as for particle acceleration in them. The Weibel-generated magnetic fields are also needed for the synchrotron/jitter radiation production that is the observable signature of these colossal events.

Instabilities and dissipation mechanisms for relativistic beams are of central importance to laboratory plasmas as well, with the fast igniter concept for inertial confinement fusion being an example. The onset of a Weibel-like instability could defeat the igniter scheme. Although the theory of Weibel instability dates back to 1959 and simulations of it have been abundant since the 1970s, there has been relatively little in the way of experiments to test Weibel instability of relativistic beams. Moreover, understanding of the long-term evolution of the Weibel magnetic turbulence will benefit astrophysical models used to interpret observations.

The mononenergetic and intense beams from short pulse high intensity laser experiments offer the opportunity to study the Weibel-like and other instabilities of these beams themselves in 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. Incidentally, the radiation intensity in GRBs is $\sim10^{19}$ W/cm^2 (for the isotropic emission energy $\sim10^{53}$ erg and the emission radius $\sim10^{13}$ cm), which is very similar to that provided in a number of Petawatt-scale laser facilities presently in operation. Other plasma parameters are also very similar (the field and the density at internal GRBs shocks are $B\sim0.1$ MG, $n\sim10^{15\text{-}16}$ cm^{-3}, compared 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!

Transverse Physics of Relativistic Beams

The basic transverse behavior of intense relativistic beams in plasmas is separated into two regimes according to whether the spot size of the beam is larger or smaller than the characteristic scale of the plasma skin depth, c/ω_p . For beams narrower than a skin depth, the plasma return current flows partially or completely outside the beam. Hence there is a net current on the beam axis and from Ampere's law an azimuthal magnetic field. If the plasma is overdense ($n_o > n_b$), then the plasma shields the beam's electric field, and the net force on the plasma is approximately $ev_zB_\theta/c \sim eB_\theta \sim 2\pi n_b e^2 r$. If the plasma is underdense, the electric field shielding is incomplete; all the electrons are blown out by the beam leaving a net electric force due to the field of the ion column $\sim 2\pi n_o e^2 r$. (The return current is again completely outside the beam, but the focusing due to the beam's azimuthal B-field is cancelled to order $1/\gamma^2$ by the beam's space charge force.) In either case the beam pinches until the thermal pressure of the beam balances the net focusing force. The individual electrons in the beam oscillate about the beam axis due to this force. The frequency of these 'betatron oscillations' follows from the momentum equation:

$$\gamma m y'' = F = -2\pi n_\alpha e^2 y \quad \text{or} \quad y'' + \omega_\beta^2 y = 0 \qquad (1)$$

with $\omega_\beta/c = k_\beta = \omega_{p\alpha}/(2\gamma)^{1/2}$ and the subscript α denotes o for underdense and b for overdense plasmas. This gives rise to the characteristic betatron radiation seen in experiments at the double Doppler shifted frequency $\omega = 2\gamma^2\omega_\beta$. In convenient units, the energy of these photons is

$$U_v = 50eV\sqrt{n_{18}}\,\gamma_{100}^{3/2} \qquad (2)$$

where the subscripts denote that n is in units of 10^{18}cm^{-3} and gamma is units of 100. For example, for a laser wakefield generated electron beam at an energy of 200 MeV in a plasma wake or bubble at plasma density 10^{19} cm^{-3}, this expression gives the photon energy to be 1.2 keV.

The power of this radiation is given by the Larmor formula $P = 2/3(e^2/c)\gamma^4\beta'^2$, where $\gamma m\beta' = F/c$. The total energy radiated is this power times L/c where L is the length of the plasma interaction. Note that this can be much longer than the pulse duration of the electron beam in lab experiments (e.g., it is 30 ps in a cm long plasma compared to 20 fs typical for the bunch length).

Filament dynamics

In addition to the whole beam focusing described above, narrow beams can undergo transverse hosing due to positive feedback when small displacements of the head relative to the tail cause a transverse perturbation of the plasma that then acts on the tail to further its offset. For very short beams, this can be avoided, and the whole beam focusing is all that is left.

For beams wider than c/ω_p, which is the case in the fast igniter and in astrophysical jets and shocks, the transverse behavior is different [Fig. A4]. Now, the plasma return current flows within the beam, so there is no net current and no net magnetic field. Similarly, the plasma shields the beam's space charge and there is no net electric field. So initially nothing happens to a wide uniform beam. However, if there is a small perturbation of the beam density and hence current on a spatial scale smaller than c/ω_p, then the plasma return current does not fully shield the perturbed magnetic field. So a small clump of the beam will develop a small azimuthal magnetic around itself that will further pinch the original clump and a filament forms. If neighboring filaments form that are both smaller than c/ω_p, then their like currents attract and they tend to coalesce. This is physically why filaments of order c/ω_p tend to form and why the formal Weibel theory gives the fastest growth rate at wave number $k_{perp}\sim c/\omega_p$.

