3. CENTER FOR BEAM PHYSICS

In nineteen ninety-six and ninety-seven, we have been witnessing significant expansion— in breadth, depth and scope — of the Center's research and development activities. Originally chartered as the Exploratory Studies Group in 1985, we were soon recognized and organized as a divisional Center, in accordance with our mission: to help meet the technical challenges of major facilities and initiatives (local, national and international) and to generally enhance Berkeley Lab's capabilities in particle and photon beam research.

Our staff played a pivotal role in the design, construction, and commissioning of the Advanced Light Source. We were also one of the primary players in the genesis of PEP-II, the energy-asymmetric B-meson factory at the Stanford Linear Accelerator Center that has since evolved into a major collaborative construction project. The project, when completed, will greatly facilitate the study of CP violation. Our scientists and engineers remain involved with the ALS and PEP-II, especially in beam dynamics studies and in rf and feedback systems. (The technical problems are similar; PEP-II benefits from ALS experience and, with care to avoid disrupting user operations, we can use the ALS as a testbed.) Meanwhile, with an eye toward the future of accelerators, we have spearheaded a collaboration on the preliminary design of the Next Linear Collider (NLC), a possible successor to the Stanford Linear Collider in high-energy physics with lepton collisions.

The NLC that we are envisioning would have a 500-GeV center-of-mass collision energy. The Center's responsibilities in this collaboration with the Stanford Linear Accelerator Center include damping rings, an interaction point for gamma-gamma collision physics to leverage the investment, and scenarios and technologies for an eventual upgrade to 1 TeV. The energy-upgrade studies are intimately tied to the Two-Beam Accelerator (TBA) concept that we have been exploring for some years in collaboration with Lawrence Livermore National Laboratory. The collaboration is now constructing a testbed at LBNL for a relativistic-klystron TBA where we would prototype the technology that could serve as the source of rf power for the NLC upgrade.

Yet another major development has been the emergence of the Muon Collider concept. LBNL has been chosen by the national muon collider collaboration to coordinate work on the collider ring and this work is predominantly done through the Center.

We continued expanding our experimental capabilities over the past year. The Beam Test Facility, which will increase the benefits of the ALS by using the injection-linac beam between injection cycles, was fully commissioned. Besides

the first two experiments under current study — plasma focusing of beams and generation, detection, and use of femtosecond x-ray pulses — preparations are under way for research into laser acceleration, laser guiding, optical stochastic cooling, and the entropy of particle and photon beams. And short-pulse tabletop terawatt lasers are being added to our Laser Optics Laboratory (now named the "l'OASIS lab") so we can embark on various laser-plasma-particle interaction studies for novel acceleration, diagnostics and control techniques.

Aside from the growth in these activities, we have also continued making progress in our traditional focus areas: accelerator theory, linear and nonlinear beam dynamics, the fundamental physics of free-electron lasers, and high-energy collider physics (including diagnostics and beam cooling for big facilities such as the Large Hadron Collider at CERN and the Relativistic Heavy Ion Collider at Brookhaven). We have joined the LCLS (Linac Coherent Light Source) collaboration with Stanford. Major collaborative initiatives with LLNL and JAERI (Japan Atomic Energy Research Institute) are under way for studies of laser manipulation of beams. And our diverse research and educational activities have enjoyed enhanced participation by students and international visitors, and collaborations, old and new, with various institutions around the world.

Swapan Chattopadhyay, Center Director

Advanced Collider Physics

Our advanced-collider-physics research in 1996 culminated in the Snowmass Workshop, under the auspices of the Division of Physics of Beams and the Division of Particle and Fields of the American Physical Society, with our scientists responsible for one of the five accelerator working groups.

A significant result, strongly promoted by the Advanced Accelerator Concepts working group leaders—S. Chattopadhyay and D. Whittum together with J. Wurtele—was a consensus that the beamstrahlung constraint in collider design must be circumvented by improvements in detectors, or compensated collisions, or some similar concept. Such a procedure would modify collider scalings to help meet the challenges faced by short wavelength (THz, plasma-based, laser, etc.) accelerator designs. In addition to conventional e^+e^- collisions, a complementary, photon-on-photon approach— a gamma-gamma collision arm—was spearheaded by LBNL with Kwang-Je Kim as its leader, in collaboration now with SLAC and LLNL.

