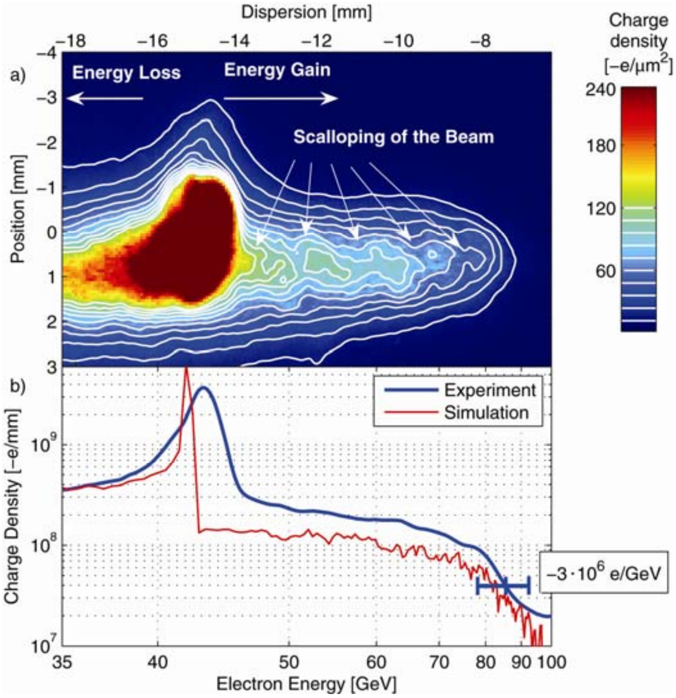
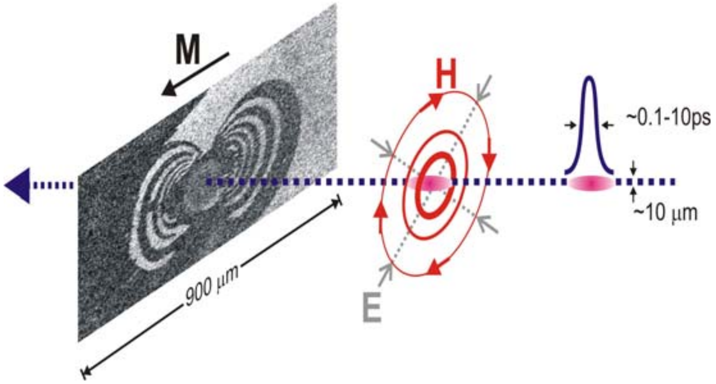
SABER

The South Arc Beam Experimental Region
at the
Stanford Linear Accelerator Center



Energy Doubling of 42GeV Electrons in a Meter Scale Plasma Wakefield Accelerator
[Submitted to Nature (2006)]



Precession and damping of magnetization in GaAs when exposed to a short pulse electron beam.
[C. Stamm *et al*, PRL (2005)]

August 1, 2006

SABER

1. Introduction

The high energy electron and positron beams from the SLAC linac have been in constant demand for many years. In the last decade, the Final Focus Test Beam (FFTB), combined with new bunch compression techniques, has opened up new areas of research in beam and plasma physics, ultra-short-pulse x-ray generation, laboratory astrophysics, advanced accelerator techniques, specialized diagnostic techniques, solid state physics, and high energy density science. The South Arc Beam Experimental Region (SABER) is a proposed relocation, refurbishment, and upgrading of accelerator components at SLAC to continue the research programs of the FFTB.

SLAC is the only place in the world that can provide the high peak current, high energy electron and positron beams that make this research possible. In recent years, a series of experiments to investigate wakefield acceleration and electro-optic pulse effects have taken advantage of the extraordinary beams available only through the FFTB and have produced striking new physics results. The potential wealth of physics accessible with these beams is summarized in the next section of this report.

Numerous other researchers have taken advantage of the linac and the FFTB to carry out short test experiments, such as the study of magnetization phenomena with extremely short duration pulses and neutron transport and attenuation to support the development of radiation shielding design tools. The FFTB facility has also been used to characterize charged particle air showers as they would be produced by 10^{19} eV cosmic rays in the ionosphere, and to study applications of the Askaryan effect for cosmic ray detection. In addition, the FFTB has provided test beams to develop and calibrate a variety of detector components for use at SLAC and elsewhere. The breadth of the research carried out at the FFTB over the last decade is illustrated by the list of peer-reviewed publications in Appendix A.

The FFTB was recently dismantled to make way for the construction of the Linac Coherent Light Source (LCLS). If configured as proposed, SABER will provide a means to continue delivering high energy beams of electrons or positrons to experiments, initially on a time-sharing basis with LCLS commissioning activities. When SABER is complete, it will operate independently of the LCLS facility.

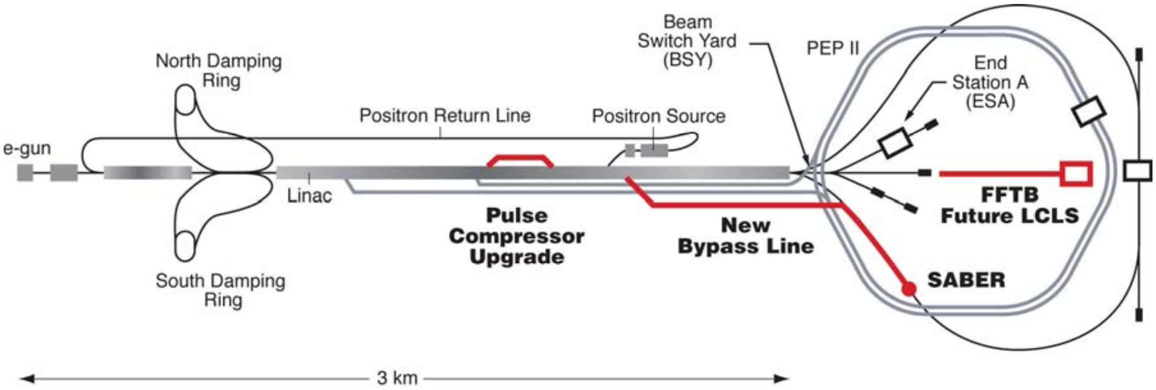


Figure 1. SABER at the SLAC accelerator facility.

SABER is designed to provide electron or positron bunches with at least 2 x 10^{10} particles in a spot size ($\sigma_{x,y}$) of 10 μm and a pulse length of less that 100 fsec (<30 μm), which are needed for several anticipated areas of research. Compression of positron bunches will be a new capability not currently available at SLAC or anywhere else. A beam of high-energy compressed positron bunches is essential for continuing the investigations of plasma wakefield acceleration effects, with potential application to future high energy colliders. The demand for low-intensity test beams is also expected to continue because of the ongoing development of detector systems and beam instrumentation for use at the proposed International Linear Collider, as well as at SLAC and other laboratories.

SABER will use the first 200 m of the South Arc of the currently unused SLAC Linear Collider (SLC). This transport system has not been operated since 1998, but the components have been preserved in their original locations, and can be restored to operation with modest effort. The experimental region will be set up in the existing arc tunnel approximately 10 m below ground, where it is well shielded by the earth above it, and where the full beam power can be absorbed safely. This is a significant advantage over the existing FFTB facility, in which radiation safety considerations have imposed limitations on beam power for several important research programs. A new controlled entry point in the existing Southwest Adit spur tunnel will provide users with convenient access to this experimental region, enabling them to set up and work on experimental apparatus without interfering with other beam programs at SLAC.

