

Accelerator Experiments for Astrophysics *

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Abstract

Many recent discoveries in astrophysics involve phenomena that are highly complex. Carefully designed experiments, together with sophisticated computer simulations, are required to gain insights into the underlying physics. We show that particle accelerators are unique tools in this area of research, by providing precision calibration data and by creating extreme experimental conditions relevant for astrophysics. In this paper we discuss laboratory experiments that can be carried out at the Stanford Linear Accelerator Center and implications for astrophysics.

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1 Introduction

Recent advances in high-energy astrophysics involve observations of extremely complex phenomena such as jets from active galactic nuclei (AGN), gamma-ray bursts (GRB), and ultrahigh-energy cosmic rays (UHECR). Observations of AGN jets, consisting of a highly collimated stream of material, show that the outflow expands at relativistic velocity and spans a distance scale of thousands of light-years. The collimation and production mechanism, most likely involving the dynamics of accretion disks around a black hole in the center of the AGN, are subjects of current research. Gamma-ray bursts, on the other hand, are some of the brightest observed light sources in the universe. The amount of electromagnetic energy output in a burst is equivalent to several times the solar mass released in a matter of seconds. The out-flowing materials of a GRB expand at relativistic velocity as well, and are possibly collimated, similar to an AGN jet. The nature of the progenitor and explanations for their observed characteristics are currently under debate. Much of our current understanding of these objects are inferred from the properties of the observed radiation.

A strong magnetic field is believed to exist in both the GRB and the AGN jets. The interaction of the relativistically expanding material with the environment can lead to nonlinear plasma phenomena that result in the acceleration of particles to high energies. Ultrahigh-energy cosmic rays, with energies observed up to around 10^{20} eV, are believed to come from extra-galactic sources. The nature and origin of these cosmic rays as well as their acceleration mechanism are still a mystery.

The study of these extreme phenomena requires tremendous effort. So far, progress in our understanding has required a combination of observation, numerical simulations, and theoretical modeling.[1] However, astrophysical observations must be carefully checked for instrumentation effects. And the complex numerical and theoretical calculations used to interpret these observations must be validated. Thus, it is important to calibrate the techniques used in the observations and to benchmark computer model calculations. Furthermore, since observational astrophysics deals with uncontrolled environments, laboratory experiments able to model the relevant extreme conditions would provide unique insight into the underlying physical mechanisms.

Laboratory studies, ranging from work on atomic spectroscopy, and the studies of hydrodynamics, radiation flow, and the equation-of-state using intense lasers[2], have been instrumental in astrophysics research. Recently, it has been suggested that accelerators can be used in the laboratory investigation of extreme astrophysical phenomena.[3] In this paper we discuss possible experiments using intense particle and photon beams to verify astrophysical observations and to study relativistic plasma dynamics and ultrahigh-energy cosmic acceleration mechanisms. An overview of the accelerator facility at the Stanford Linear Accelerator Center (SLAC) is given in Section 2. In Section 3, we discuss calibration experiments, focusing on the discrepancy in the UHECR spectrum measured by two large-aperture cosmic ray experiments, and describe an experiment that may help resolve it. In Section 4, we discuss laboratory experiments that may improve our understanding of the underlying dynamics of high-energy astrophysics phenomena. We conclude with an outlook in Section 5.

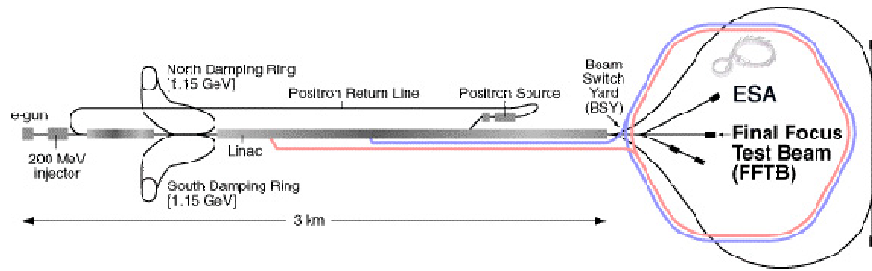


Figure 1: Layout of the SLAC facility.