LBNL was chosen by the collaboration to coordinate work on the collider ring and to give an invited presentation at Snowmass; see the chapter on the collider

ring in "$\mu^{+-}\mu^{-}$ Collider: A Feasibility Study," LBNL-38946, Chapter 8, pp. 313-360. The feasibility problem was studied and much discussed at the workshop, but the larger problem faced by the US high-energy community was not. Without some new development, we face the possibility that the United States will have no high energy facility beyond the Tevatron and PEP-II. The muon collider could be that new development. But only continued intensive collaboration, supported by a vigorous and well-conceived R&D program, can bring this to fruition. As a part of that effort, LBNL continues to coordinate the ring design and has led, together with FNAL, a week-long workshop on the collider ring and detector here. Berkeley Lab, via the Center, is also leading the upcoming Workshop on Muon Colliders.

Finally, the Center has contributed extensively to the design of the PEP-II "B factory" being built at SLAC. These results are detailed in the next chapter.

Reported by Swapan Chattopadhyay

Gamma-Gamma Collider

An e^{+}-e^{-} collider can be made into an e^{-}-γ or γ–γ collider by converting the electrons into gamma rays via Compton backscattering with terawatt laser beams, as shown schematically in Figure 3-1. This is desirable because γ–γ collisions could provide unique access to some areas of fundamental physics, for example, direct measurement of the partial decay width of a Higgs boson into two γ quanta. The data from γ–γ collisions also supply desirable redundancy to the data from e^{+}-e^{-} collisions. In March 1994, the Center organized a Workshop on Gamma-Gamma Colliders to examine these issues. It was concluded during the workshop that a future linear collider should additionally incorporate e^{-}-γ and γ–γ collisions as this will have a relatively small incremental cost, and that the technology is sufficiently advanced today to consider a γ–γ collider.

In early 1995, an international collaboration was organized to complete a gamma-gamma IR design for the ZDR (Zero-order Design Report) of the Next Linear Collider. Under the coordination of the Center, a weekly video conference has been established, and extensive work has been carried out by scientists from LBNL, LLNL, SLAC, Rochester University, University of Tennessee, Hiroshima University, KEK (Tsukuba, Japan), and BINP (Novosibirsk, Russia). This work culminated in the ZDR and in the special session of presentations on gamma-gamma collider design at Snowmass '96.

The physical processes in the γ–γ interaction region are more complicated than in the case of e^{+}-e^{-} collision. One of the most important achievements of the collaboration has been the development and benchmarking of a comprehensive Monte-Carlo simulation code

(CAIN). The code, developed by K. Yokoya at KEK, simulates both Compton conversion and gamma collision. It includes all electromagnetic processes: linear/nonlinear Compton scattering and pair creation at the conversion point (CP), beamstrahlung, disruption, and coherent pair creation at the interaction point (IP).

There are many challenging technical issues involved with the gamma-gamma collider. The high power optical beam has to be transported into the tight space limited by the vertex chamber, the mask, and quadrupoles, and later disposed of. A baseline optical design was provided by D. Klem of LLNL. To remove the spent electron beam after Compton conversion, it is desirable to introduce a magnet, called the "sweeping magnet," between the CP and the IP. A preliminary design of the sweeping magnet based on pulsed coil technology by G. Silvestrov and V. Telnov, of BINP, Novosibirsk, was proposed. Background due to synchrotron radiation from upstream may damage mirrors, and the secondary photons and particles generated in the mirrors may present further problem to the detector. A. Weidemann from SLAC studied these and other background issues and found that with a reasonable model for the synchrotron radiation, the problem appears to be manageable. To optimize luminosity for gamma collision, the final focus system is modified.

The requirements for the laser are extremely challenging: a pulse energy of about 1 Joule, a pulse length of a few picoseconds, an average power of 10 to 20 kW, and variable polarization. M. Perry from LLNL has worked out an approach based on the solid state laser. High power diode lasers for pumping and lasing materials that can handle high thermal loading are two major issues. Fortunately there has been an active development effort in these areas linked to other major military and civilian projects. Based on these developments, the laser needed for a gamma-gamma collider can in principle be built out of 1 kW unit cells.