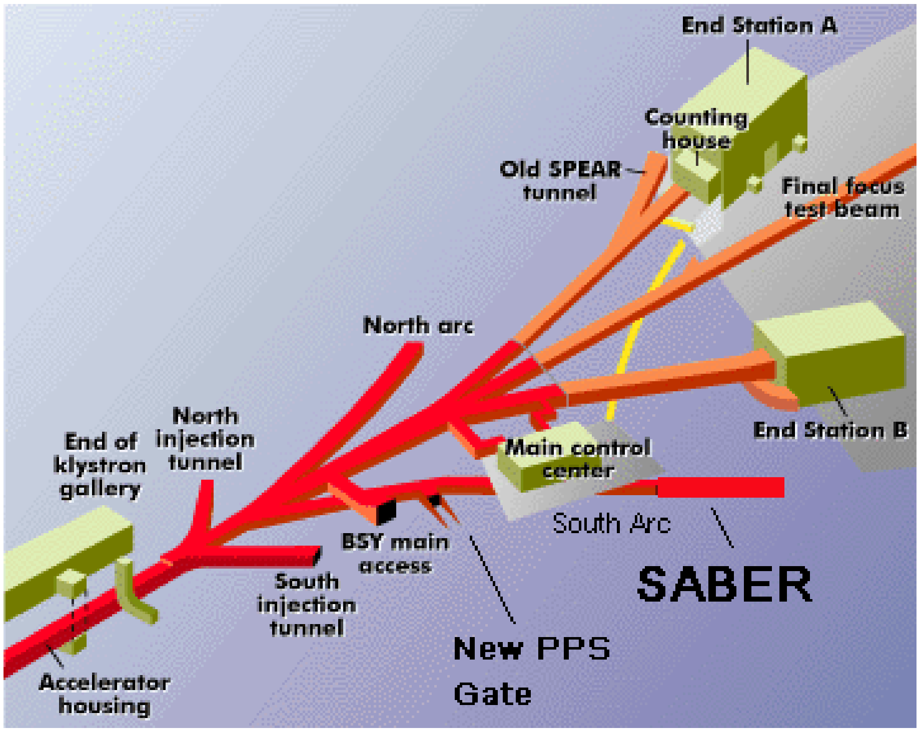


Figure 2. The SABER experimental region will be located in the South Arc tunnel and will be accessible through a new PPS gate in the Southwest Adit.

2. Science at the SABER Facility

High profile research using high peak current, high energy electron and positron beams, which was possible in the FFTB facility, will continue in the SABER facility, and new beam capabilities needed for the next discoveries will become available. A recent workshop held at SLAC drew over 75 participants to discuss the scientific opportunities anticipated with SABER. The full proceedings of the workshop are available at:

http://www-conf.slac.stanford.edu/saber/

Some of the proposed areas of research are outlined below.

2.1 Plasma-Wakefield Acceleration and Beam-Plasma Physics

The SABER facility will be a unique resource for carrying out research on new ideas for accelerating and focusing electron and positron beams at energies relevant to high energy physics. In a series of experiments done in the FFTB, beam-plasma interactions have proven to be an extremely rich area of inquiry. These experiments have shown that plasmas can accelerate and focus both electron and positron high energy beams. In addition, they have demonstrated a variety of new effects, such as the collective refraction of a charged particle beam at a plasma-neutral vapor interface, generation of betatron x-rays from a few keV to tens of MeV energy, and acceleration of electrons from the plasma itself at extremely high acceleration gradients. Striking results have come from experiments using a short ($\sigma_z \sim 20$ μm), high peak current electron beam that tunnel-ionizes a neutral vapor to produce the plasma. Accelerating wakefields in excess of 50 GeV/m have been sustained in an 85 cm long plasma, doubling the energy of some of the electrons produced by the 3 kilometer linac in less than 1 meter.

A concept for doubling the energy of a future linear collider, which has become known as the "Plasma-Afterburner," arose from the beam-plasma experiments at the FFTB. In this scheme, two plasma sections are placed at the ends of the electron and positron accelerators near the point where the beams collide. The accelerating wakefields induced in the plasma by leading drive bunches double the energies of trailing bunches before they are brought into collision. The required luminosity at the interaction point is obtained by focusing the trailing beams to smaller spot sizes than possible using conventional optics. This is accomplished by placing a high-density plasma lens after each wakefield accelerating section, just before the collision point.

Initial experiments at SABER will use the short bunch electron beam to address fundamental questions that are important for understanding the Plasma Afterburner concept. Will the drive and the trailing bunches propagate stably through plasmas longer than the 85 cm length demonstrated in the FFTB experiments? Can the erosion of the head of the drive bunch be minimized to allow its guided propagation over the pump depletion length? Can optimally shaped and phased drive and trailing bunches be crafted and aligned with submicron accuracy? Can plasma lenses capable of focusing positrons and electrons to nanometer sizes be demonstrated? Can the radiation losses be made tolerable and is matched beam propagation a sufficient condition to minimize both the radiation loss and the hosing instability? What is the mechanism for trapping and accelerating electrons from the plasma? Initial measurements suggest these trapped electron bunches are shorter than the drive bunch and might have even lower emittances. Can we optimize their production in a way as to make them useful in their own right? If necessary, can we minimize or eliminate them altogether?

Understanding the behavior of short, high peak current bunches of positrons will be a major component of advanced accelerator research at SABER because of their importance for future beam-driven plasma accelerators. In this regime, where non-linear and relativistic plasma effects are dominant, positron and electron beams are fundamentally different, because plasma electrons are repelled by an electron beam but attracted by a positron beam. The plasma-positron beam interaction must be understood through experiments, and these experiments can only be performed at SABER. Specifically, can positron beams be accelerated at high-gradients in much the same way as electron beams have been in a self-ionized plasma, or will some specially crafted plasma structures, such as hollow plasma fibers, be needed? Can the positron beam emittance be preserved? Can energy doubling of a positron beam using a 28.5 GeV drive beam be demonstrated at SABER?

The SABER beam line, offering both high energy electron and positron beams, will be an invaluable and unique tool to answer many of the basic science questions described above. The SABER facility will be designed to deliver ultra-short, high current electron and positron beams, and the beam line downstream of the interaction point will be designed to handle beams that emerge from the plasma with large energy spreads. The beams will have parameters comparable to the electron beams that were available with the FFTB (i.e., $\sigma_z < 30$ μm (100 fsec), $I_{peak} > 10$ kA, $\sigma_{x,y} < 10$μm). Furthermore, it will be important to be able to shape the current profile of the beam to give two distinct bunches. The first bunch, containing between two-thirds to three-quarters of the charge, will act as the drive bunch to excite the wakefield. The second bunch, containing approximately one-quarter to one-tenth of the charge, will trail the drive beam by 50 to 100 μm and will be accelerated by the wakefield. An imaging spectrometer capable of handling the accelerated beam will be needed, along with a local beam dump for the spent drive beam. Easy access to the beam line and space (on the order of 5 meters) to insert the long plasma will be needed, as well as space for beam position monitors, toroids, transition radiation monitors, wire scanners, and other diagnostic devices.

Beam-plasma interactions have been studied in the FFTB with fourteen experimental runs of about one month each over the past five years. Continuing this research will require three months per year of SABER beam time for at least the next five years.

2.2 Dielectric Wakefield Acceleration

Dielectric wakefield accelerators have been studied in depth over the last several years, but their maximum accelerating gradients have been limited to tens of MV/m by the lack of ultra-short drive beams. The unprecedented combination of high charge, short pulse duration, and small spot size available in the SLAC FFTB beam (e.g., $\sigma_z = 20$ μm and $\sigma_r = 10$ μm at $Q = 3$ nC) presented an opportunity to probe the GV/m regime of dielectric accelerators. The dielectric accelerator concept was tested at the FFTB in August 2005.

The primary goal of the test was to assess dielectric material survivability. The FFTB electron beam was successfully focused and directed through 1 cm lengths of fused silica capillary tubing (ID = 200 μm / OD = 325 μm). The pulse length of the electron beam was varied to produce a range of electric fields between 2 and 20 GV/m at the inner surface of the dielectric tubes. A sharp increase in visible light emissions was observed from the capillaries in the middle part of this surface field range, indicating a transition between sustainable field levels and breakdown. While the analysis of the collected data is still preliminary, the dielectric surface fields at the point of breakdown appear to be in the range 3 - 4 GV/m. Simulations indicate that this range of surface fields corresponds to 1.5 - 2 GV/m on-axis accelerating fields in the wake. The dielectric structures tolerated up to 1000 shots at these high gradients without obvious damage to the fused silica. Detailed analysis is ongoing and a journal article is in preparation.