2 An Overview of the SLAC Facility

The 3-km long linear accelerator is the backbone for SLAC's high-energy physics research program. It is capable of delivering electrons and positrons with 50 GeV energy and 120 Hz repetition rate at 10^{10} particles per pulse. Currently it serves as the injector for the PEP-II storage ring to produce copious amount of B-meson particles for CP-violation measurements. It can also deliver beams to the fix-target experimental hall End-Station A (ESA) and the Final Focus Test Beam (FFTB). A schematic layout of the SLAC facility is shown in Figure 1. High intensity photon beams, tunable from X-ray to gamma-ray, can be derived using a variety of methods, such as undulators, laser-Compton back-scattering, and bremsstrahlung. Depending on the required wavelength, typical fluences of 10^9 photons per pulse can be provided.

3 Calibration Experiments

3.1 Detector Calibration

High energy beams from the linac can be used to generate a variety of secondary and tertiary beams for calibration purposes. A secondary pion and positron beam with well-defined momentum can be generated using a combination of target and selection magnet system, with a beam intensity that can be set to below 1 particle per pulse. With the addition of a tagger magnet, this secondary beam can be converted into a photon beam with known energy up to 20 GeV.

This test beam setup in the ESA has been used for the GLAST satellite mission, whose objective is to study energetic astrophysical gamma rays with energies in the 20 MeV to TeV range. The GLAST detector package consists of sophisticated silicon tracker and CsI calorimeter. It is important to calibrate its response and understand the various analysis algorithms in a controlled test beam environment before its space launch. Details on this experiment can be found elsewhere[4].

3.2 X-ray Spectroscopy

Recent X-ray observations of AGN galaxies have revealed features in the iron emission lines that are characteristic of Doppler shifts and gravitational redshifts expected from accretion disk models.[5] The emission lines can be thought of as “clocks” moving in various circular orbits around the black hole. To further probe the spacetime structure in the accretion disk, high resolution imaging and broad-band spectroscopy, such as those planned for the Constellation-X and MAXIM missions, are needed. A detailed laboratory measurement of heavy element atomic transitions and associated polarization effects will also be required for a proper interpretation of the observational data.[6]

For this purpose, an intense X-ray source, such as those available at a synchrotron light-source facility would be valuable. The next generation of linac-based light-source, with peak brilliance in the range of 10^{32} - 10^{33} photons/sec/mrad²/mm²/0.1% bandwidth at 1-10 keV, could also play a role in this study.

3.3 Air Fluorescence Efficiency Measurement

The study of ultrahigh-energy cosmic rays has been based on observations of the secondary shower particles resulting from interactions in the atmosphere. For cosmic ray energies above $\sim 10^{14}$ eV, the shower particles can reach ground level and extend over a large area. One observation technique uses an array of sparsely spaced ground detectors to measure the density of these shower particles, which is related to the energy of the primary cosmic ray. The Akeno Giant Air Shower Array (AGASA) near Tokyo, Japan, for example, covers an area of approximately 100 km², with 100 detector units separated by about 1 km from each other.[7]

The cosmic ray shower also generates a trail of fluorescent light. The fluorescence is emitted nearly isotropically, mostly by the nitrogen molecules in air excited by shower secondaries. Instead of studying the transverse profile of the shower, as in the ground array approach, fluorescence-based detectors use a system of mirrors and photomultipliers to image the shower’s longitudinal development. The fluorescence luminosity is related to the primary’s energy; and the shape of the longitudinal profile provides information on the primary’s composition. This technique is used by the Fly’s Eye detector and its upgraded version, the High Resolution Fly’s Eye (HiRes).[8]