We have proposed and studied an alternative choice for the laser system, a free electron laser. The FEL uses a pulse stretching, FEL amplifying, and pulse compression technique to produce laser beam of the required characteristics. The requirements for the electron beam are consistent with the induction linac technology. Preliminary study shows that possible degradation of the pulse compression performance due to the phase/frequency fluctuation of the optical beam (caused by the electron beam fluctuation from the induction linac) is small.

Reported by Kwang-Je Kim

Study of a Linear Collider Beyond NLC

It is believed that a linear collider at around 1 TeV center of mass energy can be built with existing technology. But it is practically impossible to go much beyond that energy without new, largely unknown accelerator technology. Apart from knowing the details of the future technology, certain collider constraints are considered quite general and have to be satisfied, such as site power and the constraints imposed by the collision: beamstrahlung, disruption, pair creation, etc. Therefore it would be appropriate to explore the preferred regime of operation, to chart out a region in parameter space based on these constraints, and with that hopefully to offer some guidelines for the current development of advanced accelerator technology.

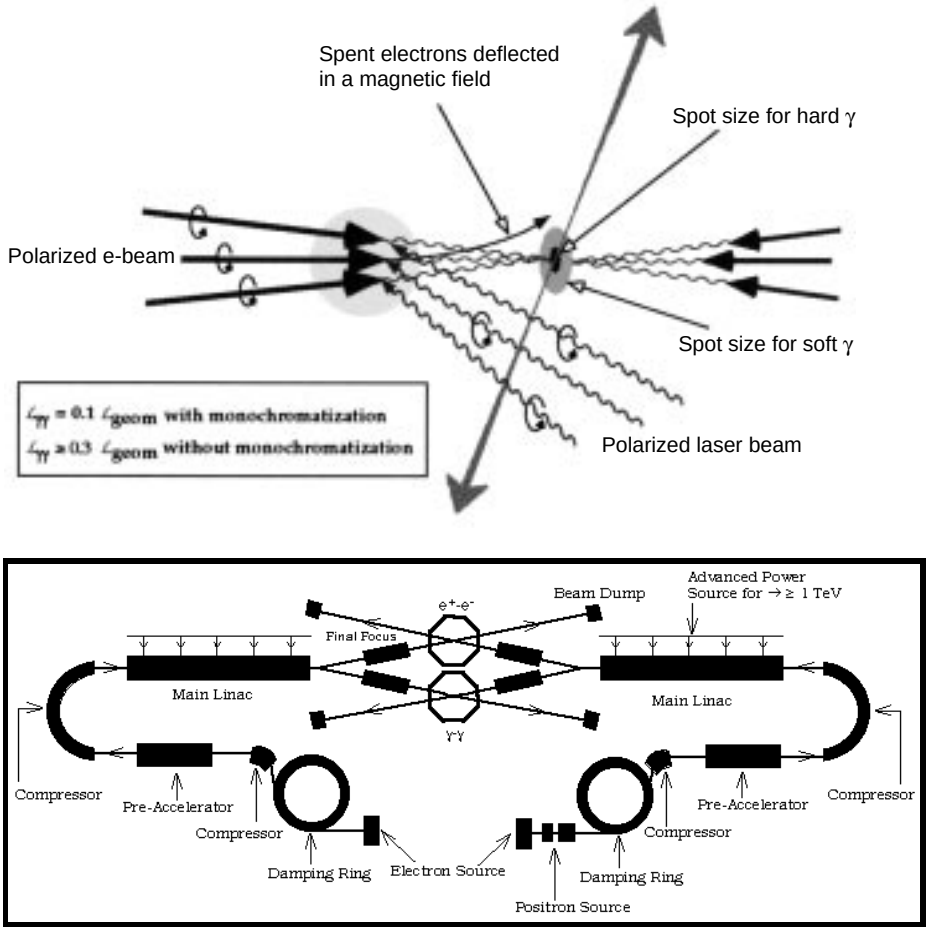

Figure 3-1*. Compton conversion into hard gamma rays by scattering laser photons of a relativistic electron beam, and a schematic of a TeV-scale linear collider with a second IP for gamma-gamma collision.*