The investigation of dielectric breakdown levels at the FFTB was the first part of planned two-part effort (Thompson, et al., Proc. PAC 2005, p. 3067). Completion of this program will be the initial focus of the Dielectric Wakefield Accelerator work at SABER. Part two will study the coherent Cerenkov radiation (CCR) emitted from fused silica fibers similar to those used in the original test. Calculations indicate that over 100 mJ of THz CCR will be emitted from the fibers under optimum gradient conditions. Measurements of the energy and spectrum of the THz CCR will give an independent measurement of the wakefield strength. This method of producing THz radiation may also prove interesting in its own right. The CCR dielectric wake investigation could be one of the first experimental programs at SABER.

When SABER becomes fully operational, the unique electron and positron capabilities will be used to examine the feasibility of a dielectric afterburner. The creation of an energy doubling linear collider afterburner has been a central goal of particle beam driven plasma wakefield accelerator (PWFA) research at the FFTB for many years. While the physics of a PWFA afterburner will continue to be examined at SABER, the possibility of alternative afterburner concepts merits investigation. Recently a dielectric wake afterburner has been proposed as such an alternative. Unlike a PWFA, a dielectric wake accelerator is symmetric under charge reversal and immune to potential ion collapse issues. While a dielectric afterburner will not achieve accelerating fields as high as a PWFA, the preliminary breakdown studies completed in the FFTB indicate that substantial accelerating fields of at least 1 GV/m are possible.

The initial dielectric afterburner experiments at SABER would measure the energy gained or lost by bunches of electrons or positrons as they pass through a long (~10 cm) dielectric tube designed to give a gradient > 1 GV/m. The general concept is to compare electron and positron beams with identical parameters and examine both beams for head to tail energy modulation. Such an experiment would demonstrate high-gradient polarity-symmetric acceleration in a dielectric wakefield accelerator and is within the planned capabilities of SABER and dielectric structures under development.

The dielectric wakefield accelerator research program will require beam parameters similar to the plasma wakefield accelerator program. Several runs per calendar year of roughly two weeks each are anticipated for a minimum of three years.

2.3 Magnetism and Solid State Physics

Experiments at SLAC and the FFTB have shown that extremely high densities of electric current can be produced with relativistic electron bunches. Associated with the electron bunches are intense electric and magnetic field pulses at amplitudes of the order of 10^{10} V/m and 100 Tesla, respectively, depending on the parameters of the focus. The pulse width ranges from 100 to 3000 fsec. Whereas pulses of oscillating fields may also be generated by lasers, quasi-DC pulses of that amplitude and duration have, with few exceptions, not been available up to now and have not found the attention in solid state physics research that they deserve.

Magnetization switching is one of the basic operations needed in advanced applications of magnetism and therefore one of the most active fields in contemporary magnetism research. More generally, magnetization dynamics is essential to the future of magnetic recording technology where smaller bits and faster magnetic switching are critical. There have been trail blazing experiments at the FFTB using magnetic field pulses with ordinary ferromagnetic metals. The precessional switching mode of the magnetization was demonstrated and some of the physics associated with precessional switching was exposed. It was shown that one can switch the magnetization most economically in a time of approximately one psec with magnetic field pulses applied perpendicular to the magnetization, while traditionally the magnetic field is applied anti-parallel to the magnetization and switching requires roughly one nsec. The next phase of this research involves experiments with femtosecond pulses, comparable to optical laser pulses, for which ultrafast dissipation of the spin angular momentum has been postulated. New physics, highly relevant for the understanding and application of magnetism, in particular magnetic recording, will emerge from these experiments. Preliminary experiments at the FFTB hint at some striking new physics appearing with the large magnetic field pulses of the compressed electron bunches.

A basic issue in ultra-fast magnetization dynamics is the speed with which the angular momentum inherent in the magnetization can be dissipated to the lattice of the solid. The SLAC magnetic field pulses are unique in that they offer the possibility of depositing a large amount of Zeeman-energy and angular momentum directly into the spin system, leading to a non-equilibrium position of the magnetization. Subsequent to this excitation, one observes the relaxation of the magnetization into one of its equilibrium positions as it depends on the duration and amplitude of the magnetic field pulse and the time elapsed after its application.

The response of solid matter to ultra-fast electric field pulses has not been investigated. As a simple example of what could be done, consider a non-magnetic metal with an electron bunch passing close to the surface. The electric field of the bunch will be screened in the metal surface of the sample through motion of the electrons away from the surface. After the bunch has passed, the electrons will flow back to the surface and possibly excite plasma oscillations of the electron gas. The screening dynamics could be studied with probing laser pulses that hit the sample at specific delay times after the field pulse, either by measuring the yield of photoemission of electrons from the metal or simply by observing the optical reflectivity. Generally, the dynamics of electro-optical phenomena are of interest in basic research and key to many applications.

The beam parameters needed to study these phenomena are a high electrical charge of the electron bunch, of order of one nC, a spot size less than 20 μm radius, and good beam stability with low beam jitter to enable multiple shots through the same location in or near the sample. Also important is the ability to vary the length of the electron bunches without affecting their electrical charge. The optimum repetition rate will depend on the type of experiment. For the initial experiments, the test samples could be mounted in a six-way cross with 10 inch flanges at the location of the electron focus. A precision manipulator for moving the samples into or close to the electron beam will require adequate clearance above the beam pipe. More elaborate experiments will need additional space on both sides of the electron beam for the probing laser and the detection systems. If photoemission spectroscopy is employed to detect the probing signal, then an ultra-high vacuum in the beam tube and a sample preparation chamber will be needed.

Because of the many applications in solid state physics, a large user demand for the SABER facility is expected. An extended research program will require significant beam time each year for many years.

2.4 Accelerator and Detector Diagnostic Development

State of the art beams require state of the art diagnostic techniques and devices. The experimental programs in the FFTB had a history of developing diagnostics suitable for characterizing the unique beams. Optical Transition Radiation (OTR) from ultra-thin metallic foils provided the transverse profile of the incoming and outgoing beam for the plasma experiments on a pulse-by-pulse basis with a spatial resolution of a few microns. Coherent THz radiation from these same foils provided both the relative bunch length information for a bunch length feedback system as well as the input for an interferometer that measured the average bunch length of the compressed pulses to be ~ 20 μm. Electro-optic sampling (EOS) of the electric fields surrounding the ultra-relativistic bunch allowed synchronization of the electron beam with respect to an external laser system with a timing jitter of 60 fs to study ultra-fast surface chemistry. Refinements of this technique demonstrated the ability to directly measure the current profile of the ultra-short electron beam in a single shot.

In the last five years, there have been nineteen test beam experiments in the FFTB. While these experiments typically last only a few days each, the high energy density SLAC beams provide valuable information to aid in the design of instrumentation for the high energy physics, astrophysics, and accelerator communities. SABER will build on this legacy and continue to advance beam diagnostic and detector research and development.

2.5 Other Opportunities

Established research programs will continue to probe the scientific frontier at SABER. However, the availability of the unique beams from the SLAC linac with their high energy, high peak current, and small transverse spot size, will also allow new areas of inquiry to flourish, and proposals for new directions of research will undoubtedly arise. Three potential examples, which were discussed at the SABER Workshop, are described below.

2.5.1 Inverse Compton Scattering

Inverse Compton scattering is a compact, alternative way to produce radiation with brightness comparable to third generation light sources. The radiation characteristics are very similar to those of spontaneous undulator radiation, except that the laser wavelength is much shorter than a typical undulator period and thus much higher photon energies can be achieved. In addition, the incident angle between the laser pulse and electron beam provides a degree of freedom to define the radiation wavelength. Several inverse Compton scattering experiments have been carried out elsewhere, but most of them were limited by moderate beam energies of a few tens to hundreds of MeV. The inverse Compton scattering facility at Spring8 has reached the highest photon energy of up to 2.4 GeV with an 8 GeV electron beam and operates as a user facility to complement their standard third generation light sources, which are based on insertion devices.