A simple derivation of the growth rate of the Weibel filamentation can be obtained by considering a cylindrical Lagrangian plasma element of radius r that is perturbed inward by an amount dr as described above. This gives rise to a perturbed current $2\pi r dr n_b ec$ and a perturbed magnetic field and force from Ampere's law of $dF=edB=4\pi n_b e^2 dr$. This force acts to push the fluid element inward further. The radial collapse of the element is given by $\gamma m dr''=dF$. This equation describes an exponential collapse on a time scale $\omega_{pb}/\sqrt{\gamma}$ which is the growth rate of Weibel instability one obtains from a dispersion type of analysis [i.e., $Re(\omega)=0$, *Max of* $Im(\omega)=\omega_{pb}/\sqrt{\gamma}$].

Again we express this in terms of an engineering formula convenient for evaluating growth in high intensity laser experiments. The *e*-folding length for Weibel is expected to be

$$L_e = \sqrt{\gamma}\, c/\omega_{pb} = 1.5mm\,\frac{\sqrt{\gamma_{100}}}{n_{16}} \qquad (3)$$

where again the subscripts denote typical units. The current filaments coalesce on a longer time-scale in a hierarchical way and produce a self-similar distribution of the magnetic field over scales. It is thought that such a process is the key one that shapes the structure of astrophysical foreshocks – the extended regions in front of weakly magnetized collisionless shocks of astrophysical outflows. It is important to study their physics in order to understand cosmic ray acceleration in the universe.

Proposed Program:

A. Weibel instability of laser wakefield-produced *e*-beams

By allowing the spot size of the beam to expand from its nominal size of 10 microns at the plasma exit to 100 microns, the beam would be much larger than c/ω_p for plasma densities higher than about 10^{18} cm^{-3}, appropriate for observing Weibel.

For example, for a beam with 0.5nC and duration 30 fs (10 microns) at a spot size of 100 microns and energy of 100 MeV, the beam density is approximately 10^{16} cm^{-3} and the characteristic growth length for Weibel from the equation above would be 2 mm. In a second plasma a few *e*-foldings long, we could expect to see filaments form and to observe these directly on a detector. By varying the plasma density over some range, the number and size of the filaments can be measured and compared to theory. Similarly, by varying the free expansion distance to the second plasma, the beam density and hence growth rate of the instability can be varied and compared to theory as well.

Thermal Stabilization

If the transverse temperature (i.e., emittance) of the electron beam is large enough that the particles drift transversely by more than c/ω_p in a growth time of the Weibel, then growth may be inhibited. In terms of an engineering formula this can be expressed as

$$\varepsilon_n > \sigma\sqrt{\frac{\gamma n_b}{n_o}} \tag{4}$$

Where ε_n is the normalized emittance and σ is the spot size of the beam ($\varepsilon_n=\gamma\sigma\theta$ for a beam at a waist where θ is its thermal angular spread). For a typical laser generated e-beam with σ=100 μm, γ=100 and n_b/n_o=.01 (where n_b=10^{16} cm^{-3}, n_o=10^{18} cm^{-3}), this gives ε_n>100 mm-mrad. Although the thermal emittance of such beams is an order of magnitude smaller than this, it may diverge with an opening angle of 1 degree, which would exceed the crossing condition for Weibel stabilization. Accordingly we can also study this with PIC simulations, beginning with cold beams, then adding the effect of temperature, opening angle, expected plasma gradients and beam profiles one at a time.

B. Radiation from the Beam-Plasma Interaction

The radiation of the electron beam is of interest for several reasons. First, by looking at the beam scattering off its own Weibel-generated magnetic fields, we are directly simulating what is thought to be observed in the case of cosmic jets. Second, the development of a radiation diagnostic could then be extended to two pulse experiments in which the short pulse e-beam (via its radiation) becomes a probe of the magnetic structures left behind by an earlier pulse.