Taking such a point of view, we have examined the IP performance of an e+e- collider in a large parameter space at 5 TeV, in collaboration with T. Tajima from the University of Texas at Austin and K. Yokoya from KEK. We found that a major change of paradigms in collider design will be necessary as we go to higher and higher energies. One of the traditional design guidelines for the NLC type of collider is to stay away from the high-Upsilon regime, where Upsilon is a parameter that characterizes the strength of beamstrahlung. However, it becomes increasingly difficult to do so at higher energies. But actually beamstrahlung could be suppressed by a previously known quantum effect, if Upsilon becomes extremely large—under some conditions, of the order of a thousand. It also appears by examining general scalings, that laser wakefield accelerator can be projected, more appropriately than other known acceleration mechanisms, to take advantage of this

effect and satisfy the collider constraints reasonably well. Our simulation of collision at very large Upsilon has confirmed the effect that beamstrahlung-induced energy spread can indeed be suppressed to an acceptable level.

Collective Effects in a High Luminosity Muon Collider

Jonathan Wurtele

Yet another important activity is the research and development for a high luminosity muon collider. Muons have important properties compared to electrons and protons when considering a possible next step for a high energy physics facility. Since radiation by muons is much suppressed compared to electrons, it is feasible to consider a relatively compact circular collider in the TeV energy range. However, the muon, like the electron, is a simple pointlike particle and can be used to explore the same physics regime as protons with approximately ten times higher energy. Accordingly, the muon collider has attracted increasing interest over the past couple of years and a collaboration led by scientists at BNL, FNAL, and Berkeley Lab has been formed.

Since the muon is an unstable particle with a free lifetime that does not allow many turns in the storage ring, there are many new facets of accelerator physics and technology that need to be examined before one can say with confidence that such a device will work. A feasibility study submitted to the Snowmass 96 conference last summer was a first step. Our specific work includes designs of the entire muon collider complex, as well as theoretical studies of beam impedance and stability in the main collider ring. Optimization of muon collider luminosity taking account of their decay time and relatively large phase-space volume leads to a choice of beam parameters markedly different from electron and proton devices. In particular, all of the muons in each of the circulating beams are stored in one or two very short bunches with a peak current two orders of magnitude higher than that of any existing proton or electron device. Controlling single-bunch coherent instabilities will be crucial for successful operation, so we would continue the investigations that have just started.

A relatively newly discovered type of instability that can be a problem at very high beam intensities is the fast ion instability. It arises from the interaction between the ionization products at the head of a bunch or bunch train with the trailing particles to produce unstable coherent oscillations which increase the beam cross section and reduce luminosity. The growth rate of the instability depends on the vacuum pressure in the beam tube. The analysis of the head-tail interaction is similar to analysis of the wakefield electromagnetic interaction between beam and the vacuum chamber, which lead to the beam-breakup instability. The first observations of the multibunch version of this instability were recently made at the ALS. Analysis of this instability for a muon collider, and development of the means to control it if necessary, would be important milestones in muon collider research.

Theoretical examination of single-bunch collective effects in the collider ring of a 2 TeV x 2 TeV μ-μ Collider complex, shown schematically in Figure 3-2. The situation involves an intense bunch, a short bunch, a small amount of momentum compaction, and luminosity lifetime limited by muon decay to a thousand turns.

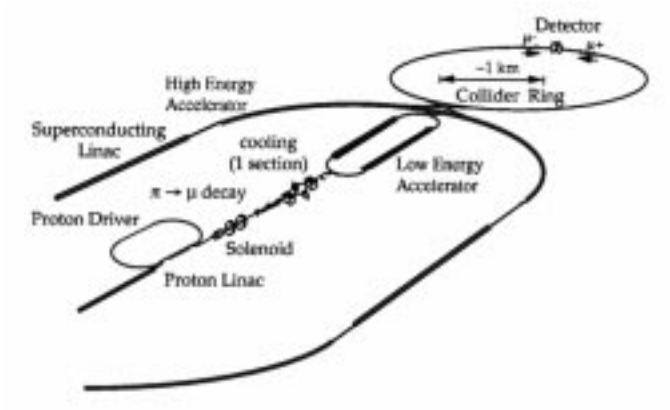

Figure 3-2. A schematic of a muon collider.