The SABER facility allows for a significant increase in the photon energy up to 18 GeV. Because the energy is comparable to the energy of the electron beam, strong quantum mechanical effects and a significant blow-up of the energy spread can be expected. This determines also the achievable bandwidth of the radiation, while other effects such as the non-linear component in the scattering process, divergence in the driving laser beam, and the Fourier limitation of the laser pulse length become negligible. Still, with an estimated efficiency of one photon per five electrons, the linewidth of the resultant on-axis radiation should be sufficiently small for experiments that require quasi-monochromatic photons. These experiments will require a large acceptance for the spent electron beam, just as the plasma wakefield experiments require. With photon energies up to 18 GeV, the induced energy spread is large and therefore requires a beam dump with a high energy acceptance.

The inverse Compton scattering layout would allow three scattering angles: head-on collisions (180º), 45º, and 10º. This layout would cover a photon energy range from 200 MeV to 18 GeV, using an electron beam energy of 10 to 30 GeV. A higher beam energy and smaller scattering angle are preferable for even lower photon energies, because the photon divergence is proportional to the inverse of the electron beam energy, and a higher beam energy would therefore increase the brightness of the source. Electron and laser beam sizes of 10 μm would provide a high yield of photons. The driver laser must provide an energy of about one J per pulse. The pulse length can be long (~ 1 psec), because a very short pulse (< 100 fsec) or high intensity would reduce the brightness of the photon beam.

The research program would be initiated by the acquisition and installation of the drive laser and the detector, and the initial experiment would be devoted to characterizing the photon beam, including measurements of the total energy, spectrum, and brightness. The experimental setup for succeeding experiments will depend on experimental details and could range from a single component detector to a full 4π detector with tracking chambers and calorimeters.

The required running time for the inverse Compton scattering experiments will depend on the specific user proposals. Typically, the detectors for these experiments are complex to set up and to move, and therefore long breaks for the set up can be expected, as well as long runs to accumulate enough data for a statistical analysis.

2.5.2 An Intense THz Light Source for Surface Chemistry

There are a vast number of economically important processes that rely on reactions at surfaces and interfaces, such as catalysis in chemical and energy production, the fabrication of computer chips, weathering and corrosion, the behavior of biomaterials and the fate of contaminants in the environment. One important example is the Haber-Bosch process that synthesizes ammonia from nitrogen and hydrogen on an iron or ruthenium catalyst. This process is considered by some to be the twentieth century invention that has had the largest impact on mankind, since it provides the basis for fertilizers and has revolutionized agriculture. As is typical of catalytic reactions, there is an underlying reaction mechanism proposed, but since the reaction intermediates are present only for a short period of time and at extremely low concentrations, they are undetectable under steady-state conditions. As a consequence, it has been extremely challenging to visualize the underlying reaction mechanism and dynamics of catalytic processes at surfaces.

At the surface of a catalyst, the breaking and formation of chemical bonds takes place on a femtosecond time scale. Thus it is necessary to follow the reactions using ultra-fast techniques. Femtosecond visible laser pulses have been used to initiate a surface reaction with optical excitations, but many catalytic processes are driven by thermal and not optical excitations. At the moment, there are no direct ways to thermally induce a catalytic reaction on an ultra-fast timescale.

The blackbody radiation spectrum has a peak in the THz regime at ambient temperature. In this regime, there are excitations of phonons, frustrated vibrational motion of molecular adsorbates, and translational and rotational motion of molecular adsorbates in the physisorption or chemisorption potential well. The temperature-jump method is the most direct way to initiate thermally driven reactions on surfaces. An intense ultra-short pulse of coherent THz radiation generated by the electron beam at the SABER facility can be a unique source for experiments based on the temperature-jump method. Assuming an electron pulse width of 100 fsec, broadband radiation will be obtained with a high frequency cut-off at 10 THz, which is close to black body radiation at room temperature. This radiation can directly excite low-energy vibrational modes below 10 THz, resulting in a temperature jump over a large area. There are no other excitations that generate any large amount of charged hot carriers, making for a clean experiment. Since the atoms and molecules in gas phase do not have these excitations, optical access to the thermally induced phenomena is constrained to the surface as desired.

One of the important developments in the last decade is direct control and manipulation of atoms and molecules. In studies of free molecules, the strong photon field generated in optical lasers has become a powerful tool for controlling atomic and molecular motions. In condensed matter studies, manipulation of individual molecules on solid surfaces is demonstrated by means of scanning tunneling microscopes. These manipulations are achieved by orienting atoms or molecules through the application of a strong photon or electric field (1 to 3×10^9 V/m typically). The coherent THz radiation from the SABER facility would generate a strong electric field that is on the same order as that in scanning tunneling microscopes, but over a much wider area of the substrate. The quasi half-cycle pulse character of the radiation corresponds to a strong ultra-short half-cycle unipolar pulse, followed by a weak extended tail of opposite polarity. During the peak of the ultra-short half cycle pulse, the atoms and molecules experience a mean field similar to the static field applied in scanning probe microscopy.

The SABER facility will be ideal for studying the dissociation of aligned molecules at the surface of a single crystal induced by a THz pulse. It will be possible to demonstrate the temperature-jump method and study THz photon field induced surface chemistry experiments. The THz pulse polarization dependence of reaction products will be analyzed. A high charge (several nC) and short pulse (sub-100 fsec) will be needed to generate intense coherent synchrotron radiation with a high cut-off frequency. The apparatus will include a dipole magnet with a large vacuum chamber to collect the coherent THz radiation and will require approximately 80 square feet of floor space in the experimental area. This program can productively use several weeks of beam time per year.

2.5.3 Laboratory Astrophysics Experiments

Ultrahigh-energy cosmic rays and photons have been observed, but their sources and production mechanisms are yet to be understood. SABER will provide beams for a laboratory astrophysics program which will contribute to the understanding of cosmic accelerators through testing and calibration of cosmic ray observational techniques and through investigations of relativistic jet-plasma dynamics to elucidate the underlying physics of cosmic acceleration. Two innovative experiments belonging to the first category have already been done at the FFTB. The FLASH experiment (E-165) helped shed light on the apparent discrepancies in the energy determinations of 10^{19} eV cosmic rays by making precision measurements of air fluorescence yields in electromagnetic showers under various conditions. The T-460 experiment demonstrated the principle of a novel detection technique for ultra-high-energy cosmic neutrinos based on a radio

Cherenkov signal produced by the Askaryan effect. Such experiments will also be possible at SABER. The uniqueness of SABER, however, lies in its capability to provide high-energy-density beams at 10^{16} J/m^3, creating extreme relativistic plasma jets in a regime relevant to cosmic acceleration studies and accessible in a terrestrial environment for the first time.

Relativistic jets, commonly observed in astrophysical sources such as active galactic nuclei and gamma-ray bursts, are key elements in models of cosmic acceleration. An understanding of their dynamics is therefore crucial. Of particular interest is the possibility that a jet's kinetic energy is converted into plasma instabilities, which in turn power particle acceleration and radiation. Recent simulation studies have shown that jet-plasma interactions result in filamentation, leading to inductive as well as electrostatic (wakefield) acceleration to the order of a GeV. This could account for the observed gamma rays and provide an injection mechanism for other ultra-high-energy acceleration models. Mechanisms have been suggested whereby cosmic particles can in principle be accelerated beyond 10^{20} eV in wakefields excited by Alfven shocks produced, for example, in gamma ray bursts. While extreme astrophysical conditions cannot be fully replicated in the laboratory, carefully devised experiments may uncover the underlying physical principles, which can then be scaled up to understand these powerful astronomical sources.