Jitter Radiation

The radiation produced by any relativistic electron accelerated transversely to its motion is given by the Larmor expression above. When the bending is produced by a magnetic field and the bending angle is much larger than the characteristic opening angle $1/\gamma$ of the instantaneous radiation in the forward direction, this radiation is traditionally called synchrotron radiation. In FEL parlance, this is the undulator regime; and when the beam deflection angle is much less than $1/\gamma$, this is called the wiggler regime. When the transverse acceleration is caused by the periodic focusing fields of a plasma or focusing optics in an accelerator, this is often called betatron radiation and the transverse beam oscillations are called betatron oscillations. Radiation in the case of small deflection angles in random (or at least, non-periodic) magnetic fields is called jitter radiation [Fig. A3]. Unlike radiation in FELs, jitter radiation is inherently incoherent. All of the above types of radiation are sometimes loosely referred to as synchrotron radiation, thus emphasizing the importance of magnetic fields and relativistic electrons.

It is interesting to estimate the angle of the jitter or betatron motion in the self-generated Weibel fields. For an impulse approximation $\delta\theta \sim F\delta t/\gamma mc = eBL/\gamma mc^2$ where L is the length the beam takes to cross a filament of typical size c/ω_p. Taking $L \sim (c/\omega_p)\delta\theta$ and using $B \sim 2\pi n_f ec/\omega_p$ where n_f is the beam density of the filament gives for $\delta\theta$

$$\delta\theta = \frac{1}{\sqrt{2\gamma}}\sqrt{\frac{n_f}{n_o}} \tag{5}$$

For the examples above this is a little more than 1° and $1/\gamma$ is about a third of a degree. The two angles are comparable, so we may expect the radiation spectrum to be in between the undulator and jitter regimes – an interesting regime that is difficult to analyze theoretically. The deflection angle is also large enough to be detected via a slight increase in the angular spread of the beam.

The radiation frequency is $\omega \sim 2\gamma^2(\omega_p/\sqrt{\gamma})$ or $\omega \sim \gamma^2\omega_B$ in the jitter or synchrotron regimes, respectively, see Eq. (2). The power emitted in both regimes from the beam interacting with its own Weibel-generated magnetic field in a second plasma can be estimated from the Larmor formula above with n replaced by the density of the focused filament (nominally an order of magnitude more than the beam density or 10^{17} cm^{-3} for the example above). For the example above, the filament magnetic fields will be on the order of 0.1 MG, the photon energy would correspond to ~50 eV soft x-rays at γ=200. The Larmor formula gives $P \sim 10^4 B_G^2\gamma^2$ eV/s, so for a 1 cm interaction (t=30ps) with B_G=10^5 and γ=200, there would be roughly 10^5 of these photons produced.

Other related experiments

Related experiments are presently being designed with high intensity lasers (such as that at the University of Michigan) to address such astrophysical issues. One experiment will address the effects that result when an electron beam interacts with the "relativistic turbulence" left behind by a previous laser beam. This type of interaction is believed to produce the electromagnetic radiation we observe from relativistic jets, but cannot be modeled by the traditional synchrotron theory that applies to large regions of uniform magnetic field.

In this scheme one laser beam would drive a wakefield in the blowout regime, producing a ~ 100 MeV quasi-monoenergetic electron beam. This beam has a divergence somewhat less than a degree experimentally. The beam travels some distance, estimated here as ~ 1 cm, before interacting with the structure described below. This implies that the beam diameter at the structure is no longer small, being in the range of 50 to 150 μm. The beam then has the shape of a pancake, being less than (c×30 fs) ~ 10 μm thick along the direction of propagation.

One goal is that some of these electrons will be deflected by interacting with some structure, producing detectable “jitter radiation”.

A physics issue for this electron beam, when it encounters the second gas jet and the plasma in it, is whether it goes Weibel unstable and breaks up.

The target for the electron beam should be the wakefield structure from another wakefield. The turns out to have a dominantly radial electric field at small amplitude but to have comparable radial electric field and azimuthal (theta) magnetic field (in energy density) for strongly nonlinear wakes. The first electron beam would interact with several oscillations of the wakefield.

The size of these fields are roughly the wavebreaking field, observed to have $eE_z/(mc\omega_{pe}) \sim 1$. The electrons in our interaction beam oscillate in the wakefield as they traverse it. The maximum impulse is that received over a time $\Delta t \sim 1/\omega_{pe}$ giving an impulse of ~ mc so $\Delta p/p \sim 1/\gamma$ since $p \sim \gamma mc$. This will be the maximum deflection. Most electrons will be deflected less than this. This amount of deflection is in the range that corresponding to the regime of interest. This interaction will not scatter the electrons much outside of the beam spot, but should change the shape of the spot, making it asymmetric. We can hope to detect this.