Longitudinal Behaviors

The quasi-isochronicity of the muon collider ring makes both the potential-well distortion (a static effect) and the coherent instability (a dynamic effect) important to the preservation of luminosity. In attempting to explore a possible operating point in parameter space, we examined the beam's longitudinal behavior in the collider ring by multi-particle simulations in which the static effect, the coherent effect, the incoherent effect, the nonlinear synchrotron oscillation, and muon decay were all included. Our study shows that, by choosing the parameters properly, the longitudinal behavior of a muon beam in the collider ring is controllable (Figure 3-3).

Transverse Behaviors

The quasi-isochronicity of the muon collider ring also makes the transverse dynamics similar to that of a linac. The use in rings of techniques such as BNS damping, developed for linear colliders, to study the beam-break-up behavior, is investigated. The effects of combination of the chromatic tune spread, beam-beam tune shift, BNS tune shift and coherent tune shift due to the ring and rf impedances, are under examination.

An assessment of the impedance budget is underway to achieve a better study of the collective effects in the muon collider ring. Furthermore, possibilities offered by other technologies, such as bunch rotation and rf gymnastics or temporal modulation of accelerator parameters, are being examined.

Reported by Ming Xie

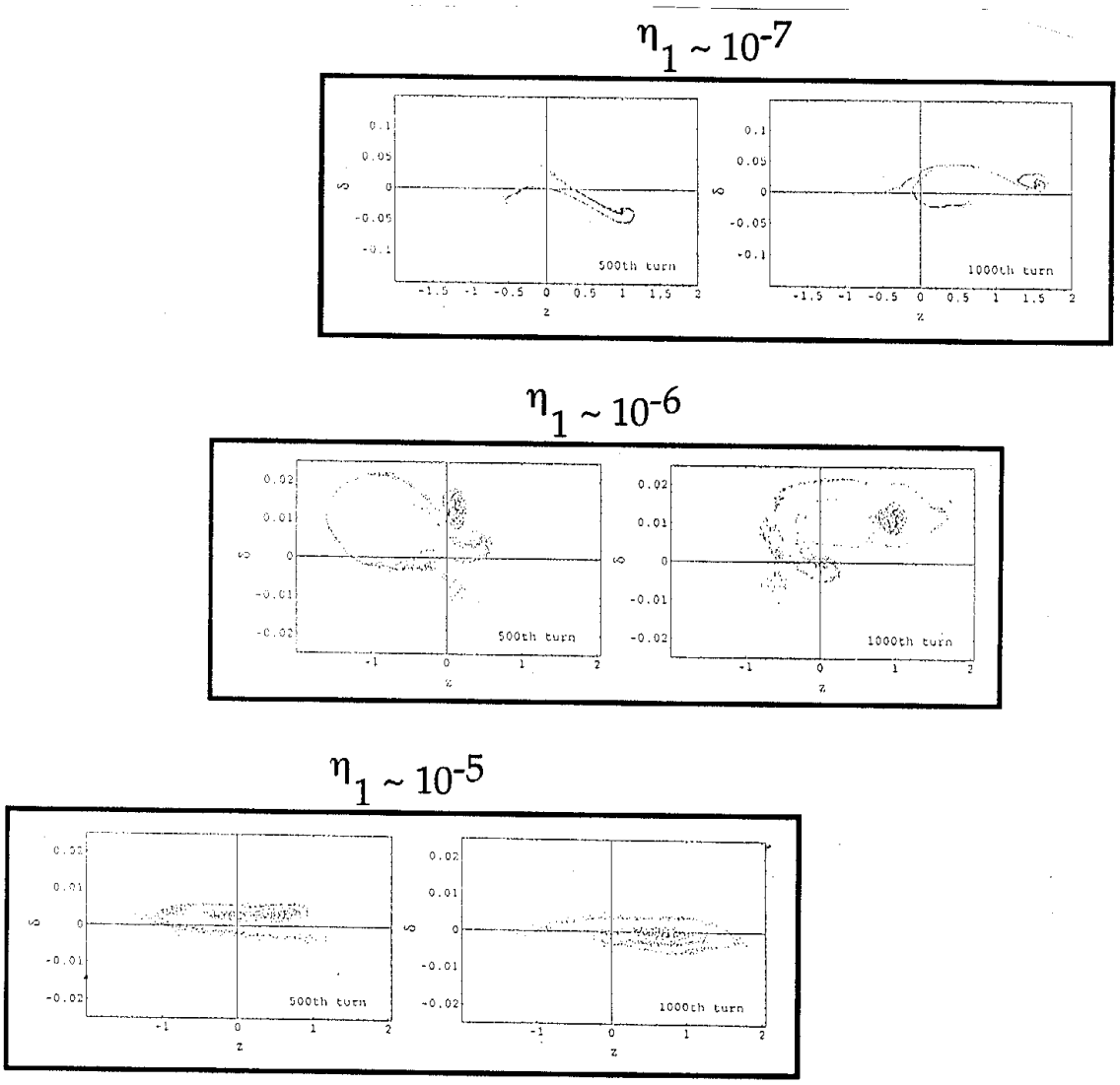

Figure 3-3*. Muon-beam evolution in transverse phase space for various phase slips.*

Temporal Variation of Accelerator Parameters

In addition to R&D oriented toward a muon collider, we performed more-general studies of how instabilities might be controlled in storage rings by varying parameters over time.

Varying Chromaticity

Analytical and numerical study of the suppression of the transverse head-tail instability by modulating the chromaticity over a synchrotron period are studied. We find that a threshold

can be developed, and it can be increased to a value larger than the strong head-tail instability threshold. The stability criterion derived agrees very well with the simulations. The underlying physical mechanisms of the damping scheme are the rotation of the head-tail phase (such that the instability does not occur), and the Landau damping due to the incoherent betatron tune spread generated by the varying chromaticity.

In the previous work, via both theoretical analysis and multi-particle simulations, we have successfully demonstrated that by periodic modulation of the chromaticity, the head-tail instability is damped due to enhanced Landau damping. We found that a threshold can be developed, and it can be increased to a value larger than the strong head-tail instability threshold. This implies that the limitations of peak current in a storage ring can be increased by the varying chromaticity scheme. Studies of practical operational issue, such as rapidly modulated sextupole magnets, and theoretical issues, such as the reduction of dynamic aperture, and exact calculations of the azimuthal mode-coupling, are in progress.