At SABER, relativistic electron-positron plasma "jets" can be created by a high-energy-density beam showering in a solid target. The dynamics of jet-plasma interaction can be investigated over a scale-length of tens of collisionless skin-depths. In a collisionless plasma, the mean free path is long compared to the skin-depth, so the latter is the relevant scale. Current simulation techniques can accurately resolve the physics on this scale. Laboratory results can thus be applied to astronomical collisionless plasmas and provide important tests of these simulations. Some of the important questions to be addressed are the following. Will magnetic filamentation occur, and cause inductive and wakefield acceleration? Will the radiation spectrum mimic that observed in astrophysical sources? What are the damping and saturation mechanisms that allow astrophysical jets to survive these violent plasma instabilities and propagate long distances? Magnetic fields probably contribute to this stability and will be addressed by imposing a background field of varying strength and configuration. The effects of radiation damping will be studied as well. Can an Alfven shock propagating in a relativistic plasma excite wakefields, and thereby accelerate particles to ultra-high-energy? A two-stage experiment will test whether particles accelerated as a result of magnetic filamentation will be able to seed ultra-high-energy acceleration in the Alfven shock wakefield.

A key parameter in the filamentation process is the skin-depth, which needs to be small compared to the transverse beam size. The skin-depth is inversely proportional to the plasma density. SABER is needed to provide high density bunches (2 to 4 x 10^{10} e^-/pulse; $\sigma_{x,y}$ = 10 to 50 μm; σ_z = 40 μm) at energies above 10 GeV. The facility must be shielded to accommodate the beam showering in a 6 to 7 radiation length target, and have sufficient space to mount experimental and diagnostic equipment. Beamline space will be needed for the target and solenoid magnets, and for current toroids, beam position monitors, transition radiation diagnostics, and spectrometer apparatus.

SABER is designed to provide the beams needed to carry out the science programs described above. The parameters of these beams are summarized in Table 1. As the program descriptions above indicate, the listed beam parameters are not all needed for each experimental program.

The laboratory astrophysics program, as currently envisioned, could productively use two months of beam time per year, distributed in blocks of three weeks each, for three to five years.

2.6 Summary and Conclusions

The SABER facility will provide high peak current, high energy electron and positron beams for high profile research in several areas of physics. SABER will build on the legacy of the FFTB and provide new capabilities that may lead to new discoveries.

Several ongoing research programs have clear paths forward at SABER. This facility will be a unique resource for investigating new ideas for accelerating and focusing both electron and positron beams at highly relativistic energies. Experiments with short electron bunches at the FFTB have already demonstrated that plasma accelerators can sustain accelerating fields of ~ 50 GeV/m for almost a meter. Similar experiments will be possible at SABER to investigate the acceleration of positrons, as well as electrons, and with similar gradients. Another FFTB experiment explored a wakefield accelerator concept based on electric fields near dielectric materials and indicated that dielectric materials can sustain surface fields of more than a few GeV/m. Experiments at SABER will take the next step by using these fields to accelerate electrons and positrons.

Magnetization dynamics is essential to the future of magnetic recording technology, where the quest for smaller bits and faster magnetic switching is critically important. FFTB experiments have demonstrated that while conventional magnetic switching (where an external magnetic field is applied anti-parallel to the magnetization) is limited to nanosecond timescales, switching can occur at the picosecond timescale when the external field is applied perpendicular to the magnetization. Experiments at SABER will use the femtosecond bunches to investigate the ultimate speed limit for magnetic switching.

A look at the rich publication history of the FFTB (Appendix A) illustrates that many areas of research were not foreseen when the FFTB was originally constructed. A recent workshop at SLAC demonstrated that the range of ideas for additional areas of inquiry continues to expand. SLAC is the only place in the world that can provide the high peak current, high-energy electron and positron beams that make this research possible.

3. SABER Description

3.1 SABER Systems

The SABER consists of modifications to three areas of the SLAC linac and beam delivery systems. The overall site layout is shown schematically in Figure 1. The bunch compressor in Sector 10 of the linac will be upgraded to compress positron bunches as well as electron bunches. A new bypass line will be installed to extract the accelerated beam from the linac at Sector 20 and transport it to the Beam Switch Yard (BSY). The bypass line will then be coupled to the South Arc where the bunch will be further compressed and focused as it is delivered to an experimental region near the Main Control Center.

3.1.1 South Arc

The SLAC Linear Collider (SLC) facility, which completed its experimental program in 1998, consisted of two arcs which transported beams of electrons and positrons to a collision point in a large experimental hall. The magnets, vacuum systems, and other components of the South Arc have not been used since the SLC program ended, but have been preserved in the tunnel and can be restored to working condition with modest effort.

During SLC operation, the accelerated positron beam was separated from the electron beam and deflected into the South Arc by a dipole magnet at the end of the linear accelerator. From this point, the beam was further bent and focused as it passed through the BSY to the first of 460 combined-function alternating-gradient magnets which guided the beam to the final focus. These magnets formed 23 achromatic groupings of 20 magnets each. Each achromatic group was designed to deflect the beam through a total angle of approximately 10.3 degrees without changing its size, shape, or angular divergence.

Following the second achromatic group is a 200 foot long straight section designated the Instrument Section, which consists of a sequence of quadrupoles, dipoles, and various diagnostic instruments. This straight section will be modified with a beam dump and a dispersion-free drift section to accommodate experimental apparatus. Additional quadrupole magnets will be added to focus the beam to small spot suitable for a variety of experiments. If needed, a portion of the arc downstream of the Instrument Section will be removed to create more space for experimental apparatus.

As an option for later expansion, the beam could be transported through six more achromatic groups to the Reverse Bend Section. This is another straight section similar to the Instrument Section, which could also be modified to accommodate experiments, although tunnel access issues and the additional beam transport requirements make this option less desirable than the Instrument Section. Refurbishment of the Reverse Bend Section is not part of the present plan, but the accelerator components will be preserved in place in the tunnel.

3.1.2 Tunnel Access

The South Arc tunnel as currently configured can be entered from the Southeast Adit spur tunnel, an entrance point approximately 1000 m along the arc tunnel from the proposed new experimental area. This entrance may be adequate for initial restoration and arc hardware tests, but is very inconvenient for use in installing experimental equipment and carrying out a scientific program.

The Southwest Adit was originally used as a tunneling excavation access point during the SLC construction project, but was sealed with concrete shielding blocks before SLC beam commissioning activities began. This adit, which consists of a ramp and a short spur tunnel, intersects the South Arc tunnel near the upstream end of the Instrument Section at a point ideal for access to the SABER experimental area. A new entrance door and appropriate radiation shielding will be installed at this point with standard personnel-protection-system (PPS) provisions to allow user access under controlled conditions. The top of the ramp opens into a large paved area currently used for parking and material storage. This area offers ample room for a portable laboratory building or trailer to house experimenter data acquisition and control facilities. The layout of the tunnels, including the proposed new entrance point, is illustrated in Figure 2.

3.1.3 Positron Compressor

A bunch compressor system was installed in Sector 10 of the linac in 2002 and was used in conjunction with previously existing accelerator systems to compress electron bunches to less than 100 fsec as they were delivered to experimenters in the FFTB tunnel. The key components of the electron compressor system are four identical dipole magnets which form a magnetic chicane. Upstream of this chicane, the linac RF system is tuned to introduce a correlation between the momentum of the electrons and their longitudinal position within the bunch, such that the higher momentum electrons are shifted toward the trailing end of the bunch. As the bunch passes through the chicane, the electrons with lower momentum follow a longer path, allowing the higher momentum electrons to catch up, resulting in a significantly shorter bunch.

This system works well for electron bunches, but cannot be used for positrons. This lack of symmetry comes about because positrons are produced by first accelerating electrons, which must pass through the same section of the linac. The compressor system as it currently exists allows only negatively charged particles to pass. This limitation can be overcome by installing two more dipole magnets identical to the others, but on the opposite side of the linac. The support structures that were installed for the electron compressor can also support the additional hardware needed for positrons with only minor modifications. New vacuum chambers will be needed to pass the diverging and recombining beam paths of the electrons and positrons, and some additional instrumentation will be required to facilitate steering and focusing the two beams simultaneously.