The beam electrons will radiate in the jitter regime and the peak radiation frequency will be $\gamma^2\, c/d$, where d is the interaction distance. This gives x-ray radiation for such experiments, which we could hope to detect:

E ~ 100 MeV, γ ~ 200, d ~ 3 μm, c/d ~ 10^{14}/s, ω ~ 4 x 10^{18}/s,
Photon energy ~ 2.5 keV

These x-rays will be strongly forward directed, but there also may be some x-rays from the first wakefield interaction. There are at least three options for detection:
1. Compare the signal with and without the second wakefield.
2. Screen the first x-rays by sending the electron beam through a filter.
3. Deflect the electron beam magnetically before the second interaction.

This interaction of electrons with the wake structure has some additional interest as a possible AC free-electron-laser wiggler for short wavelength. There are papers by C. Joshi et al. in J. Quantum Elec. '85 and by R. Williams et al. in the late 1980's.

There are other options, though more complicated. One would be to use a longer-pulse, lower-irradiance second beam to drive stimulated Raman backscatter. This would then produce a forward going beam of electrons by wavebreaking. These electrons in simulations would definitely undergo Weibel and thus would produce magnetic structures. But unless we can devise techniques to examine these structures, such experiments would be very dependent on simulations. Even so, such Weibel is of significant astrophysical interest.

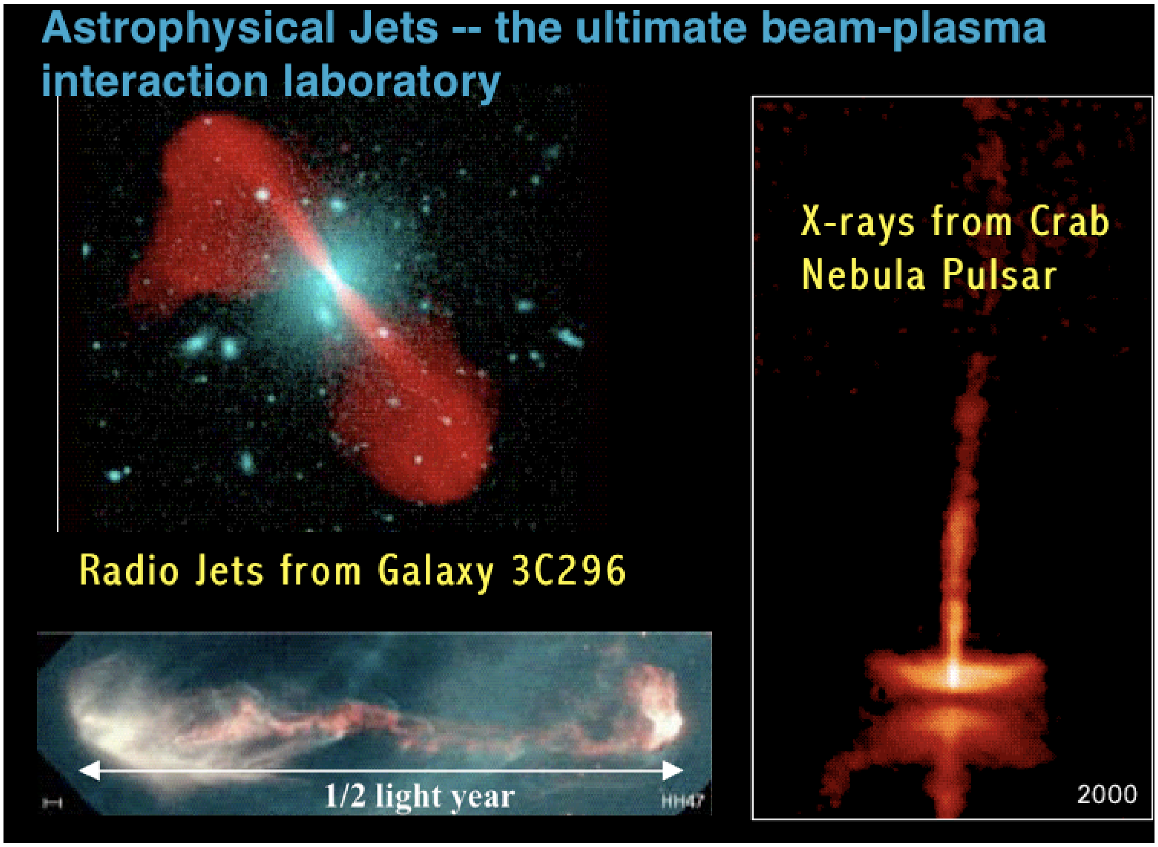


Figure A2.