Studies of UHECR events showed that they are not related to any known galactic sources. If they originated in extra-galactic sources, interactions with the cosmic microwave background radiation would result in the attenuation of their energy. The flux above 10^{19} eV is expected to drop significantly due to the production of pions – the so-called GZK cutoff.[9] However, the Fly’s Eye/HiRes and AGASA experiments have observed events greater than 10^{20} eV, well above the GZK cutoff. The two experiments have now accumulated similar exposure at the highest energies. With increased statistics, differences between the two measurements have become apparent. In particular, the flux measured by HiRes is systematically lower than that reported by AGASA above 4×10^{18} eV; there is also a difference in the energy at which the observed power-law spectrum changes slope, the so-called “ankle” structure.[10] This can be due to tails in the energy resolution function or other systematic

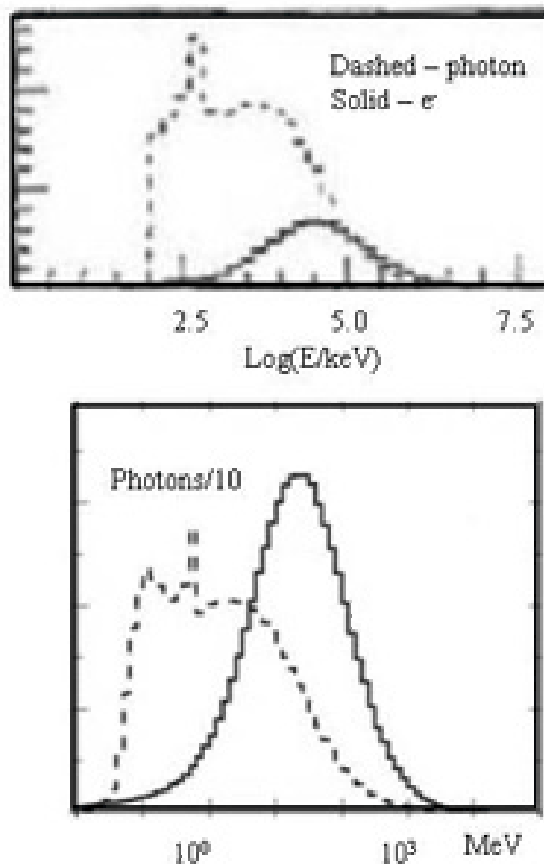


Figure 2: Simulations of shower secondary electron and photon energy distributions for a 10^{17} eV cosmic ray proton (top, CORSIKA) and a 28.5 GeV electron beam (bottom, GEANT) at the shower maximum.

errors, and is currently being investigated by both experiments.

One possible contribution to this discrepancy is the air fluorescence yield. Current understanding of air fluorescence, based on previous measurements, is incomplete. Many issues still remain: the detailed shape of the fluorescence spectrum, the pressure and atmospheric impurities dependences, and the dependence of fluorescence yield on shower particle energy. The associated systematic uncertainty is estimated to be 15%. A more precise measurement is desired as improvements are being made to other systematics in the observation.

Recently, it has been suggested that the high intensity electron beams at SLAC can be used for such study.[11] At the relevant energies, air showers produced by a cosmic ray hadron is a superposition of electromagnetic sub-showers. At the shower's maximum, it consists of mostly electrons with energies dissipated to the 100 MeV level, near the critical energy of air. Further shower development is dominated by energy loss through ionization and excitation rather than shower particle creation. SLAC's electron beams interacting in an air-equivalent alumina target produce similar secondary electron energy distributions – see Figure 2. The SLAC E-165 experiment – Fluorescence in Air from Showers (FLASH) –

has been proposed to study in detail the fluorescence yield in an air shower. It aims to make precision measurements of the total air fluorescence yield, as well as the spectral, pressure, composition, and energy dependencies. Details on this experiment have been presented elsewhere at this Workshop.[10]

Other examples of accelerator-based experiments that support astrophysical investigations are measurement of the Landau-Pomeranchuk-Migdal (LPM) effect, which has implication for photon/hadron identification at high energies, and observation of the Askarian effect, which can be used to detect UHE neutrinos. These experiments have been carried out using SLAC beams.[13]