3.1.4 Bypass Line

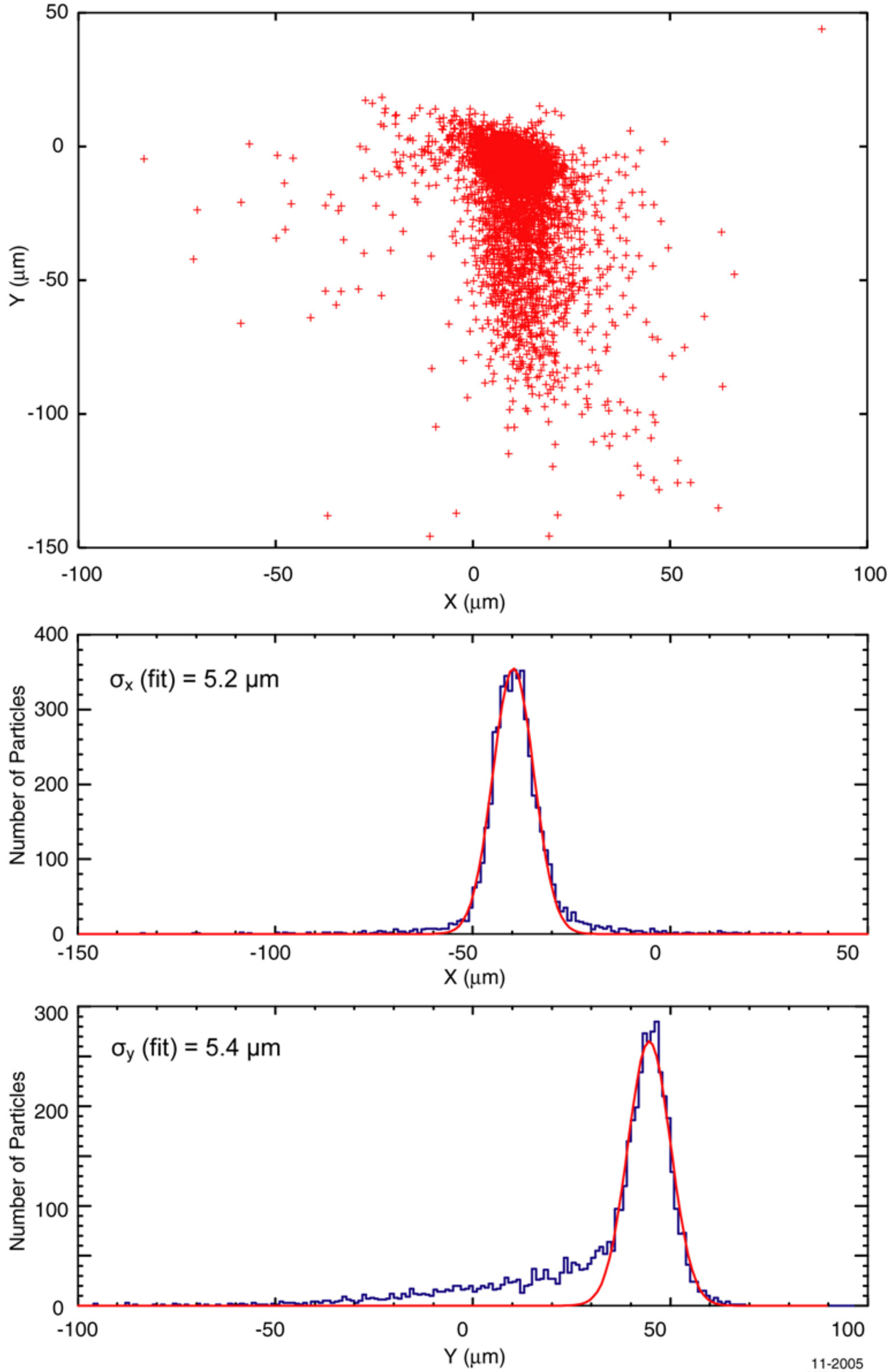
The bypass line will start with a new bending magnet installed along the linac in Sector 20 downstream of the existing positron production system and upstream of the new LCLS injection system. From this point, an accelerated beam can be deflected from the linac and transported gradually upwards and outwards to a new trajectory parallel to the linac above the walkway in the existing tunnel. The beam will be transported nearly 1000 m through a beam pipe suspended from the tunnel ceiling to the BSY, where it will be deflected through a series of bend magnets to match the original South Arc beam trajectory and optical parameters. The bypass line will also require a sequence of quadrupole and steering corrector magnets to focus and steer the beam as it is transported to the BSY. In addition, sextupole magnets will be needed in the dog-leg bending sections near the beginning and end of the long transport line to cancel second-order chromatic effects that would otherwise lengthen the final bunches. The vacuum system, mechanical supports, diagnostic instruments, and many of the magnets are identical or very similar to the corresponding devices in the two existing transport lines used to deliver electrons and positrons to fill PEP-II.

3.2 Beam Parameters

The beam parameters needed to carry out the science program outlined above are summarized in Table 1. Tracking programs that include second order effects have been used to compute the beam properties that can be expected with SABER. The spot size at the focal point is shown in Figure 3, and the bunch length and energy spread are shown in Figure 4.

Table 1. SABER beam parameters.

Energy	Adjustable up to 30 GeV nominal. 28.5 GeV when the bypass line is used concurrently with PEP-II operation.
Charge per pulse	2×10^{10} (3 nC) e^- or e^+ per pulse with full compression; 3.5×10^{10} e^- or e^+ per pulse without full compression.
Pulse length at IP (σ_z)	33 μm with 4 % fw momentum spread; 45 μm with 1.5 % fw momentum spread.
Spot size at IP ($\sigma_{x,y}$)	10 μm nominal (5.2 x 5.4 μm achieved in computer simulations).
Momentum spread	4 % full width with full compression; < 0.5 % full width without compression.
Momentum dispersion at IP (η and η')	0
Drift space available for experimental apparatus	2 m from last quadrupole to focal point. Approximately 23 m from the focal point to the Arc 3 magnets. Further expansion is possible by removing unused arc magnets downstream.



11-2005
8732A01

Figure 3. Spot size at the focal point, as computed by tracking simulation.