Longitudinal Beam Dynamics of Alternating Slippage Factor in Circular Accelerators

The success of the varying chromaticity scheme in damping of the transverse head-tail instability implies that, the temporal variation of accelerator parameters could be a generic scheme to improve the performance of accelerators. We apply this new approach to the longitudinal dynamics of coasting beam and bunched beam. Specifically, explorations for the possibility of suppression of the negative-mass instability and/or the microwave instability by a varying slippage factor, are underway.

Experimental and Theoretical Studies of the Nonlinear Beam Dynamics in the Advanced Light Source

In collaboration with the Advanced Light Source (see Chapter 2), study of nonlinear beam dynamics in an electron storage ring is currently in progress. Specifically, through periodic modulation of the rf phase and/or rf voltage, particle tracking as well as the amplitude and phase of the beam transfer function are measured. Experimental data are compared with the numerical and analytical results. Effects of radiation damping, quantum fluctuation, noise, and bifurcation are taken into account.

Reported by Jonathan Wurtele and Wen-Hao Cheng

Physics of Laser Channeling and Laser Wakefield Acceleration

We have been examining the wakefields produced by an intense, short laser pulse propagating in a plasma channel which has an arbitrary (continuous) density profile. Previous theoretical studies of plasma wakes in channels have considered either step-function density profiles, for which there is an exact expression for the wake, or, alternatively, parabolic profiles for which the wake is only computed approximately. We

approach this problem by solving for the exact wake eigenmode, taking into full account the channel profile.

A consequence of a general channel profile is a spatially dependent plasma frequency; thus in a temporal Fourier decomposition, there exists the possibility of a resonance between the mode frequency and the plasma frequency. This resonance is manifest in the presence of (typically regular) singular points in the differential equation for the wakefield amplitude. To obtain an accurate solution for wake eigenmode, such singular points must be handled with care. We have analyzed the transverse structure of the wake for a wide range of experimentally accessible channel profiles. In addition to solving the Fourier domain equations for the wake field, we are currently working on solving the cold fluid equations in the time domain to corroborate our Fourier space analysis. The study of intense pulse propagation in plasma channels is important not only for the laser accelerator but also for other applications, such as the fast-ignitor concept for the proposed National Ignition Facility in fusion energy.