4 Relativistic Plasma Experiments

While important issues remain to be resolved in the observational results of super-GZK events, the existence of extra-galactic UHECR above 10^{18} eV is well established. The nature of these cosmic rays and their acceleration mechanism are still a mystery, and various models have been proposed as solutions.[1] In the so-called “top-down” approach, the decay products of massive particles produced in the early universe could account for the observed UHECRs, especially those above the GZK cutoff. Certain “grand-unification” theories predict the existence of particles with mass around 10^{16} GeV. Particles more massive than this, if they were to explain super-GZK events, would have to be produced continuously since their lifetimes would be extremely short. In some theories these particles can be emitted from topological defects created between causally disconnected regions during early epochs of cosmological phase transitions.

In the “bottom-up” approach, conventional particles accelerated in powerful astrophysical systems are thought to be responsible for the observed UHECR spectrum. The acceleration mechanisms are complex, involving strong magnetic fields and nonlinear plasma effects. Diffusive shock acceleration has been the generally accepted model.[14] More recent ideas include unipolar induction acceleration[15] and high gradient plasma acceleration in wakefields created by Alfvén shocks[16]. Possible acceleration sites are AGNs and gamma-ray bursts where typically relativistic plasma outflows are present. The key observational feature of UHECR is the power-law spectrum. The appropriate spectral index is predicted by existing models. Our goal is to experimentally test some of these models in the laboratory.

Typical beams delivered for experimentation in the FFTB are in short pulses pico-seconds long, $10 \mu\text{m}$ in radius, and consists of 10^{10} particles. Thus, the pulse power is approximately 40 Petawatts, and the intensity is $\sim 10^{20}$ W/cm². The energy density in the bunch is on the order of 10^{13} J/m³. For comparison, the threshold for high-energy-density conditions, the energy density in a hydrogen molecule or the bulk moduli of solid-state materials, is 10^{11} J/m³. The strong nonlinear and collective responses of a bunched relativistic particle beam to external stimuli are some of the important characteristics of a high-energy-density system relevant for astrophysical studies. Here we discuss possible relativistic plasma experiments. In particular, we explore the possibility of merging electron and positron beams to form a kinetically relativistic plasma, allowing the laboratory investigation of cosmic high-energy acceleration and radiation production phenomena.

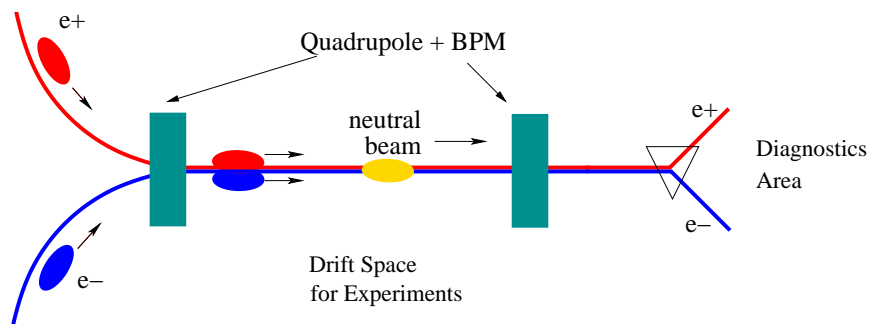


Figure 3: Combining electron and positron bunches to form a relativistic plasma.

4.1 e^+e^- Beams as Relativistic Plasma

Neutral co-moving e^+e^- beams have been investigated in an effort to improve the luminosity limit in high energy e^+e^- storage ring colliders. The disruptive effect of one beam's electromagnetic fields on the other can be compensated, in principle, by colliding neutral beams. This idea had been studied using two pairs of 0.8 GeV beams.[17] The experiment demonstrated beam-charge compensation with improved luminosity.