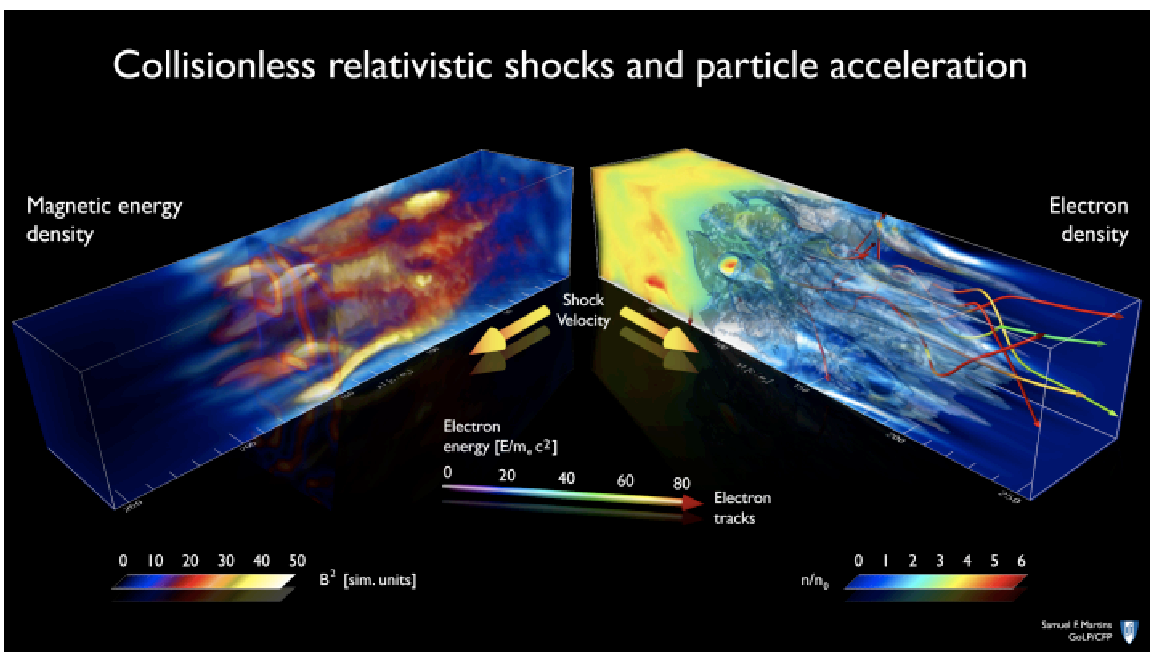


Figure A3.

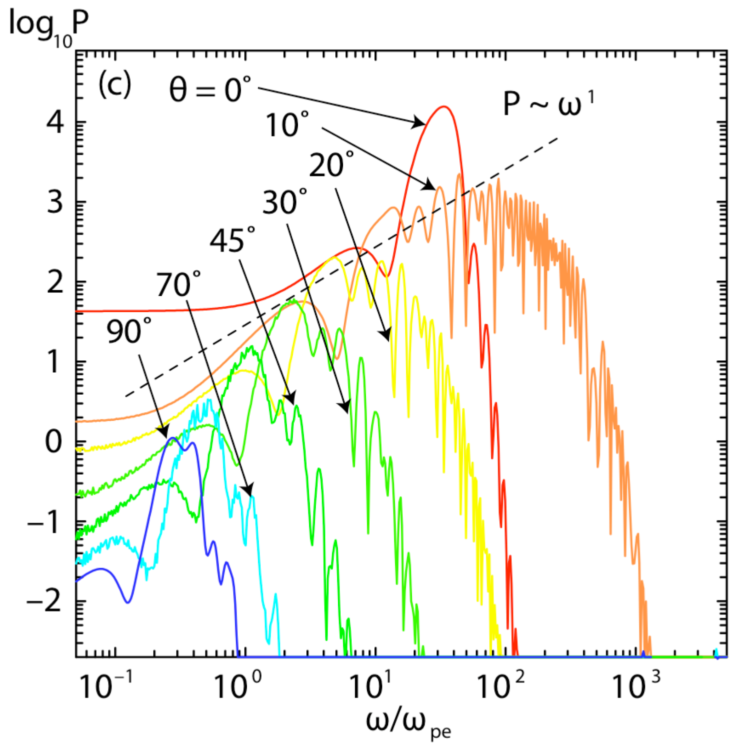


Figure A4. Power spectra of jitter radiation obtained from 3D PIC simulations (Nishikawa et al 2009) for different angles between the electron beam and line-of-sight. The characteristic ω^1 jitter spectrum follows from the convolution of individual ones.