We have analytically and numerically examined particle beam injection into a hollow-channel laser wakefield accelerator. The code we employ follows full six dimensional particle motion and loads a beam using the TDA code loading algorithm. The optimal wake phase for beam injection was computed to provide maximum acceptance, given the beam energy and wakefield parameters. We are also investigating the use of high-brightness lasers to accelerate particle beams (vacuum acceleration). The growth of beam emittance and energy spread during acceleration over distances of a Rayleigh range is currently being studied. The goal of this work is to study the performance of laser/plasma and vacuum laser accelerator schemes using realistic beams. Among the topics we plan to study are an analysis of sensitivities to: a) jitter in the laser and plasma parameters, b) plasma instabilities, and c) channel deformation.

Reported by Bradley Shadwick

Optical Stochastic Cooling

During this past year, several of the Center's staff have been involved in a study of optical stochastic cooling (OSC) — a new technique that has the potential to make the cooling of relativistic protons and heavy ions in storage rings quicker by several orders of magnitude compared to what has been achieved with microwave stochastic cooling.

A detailed theoretical analysis of OSC is being developed. Considering stochastic cooling in the optical wavelength regime, we were able to clarify the role of the phase space volume in general stochastic cooling. The concept of the sample is seen to be the coherent neighborhood in 6-D phase space, and the optimum cooling could be achieved by maximally mismatching the radiation and the particle phase space distributions. This way of thinking leads to a new way of stochastic cooling, such as the energy sampling rather than the time sampling. For explicit analysis, the field of a particle as a function of the kinematic variable at the pick-up is determined by solving the appropriate Maxwell's equation, and is approximated by a simple Gaussian function. At the kicker an amplified superposition of fields from all particles of the beam is applied to a particle. The change of rms spreads of the beam is evaluated using distribution function of kinematic variables. We find that a

sample in OSC is delineated not only by its length, as in microwave stochastic cooling, but also by the 6-D phase space volume of the optical signal. Therefore the sample corresponding to a particle should be defined as the coherent 6-D phase space neighborhood.

We have also identified two problems that have to be resolved experimentally to verify the feasibility of OSC. The first is isochronicity of the lattice in the presence of a cooling insertion, along with preservation of fluctuations in the beam when it passes the insertion. The second is transport and amplification of the pulse of undulator light while preserving fluctuations in the initial signal. Looking for an opportunity to do the experimental work at Berkeley Lab, we settled on the electron beam from the ALS booster synchrotron at 150 MeV (which is far lower than the normal injection energy for the ALS storage ring, but is attainable). After extraction, the electrons would be directed to a special beamline that will include two undulators connected by a highly isochronous lattice, a setup that resembles a cooling insertion for a storage ring. Several variants of this beamline that would fit in the available space in the extraction area of the booster have been designed. The first experiment would consist of observation of the interference pattern of the radiation extraction from the two undulators.

Reported by Alexander Zholents

Beam Electrodynamics

The increasing variety and difficulty of the radiofrequency manipulations needed by today's accelerators has opened new opportunities for what began as our beam-cooling activity some years ago. Now called the Beam Electrodynamics Group, its activities during the years involved crucial work for the PEP-II B-factory, the ALS, the NLC design effort, and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory.

Particular attention has been focused on radiofrequency (rf) and microwave components and systems for PEP-II. Those accomplishments are described in the next chapter.

Reported by John Corlett

Feedback Systems and Collective Effects Measurements for the ALS

We are continuing to apply our group's capabilities to the improvement of the Advanced Light Source (ALS) here at Berkeley Lab. Besides the obvious benefit of enhancing this important user facility, the opportunity to use a state-of-the-art storage ring like the ALS in developing systems for PEP-II is not to be missed. Bunch-by-bunch coupled-bunch feedback systems control all rigid-body coupled-bunch modes of oscillation in the ALS electron beam, and control of similar oscillations is essential in maintaining beam current and luminosity in PEP-II.