For our purpose, the 1-GeV electron and positron beams emerging from the damping rings at the beginning of the SLAC linac (see Figure 1) could be combined, forming an e^+e^- plasma streaming at relativistic velocity.[18] The transverse positions of the two beams would be aligned to micron precision using high resolution beam position monitors. The temporal locations would be synchronized using the damping rings' RF phase control, which is stable at the sub-picosecond level. This level of precision beam control has been demonstrated in measurements of wake-fields in accelerator structures.[19] The concept is illustrated in Figure 3.

For a relativistic bunched beam, temperature can be defined in terms of its emittance. Analogous to entropy, emittance is a measure of disorder. The discussions here follow those in Lawson[20]. The beam's transverse temperature is given by

$$kT_{\perp} = \frac{\beta^2 \gamma m c^2 \epsilon^2}{4\sigma_r^2} \quad (1)$$

where ϵ is the beam's emittance, γ the Lorentz factor, and σ_r the transverse beam size. The longitudinal temperature due to energy spread is negligible for relativistic beams.

The other plasma parameters can now be calculated. Results are shown in Table 1, using typical SLAC parameters at the exit of the damping rings. Plasma parameters are given in the frame co-moving with the beams. As can be seen, the number of particles inside a "Debye sphere" (N_D) is much greater than one, so that the effects of individual particles on each other are negligible compared to the collective effects, and the plasma description is indeed appropriate.

For typical AGN jet parameters, the plasma length scales are much smaller than the jet dimensions. Thus, the AGN jet plasma is usually treated as having infinite extent. For typical relativistic bunched beams, however, the Debye radius (λ_D) is smaller than the

Table 1: Beam parameters in the laboratory frame and corresponding plasma parameters in the co-moving frame.

Beam Parameters (Lab frame)		Plasma Parameters (Co-moving frame)	
	Value		Value
Energy (E)	1.19 GeV	Density	$4 \times 10^{11} \text{ cm}^{-3}$
σ_E/E	10^{-3}	Debye Length (λ_D)	1.7 mm
Bunch Length	600 μm	Plasma Parameter (N_D)	6×10^6
Bunch Radius	50 μm	Frequency ($\omega_p/2\pi$)	6×10^9 (Hz)
Intensity	2×10^{10}	Wavelength (λ_p)	50 mm
Density	10^{15} cm^{-3}	Skin depth (c/ω_p)	8 mm
Emittance:		Temperature:	
ϵ_x	1.3×10^{-8} m-rad	Transverse (kT_\perp)	23 keV
ϵ_y	6.4×10^{-10} m-rad	Longitudinal	0.3 eV

bunch length but larger than the transverse beam size. As a consequence, the perpendicular plasma waves (involving particle motion in the transverse direction) have different properties compared to those excited in an infinite plasma. However, properties of the parallel propagating waves remain the same as those in an infinite plasma. The laboratory e^+e^- plasma discussed here can thus model the parallel propagating waves in an infinite plasma. As discussed below, this mode is most relevant for AGN jet dynamics.

So far our discussion have concentrated on neutral plasmas. The composition of astrophysical jets is, however, far from being understood. Magnetic confinement is generally accepted as the collimation mechanism, but it is also highly unstable. Models of current-carrying jets provide a possible alternative mechanism where the self-magnetic fields create a pinching force. This is very similar to the plasma-lens effect familiar to the beam-plasma physics community. Non-neutral plasma instabilities relevant for AGN jets could be studied using charged beams readily available at a facility such as SLAC. Possible experiments are under study.

4.2 Scaling Laws and Relevance to Astrophysics

The challenge for laboratory astrophysics is to create a terrestrial setting which can be scaled to the astrophysical environment. Magnetohydrodynamic (MHD) models have been used to describe many astrophysical processes such as bow-shock excitation in AGN jets or supernova explosions. The MHD equations have the property that they are invariant under the appropriate scale transformations. This has been the basis, for example, for designing laser experiments to simulate supernova remnants.[2, 21, 22]

The MHD models are applicable when certain assumptions are satisfied. These, however, may not be applicable to the astrophysical conditions of interest here. In the following, we discuss a more general approach based on kinetic plasma theory. In particular, we concentrate on astrophysical plasma processes that might be investigated using high-energy-density particle beams.