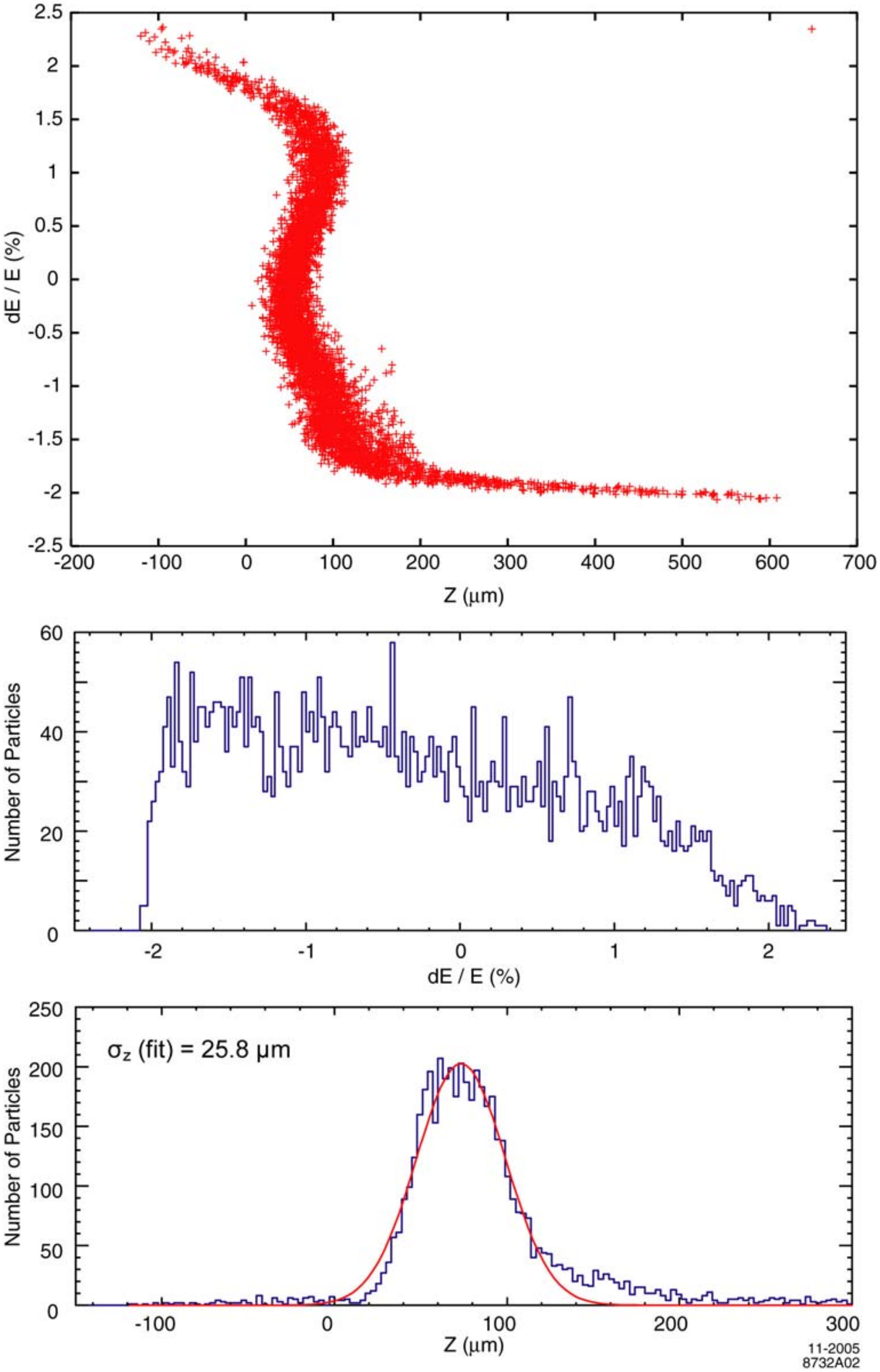


Figure 4. Bunch length and energy spread for compressed bunch at the focal point.

Compressing a bunch longitudinally involves increasing the momentum spread due to phase space considerations. Achieving a pulse length of 32 μm will require transporting a beam with a momentum spread of 4 percent full width. Calculations show that if the momentum spread is limited to 1.5 percent full width, then a bunch length of 45 μm can still be achieved.

SABER can be used to compress and deliver either electrons or positrons to the experimental area. Switching between electrons and positrons will require reversing the polarities of a large number of magnets, so this will not be practical as a routine operation; however, switching polarities can be done when the research program requires the opposite charge, and identical beam parameters can, in principle be, achieved. The work required to switch polarities can be done outside the linac housing without interfering with any other running accelerator program.

3.3 Component Production

Many of the components for SABER, including magnets, vacuum equipment, diagnostic devices, electronics, and power supplies have been salvaged from the FFTB and SLC facilities and will be reused directly or refurbished as needed. Other components will be acquired from outside vendors or fabricated in SLAC shops. Many of the new components will be constructed using proven designs from other SLAC facilities. For example, the new components for the positron compressor chicane will be similar to components that are now used to compress electrons. The vacuum system for the bypass line is nearly identical to that of the PEP-II injection lines, and the quadrupole magnets will have the same cross sectional profile as those of the PEP-II injection lines and therefore can be constructed with identical laminations. Many of the other components are identical to, or simple extensions of, designs used in the PEP-II injection lines or the SLC final focus.

3.4 Time Scale

The installation of SABER components will extend over a three year period. However, beams will be deliverable to experiments between installation downtimes throughout this period, with performance and functionality improvements as new features are commissioned. The installation and commissioning will proceed as follows, subject to funding limitations:

Spring-Summer 2007:
Delivery of initial beam to a crude experimental region. Beam operation with either electrons or positrons will be compatible with simultaneous PEP-II operation and with most LCLS injector commissioning activities during this period. A 10 Hz beam of 2×10^{10} particles/pulse at 28.5 GeV will be deliverable to SABER with a spot size ($\sigma_{x,y}$) of about 120 μm x 40 μm. A compressed electron bunch length (σ_z) of about 50 μm may be achievable with a concerted machine studies program. The positron bunch length (σ_z)

will be limited to about 300 μm minimum until the positron compressor system is installed. An experiment compatible with these beam parameters could expect two to four weeks of beam time.

The first phase of LCLS beam commissioning will begin during this period. This commissioning work, which is fully compatible with simultaneous PEP-II operation, will sometimes require the last third of the linac, and then will be incompatible with SABER operations. The LCLS is designed to accommodate switching between LCLS and SABER operating modes in a few minutes without entering the tunnel. Another possible operating mode during this period would use the LCLS injector system to provide compressed electron bunches for SABER, but the beam energy would be limited to about 14 GeV, and the charge per pulse would be limited to about 2×10^9 electrons/pulse.

Fall 2007:
Installation of the positron bunch compressor in the linac housing and upgrade of the experimental region. This work will include the addition of focusing quadrupoles and other devices to accommodate experiments and the installation of a controlled entry point in the Southwest Adit tunnel.

Spring-Summer 2008:
Delivery of high quality beams to the upgraded experimental region as consistent with the LCLS commissioning program. Electron or positron beams will be deliverable to the experimental area with fully compressed bunches.

Fall 2008:
Installation of half the bypass line, beginning at Sector 20 in SLAC linac tunnel.

Fall 2008 to summer 2009:
Delivery of high quality electron or positron beams to the fully developed experimental region, as consistent with LCLS commissioning activities, as in summer 2007 and summer 2008.

Summer 2009:
Completion of installation of the bypass line in the SLAC linac tunnel, subject to other program scheduling requirements.

Fall 2009:
Full SABER operation, independent of LCLS operation.

Future Opportunities

The beam parameters achievable with SABER as proposed here will be adequate to support the science programs outlined above. However, if the results from these programs lead to proposals with more stringent demands on the beam, then the facility could be upgraded with one or more hardware improvement projects or changes in operating parameters, depending on the specific requirements. Among the possibilities are the following:

1. The energy of the damping rings could be lowered, which would reduce the beam emittance. This would provide higher charge density in both electron and positron bunches. Calculations have shown that if the damping ring energies were lowered from 1.2 GeV to 0.9 GeV, a final bunch length of 13 μm could be achieved.

2. A new photo injector, based on the design developed for the LCLS project, could be installed at the west end of the linac to produce very short, low-emittance electron bunches without the need for the damping ring.

3. The compressor chicane in Sector 10 could be moved upstream, which would improve the bunch compression without increasing the momentum spread.

4. An additional experimental area could be developed in the “reverse bend” straight section of the South Arc, allowing greater flexibility in setting up two or more experiments.

5. With a systematic program of machine studies and tuning, it may be possible to increase the charge per pulse by up to a factor of two while maintaining an emittance acceptable for most experiments.

3.5 Budget

The budget estimates for SABER are listed in Table 2, with separate estimates shown for the positron bunch compressor, bypass line, South Arc upgrade, and changes to the personnel protection system. The column labeled B&H includes all materials and shop labor. The total estimated cost is 17.3 M$, including SLAC laboratory burden and an overall contingency of 25%. The installation work will be completed over a three year period. During this time, beams will be delivered every year starting in calendar year 2007.

The cost of the bypass line could be reduced by about 5 M$ if one of the existing PEP-II injection transport lines could be reconfigured for this purpose. This will become an option when the PEP-II program is completed at the end of FY08, unless some other research program arises that requires the use of the complete PEP-II system.