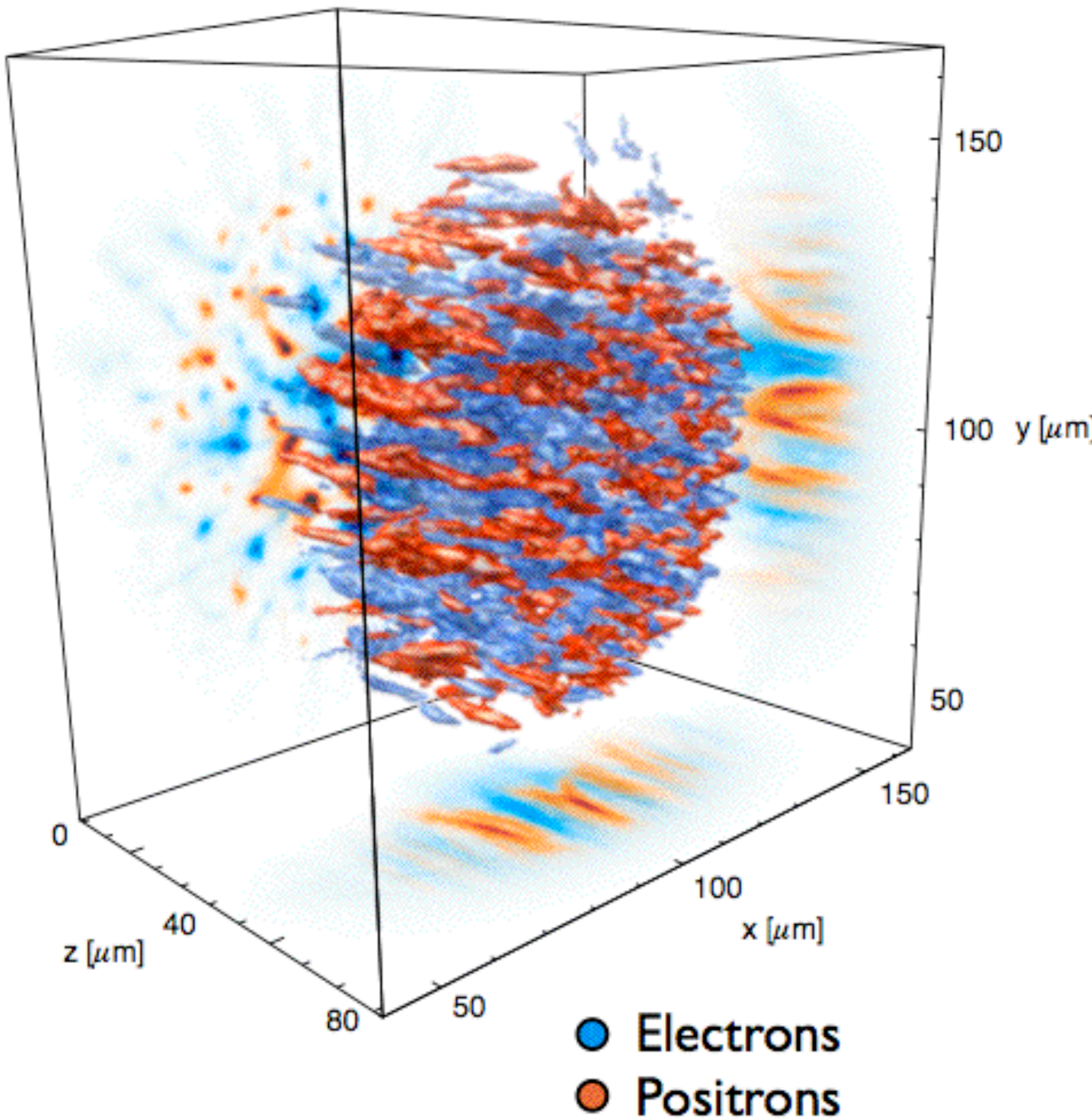


Figure A5. 3D PIC simulations of the Weibel instability in electron-positron laser-produced plasma. (Reproduced with permission from Luis Silva publication.)