The observed non-thermal radiation spectrum from AGNs is the subject of many recent

studies. In some models, broad-band Blazar emission has been attributed to synchrotron radiation and/or various forms of Compton processes.[23] While in other models, it is described by the production of photon-pairs from the decay of mesons produced via the interaction of energetic protons with ambient photon and/or matter.[24] These models successfully describe various features in the observed spectrum, and thus are useful for understanding the radiation processes. But such phenomenological approach does not describe details of the underlying micro-physical dynamics of AGN jets. In particular, it does not address the issue of how the relativistic jet gives rise to energetic electrons and/or protons which subsequently produce the radiation. For example, these models typically assume that diffusive shock acceleration produces the required power-law spectrum.

In the plasma physics approach, details of the underlying dynamics for transferring kinetic energy in the relativistic jet into radiation are described. In the model proposed by Schlickeiser *et al.*[25], the jet is described by a one-dimensional outflow consisting of electron and positron pairs with bulk relativistic velocity, directed parallel to a uniform background magnetic field. The pairs have non-relativistic temperature in the co-moving frame. The e^+e^- jet propagates into an interstellar medium consisting of cold protons and electrons.

This two-stream multi-fluid system is studied in the jet rest frame. The analysis starts with a general phase space distribution, and the calculations then give the dispersion relations of the parallel propagating electrostatic (longitudinally polarized) and low-frequency transverse (Alfven-type) plasma waves. These waves are excited via a two-stream instability in the pair plasma. For typical AGN parameters, the calculations show that the jet kinetic energy is transferred via plasma turbulence to the initially cold interstellar protons and electrons, which then reach a plateau distribution in momenta. The resulting radiation spectrum is consistent with observation.[26]

These kinetic plasma calculations also show that the instability build-up times and growth rates *scale* with the densities and the bulk relativistic factor, while the damping rates scales also with temperature. For example, the time it takes to build up the transverse instability in the protons is given by $t_{t,p} \sim (1/\omega_{p,e})(n_j/n_i)(m_p\Gamma/m_e)^{4/3}$, where $\omega_{p,e}$ is the electron plasma frequency, n_j and n_i are the jet and interstellar plasma densities, and Γ is the bulk Lorentz factor. The Landau damping rate is found to scale with $\Theta^{3/2}\omega_{p,e}\Gamma^2\exp[-(\Gamma - 1)/\Theta]$, where $\Theta = kT/m_e c^2$ is the dimensionless temperature parameter.

4.3 Parameters for Laboratory Experiments

To determine whether the parameters of the relativistic plasma created by merging electron and positron bunches are relevant for an experimental investigation of AGN dynamics, the various dynamical time scales are calculated. The results are shown in Figure 4 for the parameters given in Table 1. In the setup being considered here, the pair plasma in the co-moving frame appears to be ~ 1 -m long to the ambient plasma traveling through it. As can be seen from Figure 4, all dynamical time scales are shorter than the plasma traversal time: the time during which the relativistic plasma and the ambient plasma interact with each other. Typical plasma time scales are shown as the inverse plasma frequency. The build-up of the electrostatic waves is rather quick, for both the electrons and the protons, even with