Table 2. SABER Cost Estimate

WBS		B&H (k$)	EDI (k$)	Indirects (k$)	Contingency (k$)	Total (k$)
1	**Overall SABER Cost**	**8644**	**1331**	**3468**	**3449**	**17295**
1.1	**Personnel Protection System**	**70**	**40**	**30**	**30**	**170**
1.2	**South Arc Upgrade**	**944**	**443**	**499**	**472**	**2358**
1.2.1	Magnets	68	66	65	50	249
1.2.2	Supports	112	54	50	54	270
1.2.3	Plumbing and facilities	165	135	125	106	531
1.2.4	Power supplies and cables	105	27	40	43	215
1.2.5	Vacuum system	229	114	119	116	578
1.2.6	Controls and instruments	62	25	27	28	142
1.2.7	Alignment and installation	203	22	73	75	373
1.3	**Positron Bunch Compressor**	**813**	**156**	**286**	**301**	**1556**
1.3.1	Magnets	328	39	104	108	579
1.3.2	Supports	69	14	27	27	137
1.3.3	Plumbing and facilities	30	2	11	12	55
1.3.4	Power supplies and cables	54	20	22	24	120
1.3.5	Vacuum system	233	65	87	92	477
1.3.6	Controls and instruments	50	10	18	20	98
1.3.7	Alignment and installation	49	6	17	18	90
1.4	**Linac Bypass Line**	**6817**	**1095**	**2653**	**2646**	**13211**
1.4.1	Magnets	1258	262	536	514	2570
1.4.2	Supports	1270	181	505	489	2445
1.4.3	Plumbing and facilities	555	154	243	238	1190
1.4.4	Power supplies and cables	679	97	233	252	1261
1.4.5	Vacuum system	2207	213	803	810	4033
1.4.6	Controls and instruments	304	98	121	131	654
1.4.7	Alignment and installation	544	90	212	212	1058

4. Summary and Conclusion

The SABER facility is being proposed for the relocation of the FFTB. The preceding descriptions show there would be a wide variety of science at SABER ranging from advanced accelerator research to solid state physics to laboratory astrophysics. This world-class science can only be performed with the unique SLAC electron and positron beams, and SLAC is uniquely positioned to realize these opportunities by constructing SABER.

5. References

- *The Stanford Two Mile Accelerator*, R.B. Neal, Editor (November 1968).
- *SLC Design Handbook*, R. Erickson, Editor (November 1984).
- P. Krejcik et al, *Commissioning of the SPPS Linac Bunch Compressor*, PAC'03, Portland, OR, USA, SLAC-PUB-9858, (2003).
- P. Krejcik, *A New Beamline for High Density Test Beams at SLAC*, internal note, February 2003.
- *LCLS Conceptual Design Report*, SLAC-R-593, 2002.
- R. Erickson et al, *SABER Optical Design*, SLAC-PUB-11944 (2006).

Appendix A: Peer Reviewed Publications From Work Done in the FFTB

Beam-Plasma:

1) M. J. Hogan *et al., "*E-157: A 1.4 Meter-Long Plasma Wakefield Acceleration Experiment Using A 30 GeV Electron Beam From The Stanford Linear Accelerator Center Linac", Physics of Plasmas **7**, 2241 (2000).

2) P. Muggli *et al.,* "Collective Refraction Of A Beam Of Electrons At A Plasma-Gas Interface", Nature **411**, 43 (3 May 2001)

3) P. Catravas *et al.,* "Measurements Of Radiation Near An Atomic Spectral Line From The Interaction Of A 30 GeV Electron Beam And A Long Plasma", Physical Review E **64** 046502 (2001).

4) P. Muggli *et al.,* "Collective Refraction Of A Beam Of Electrons At A Plasma-Gas Interface", Physical Review Special Topics - Accelerators and Beams **4**, 091301 (2001).

5) J. S. T. Ng *et al.*, "Observation of plasma focusing of a 28.5-GeV positron beam" Physical Review Letters **87**:244801 (2001).

6) S. Lee *et al.,* "Energy Doubler For A Linear Collider", Physical Review Special Topics - Accelerators and Beams **5**, 011001 (2002).

7) Shouqin Wang *et al.,* "X-Ray Emission From Betatron Motion In A Plasma Wiggler", Physical Review Letters **88**, 135004 (2002)

8) C. E. Clayton *et al.,* "Transverse Envelope Dynamics Of A 28.5 GeV Electron Beam In A Long Plasma", Physical Review Letters **88**, 154801 (2002)

9) C. Joshi *et al.,* "High Energy Density Plasma Science With An Ultra-Relativistic Electron Beam", Physics of Plasmas **9**, 1845 (2002).

10) C. O'Connell *et al.,* "Dynamic Focusing Of An Electron Beam Through A Long Plasma", Physical Review Special Topics – Accelerators and Beams **5**, 1121301 (2002)

11) C. Field *et al*., "A Monitor of the focusing strength of plasma lenses using MeV synchrotron radiation" Nuclear Instruments and Methods A **489**:68-74 (2002).

12) M. J. Hogan *et al.,* "Ultrarelativistic-Positron-Beam Transport through Meter-Scale Plasmas", Physical Review Letters **90**, 205002 (2003).

13) B. Blue *et al.,* "Plasma Wakefield Acceleration of an Intense Positron Beam", Physical Review Letters **90**, 214801 (2003).

14) C. Joshi and T. Katsouleas, "Plasma Accelerators at the Energy Frontier and on Tabletops", Physics Today, 47 (June 2003).

15) P. Muggli *et al.,* "Meter-Scale Plasma-Wakefield Accelerator Driven by a Matched Electron Beam", Physical Review Letters **93**, 014802 (2004).

16) R. Maeda et al., "On the Possibility of a Multi-bunch Afterburner for Linear Colliders", Phys. Rev. ST Accel. Beams 7, 111301 (2004).

17) M. J. Hogan *et al.,* “Multi-GeV Energy Gain in a Plasma-Wakefield Accelerator”, Physical Review Letters **95** 054802 (2005).

Compton Scattering:

1) C. Bula *et al*., “Observation of nonlinear effects in compton scattering”, Physical Review Letters **76**(17):3116–3119 (1996).

2) T. Kotseroglou *et al*., “Picosecond Timing of Terawatt Laser Pulses with the SLAC 46 GeV Electron Beam”, Nuclear Instruments & Methods A, **383**, 309 (1996).

3) D. L. Burke *et al*., “Positron production in multiphoton light-by-light scattering” Physical Review Letters **79**(9):1626–1629 (1997).

4) C. Bamber *et al*., “Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses” Physical Review D **60**(9):092004 (1999)

Magnetism, Solid State and Fast Time-Scale Physics:

1) I. Tudosa *et al*., “The Ultimate speed of magnetic switching in granular recording media” Nature **428**:831-833 (2004).

2) C. Stamm *et al*., “Dissipation of Spin Angular Momentum in Magnetic Switching” Physical Review Letters **94**, 197603 (2005).

3) K. J. Gaffney *et al*., “Observation of structural anisotropy and the onset of liquidlike motion during the nonthermal melting of InSb”, Physical Review Letters **95**(12):125701 (2005).

4) A. M. Lindenberg *et al*., “Atomic-scale visualization of inertial dynamics”, Science, **308**:392–395 (2005).

5) A. L. Cavalieri *et al*., “Clocking femtosecond x-rays”, Physical Review Letters **94**:114801 (2005).

6) D. M. Fritz *et al*., “Femtosecond mapping of the interatomic potential of a highly excited solid”, submitted to Nature (2006).

Laboratory Astrophysics:

1) D. Saltzberg *et al*., “Observation of the Askaryan effect: Coherent microwave Cherenkov emission from charge asymmetry in high-energy particle cascades” Physical Review Letters **86**:2802-2805 (2001).

2) P. W. Gorham et al., “Accelerator measurements of the Askaryan effect in rock salt: A Roadmap toward teraton underground neutrino detectors” Physical Review D **72**:023002 (2005).

3) J.W. Belz *et al*., “Measurement of pressure dependent fluorescence yield of air: Calibration factor for UHECR detectors” Astroparticle Physics 25:129-139 (2006).