D. Collisionless shocks in the laboratory: uncovering the secrets of cosmic accelerators.
Draft by *Anatoly Spitkovsky* for the LPAWG White Paper. Version 1.0

Collisions of highly supersonic flows occur frequently in astrophysics and the resulting shock waves are responsible for the appearance of many sources, such as supernova remnants, Gamma Ray Bursts and jets from Active Galactic Nuclei, are a few examples. Because of the low density of astrophysical plasmas, the mean free path due to Coulomb collisions is typically very large, so most shock waves in astrophysics are "collisionless," or mediated by plasma instabilities and magnetic fields. Astrophysical shocks span a wide range of shock speeds, Mach numbers, magnetizations, and can occur in plasmas of varying composition, such as electron-ion or electron-positron plasmas. Despite the diversity, collisionless shocks share common characteristics: they are inferred to efficiently accelerate nonthermal particles and to generate and amplify magnetic fields, in addition to effectively decelerating supersonic flows. As a result of nonlinear plasma processes involved in the shock formation, the physics of such shocks remains unclear, and the conditions for efficient particle acceleration are not fully understood. The closest examples of collisionless shocks are shocks resulting from the interaction of the solar wind and the Earth's magnetosphere. They cover a relatively small range of parameter space, and require spacecraft to perform measurements. The laboratory component, however, is currently largely absent in this field. The ability to perform collisionless shock experiments in the laboratory will dramatically expand the potential for understanding the complex plasma physics involved in shocks, and will have a significant impact on the theory of cosmic accelerators.

Parameter space of shock physics.

The mechanisms of shock formation depend on the parameters of the pre-shock flow. Broadly speaking, in the collisionless regime, the main parameter is the magnetization of the flow, or the ratio of the magnetic to kinetic energy in the upstream region. When the magnetization is above a certain threshold, the shock is mediated by magnetic reflection from the compressed downstream magnetic field. Below the threshold, the flow is effectively unmagnetized, and the shock is mediated by streaming instabilities, such as two-stream electrostatic instability and electromagnetic Weibel instability. In general, the picture is more complicated, of course, as certain streaming instabilities play a role in the magnetized shocks (e.g., the phenomena in the "shock foot"), and the geometry of magnetic field is also important (resulting in differences between "parallel" and "perpendicular" shocks). Moreover, in astrophysics shocks occur in both nonrelativistic and relativistic flow regimes, so a range of shock parameters should be explored. Despite the disparity of scales between the astrophysical setting and the lab, the physics can be rescaled in terms of dimensionless numbers, such as the ratios of cyclotron to plasma frequency and Larmor radius to the skin depth. It is currently possible to achieve the relevant regimes in laboratory experiments.

Outstanding scientific questions.
There are several issues that have to be clarified through both experiments and simulations:

1) The structure of the shocks as a function of parameters, such as magnetization, composition, and field geometry. The processes responsible for shock formation in a

collisionless plasma need to be identified, as the transition between different shock mediation mechanisms can affect the shock acceleration process.

2) Magnetic field generation and survival in shocks. Shocks in gamma ray bursts and supernova remnants are inferred to strongly amplify preexisting magnetic fields, or create them from scratch. Whether microphysics of shocks is responsible for this, or some large-scale turbulence is required is currently under debate. In particular, it is not clear whether the small-scale fields generated by plasma instabilities can survive for long times needed to explain the astrophysical sources of radiation.
3) Mechanisms of electron and ion injection into the shock acceleration process, and the efficiency of shock acceleration. The overall number of accelerated particles and their partition into ion and electrons depend on both shock physics and the nonlinear shock modification driven by the accelerated particles.

Once the fundamental physical questions above are clarified, many astrophysical models will be severely constrained or ruled out. For example, the composition and magnetic geometry of astrophysical jets will be clarified by identifying which conditions lead to particle acceleration. The origin of cosmic rays, and their effect on the galactic structure, will be settled with clear constraints on the acceleration efficiency of shocks. Also, an experimental investigation of the magnetic field generation in shocks will identify the origin of the interstellar magnetic fields.

Laboratory experiments and technological progress.