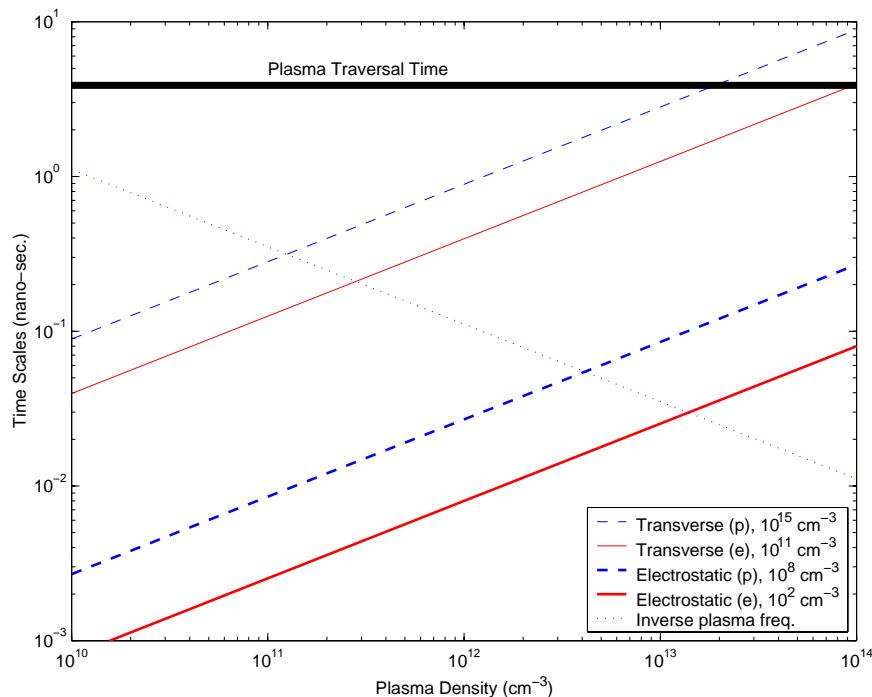


Figure 4: Various time scales for a laboratory experiment to test the dynamical model of AGN jets. The scaling of the plasma wave build-up times are shown as a function of the jet plasma density, for various interstellar medium densities – see text.

a fairly thin ambient plasma. The build-up of the transverse waves takes much more time, particularly for the protons, in which case an ambient plasma density of 10^{15} cm^{-3} in the laboratory is required.

Also, the maximum growth rate of the electrostatic turbulence is much greater than the Landau damping rate; similarly, the transverse turbulence growth rate is much larger than the cyclotron damping rate. Thus, this set of experimental parameters is in a regime where strong nonlinear plasma turbulence similar to those excited in AGN jets can be created and studied in detail experimentally in the laboratory. Further theoretical calculations are needed to guide the design of the experiment. A detailed numerical simulation using particle-in-cell techniques is needed as the next step.

The transverse magneto-hydrodynamic (Alfven-type) wave is especially interesting for testing various cosmic acceleration mechanisms. This type of turbulence is crucial in the formation of collisionless shocks and for efficient particle deflection in the diffusive shock acceleration process. The Alfven wave is also expected to excite plasma wakefields, which can provide high gradient particle acceleration. The spectrum and polarization properties of the radiation produced in the interaction of this e^+e^- “jet” with an ambient plasma can be measured and compared with astrophysical observations. Detailed simulation studies for these experiments are underway.

The laboratory experiments described here could have applications beyond the understanding of AGN jet dynamics. The dynamics in the polar caps of a spinning neutron star

have been studied in the context of relativistic streaming electron-positron plasma.[27] Also, if GRB radiation is beamed, its dynamics would be similar to those found in AGN jets. Thus, our laboratory experiments would also shed light on these systems.

5 Summary and outlook

The field of laboratory astrophysics holds promise to the understanding of some of the most exciting astrophysical observations today. We have shown that particle accelerators are excellent tools for laboratory astrophysics, providing calibration data for observations and bench-marking computer models, as well as creating extreme conditions that make possible investigation of astrophysical dynamics in a terrestrial laboratory. SLAC, with the existing expertise and infrastructure, is well-positioned to contribute to this rapidly growing field.[28] The proposed ORION[29] facility for advanced accelerator research and beam physics will also be able to support dedicated laboratory astrophysics experiments with its unique combination of high quality electron beams and diagnostic lasers.

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<http://www-conf.slac.stanford.edu/labastro/>,
<http://www-conf.slac.stanford.edu/orion/>.
- [29] Details on the ORION project can be found at the web-site:
<http://www-project.slac.stanford.edu/orion/>.