The physical processes in shocks can be directly probed with the appropriate laboratory experiments on high power laser facilities. The upcoming generation of laser experiments will be able to accelerate bulk plasmas and electron beams to highly supersonic and relativistic velocities. Collisions of laser-accelerated plasmas with targets or with other plasmas will result in the formation of collisionless shocks under the right conditions. Several existing experimental facilities are well positioned to create shocks (e.g., experiments at NIF, LLNL, OmegaEP laser at the University of Rochester, Hercules experiment at the University of Michigan). A typical experiment can involve a laser-created electron beam (10^{18}cm^{-3}) propagating through a background plasma (10^{19}cm^{-3}). If the length of the beam is several millimeters, it will encompass several hundred ion skin depths of the background plasma. These scales are interesting for observing shock formation due to Weibel filamentation, if the transverse size of the beam is sufficiently large (>10 skin depths, or 60 microns). It is important to note that shock formation happens in plasmas of sufficiently large scale compared to skin depth, so that collective instabilities have enough time to grow and affect momentum and energy exchange between streaming components. Only then can global conservation of energy and momentum lead to the eventual separtion of the flow into the “shocked” and “unshocked” regions satisfying jump conditions. Some experiments are bound to be on the verge of
validity of this regime. In order to facilitate progress, two developments must occur. On the experimental side collisions of larger scale plasmas, especially with large transverse size compared to the skin depth should be on explored. On the theoretical side, multidimensional simulations must be done in the regime where the plasmas involved in the collision are finite and may not span the enormous range of skin depths expected in astrophysics. Then, the laboratory experiments can be used to focus on particular elements of shock formation, such as the deceleration of the beam, the development of a contact discontinuity, and the evolution of the forward and reverse shocks propagating in the colliding media. Creative experimental setups,

such as the collisions in the center of mass frame, at an angle, or in an external magnetic field should also be explored and complemented by simulations.

Strategy for a national program.

Laser accelerated electron and ion beams will be become relatively commonplace in the high power laser laboratories in the near future. Collisionless shock experiments therefore can benefit from the technological developments associated with the inertial fusion and high energy density plasma programs. The inertial fusion experiments such as the fast igniter concept will be sensitive to the collisionless physics effects which are also involved in shocks, such as the filamentation instabilities. Extension of the existing experiments to larger scales can therefore answer many important astrophysical questions related to shocks. The development of diagnostics sensitive to the particle distribution function in the shock layer and accurate measurements of the generated magnetic fields will be needed to analyze the experiments. The fusion program will also benefit from such diagnostics. On the simulation front, 3D kinetic simulations in realistic geometries and laser profiles will be required. The scope of both experimental and theoretical work can be accommodated as part of a DOE Plasma Science Center with the emphasis on laboratory astrophysics.

E. Turbulent dissipation and particle acceleration in astrophysical plasmas.
Draft by *Maxim Lyutikov* for the LPAWG white paper Version 1.0.

Many astrophysical plasmas exist in a strongly turbulent state, when the local properties like density or 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 supra-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 observed radiation form plasma. Thus, interpretation of many astrophysical observations, especially those related to high energy astrophysics requires understanding of turbulent processes. Examples of astrophysical turbulence applications include, to name a few, (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 separated into several categories:

Collisional MHD turbulence. This most basic type of plasma turbulence remains an unsolved problems: what are the spectra and anisotropic properties?

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 in this case?

Turbulence in collisionless high beta plasmas. In many astrophysical applications binary collision times are much longer than plasma dynamical time scales and the cyclotron and plasma oscillations periods (plasma in clusters of galaxies are, perhaps, the best example of such regime). How does dissipation proceed at sub-viscous scales?

There is potentially a new plasma turbulence regime which takes place in a number of astrophysical setting (eg., corona of magnetars, AGN and GRB jets): turbulence in strongly magnetized plasmas, where the energy density of the magnetic field dominates the plasma energy density, including rest mass. What are the spectra and anisotropic properties of turbulence in this case?

In virtually all of these turbulence types the key questions are the same: what are the spectra and anisotropic properties of the fluctuating quantities and what are the possible spectra of particles accelerated, presumably, by the Fermi acceleration mechanism.

In fact, beside Fermi-type acceleration in a turbulent medium, there are alternative ways to produce a non-thermal population of high energy particles. Particles may be accelerated in a DC type electric field in reconnection sites. This is an especially promising route in a magnetically-dominated plasma, where most of the energy is stored in the magnetic field.
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1. Astrophysical **Applications**: Solar wind, ISM, accretion disks, intercluster medium (ICM), astrophysical jets
2. **Types of turbulence**:
MHD (collisional): spectra and anisotropy
Whistler/Hall: spectra and anisotropy
Shock- and reconnection-generated turbulence, Fermi acceleration
Turbulence in collisionless high beta plasmas: dissipation at sub-viscous scales
Turbulence in strongly magnetized plasmas (sigma >1): spectra, anisotropy, acceleration spectra
Turbulence in pair plasmas
Turbulence in relativistic plasmas
3. **How particles are energized/accelerated in all these turbulence types?**
4. What is the role of current sheets and reconnection in turbulence dissipation?
4. **Potential Experiments**
Need facility that can produce high beta and high Alfven Mach number plasmas with small collisions and strong magnetization of the ions
Next-generation (less collisional) reconnection experiment
(additional contributions by experimentalists).