Feedback systems are essential to provide the ALS's advertised source properties, and commissioning of the feedback systems is proceeding. The design, fabrication, and commissioning of the ALS transverse feedback systems was the responsibility of the Beam Electrodynamics Group, and the responsibility for the longitudinal feedback systems was held jointly with SLAC.

Installation of the coupled-bunch feedback systems at the ALS is complete, and the systems operate routinely during user shifts. Spontaneous betatron and synchrotron oscillations are successfully damped at the nominal ALS user conditions - 400 mA in 320 bunches (this includes a short gap for ion clearing and feedback system re-synchronization).

Commissioning of the feedback systems involved some optimization of the accelerating rf cavity conditions, in particular the temperature of the two rf cavities. Coupled-bunch motion of the beam is sensitive to cavity temperatures since the frequencies of the higher-order modes (HOMs) that drive the beam motion are a strong function of the cavity conditions. Changes in cavity cooling water temperature cause small dimensional changes in the cavity which in turn cause frequency changes in cavity modes. The fastest-growing longitudinal coupled-bunch modes are mode numbers 96 and 125, which are driven by the dominant cavity HOMs at 808 MHz and 2849 MHz. These cavity HOMs are high-Q (i.e., narrowband) and are not damped by the filters located in the power feed waveguide. Transverse coupled-bunch motion is less sensitive to cavity conditions.

Traveling-wave-tube amplifiers have been used as power amplifiers in the longitudinal feedback system, but we have experienced some unreliable operation with these devices and we are currently considering the purchase of solid-state power amplifiers. A 500 W solid-state amplifier has been on test for the B-factory project and has worked exceptionally well in the ALS longitudinal feedback system. Measurements of the beam characteristics at the ALS have led to a greater understanding of the storage ring beam impedance. Bunch length measurements, tune shift with beam current measurements, and transverse beam dimensions measurements have been made, and instability thresholds measured. The broadband impedance derived from these measurements is estimated to be 0.2 . This is consistent with the small ALS-component impedances that we have measured in the laboratory and computed.

Reported by John Byrd and John Corlett

Stochastic Cooling and Beam Diagnostics

The group has maintained its history of involvement in stochastic cooling by continued study of the beam cooling and diagnostics requirements for the Relativistic Heavy Ion Collider. Stochastic cooling is the process by which the deviations from nominal energy or position of particles in a beam are measured and corrected. The control of gold ions in this machine is a particular problem, and microwave frequency stochastic cooling systems are likely to be required to provide sufficient integrated luminosity to effectively study the

collisions of these heavy ions. Cooling in both transverse directions and longitudinally is under consideration.

Diagnostics are needed to determine the behavior of the beam and make necessary corrections. Beam Electrodynamics Group members are developing cavity based detectors for the purpose of measuring the Schottky noise signals of the beam—an important quantity in hadron and heavy ion colliders. A prototype cavity has been designed, and the associated electronics are in conceptual design. Measurements of the prototype cavity should allow fine-tuning of the cavity parameters.

An exciting new venture for the group has been in the area of spin measurement techniques. A novel system using superconducting quantum interference devices (SQUIDs) has been developed by BNL with the assistance of the Beam Electrodynamics Group. It is hoped that the concept may be tested in an experiment at Brookhaven's Alternating Gradient Synchrotron before a detailed design for RHIC is developed.

A new venture for us in the past years has been the collaboration with SLAC on the NLC, which involves several groups within the Center for Beam Physics. In particular, our group is involved in the rf systems design and studies of collective effects and feedback systems for the damping rings. The large beam current (1A), divided into four trains of bunches, results in transient loading of the rf system, which must be compensated to maintain beam quality. Beam instabilities must be avoided by impedance minimization and feedback systems. We also analyzed the damping rings' coupled-bunch instabilities and an outline of the rf system design to the preliminary design. These results were incorporated in the NLC ZDR (Zero-Order Design Report) and reported at the 1996 Snowmass Workshop and study.

Reported by David Goldberg

The RK-TBA as a Power Source for the NLC

As a power source for linear colliders, the two-beam accelerator or TBA (see Figure 3-4), a concept developed by Andrew Sessler of the Center for Beam Physics, has the inherent advantage of very high efficiency for power conversion from the drive beam to rf power. In addition, TBAs based on induction linacs would scale quite favorably to high frequencies (11.4 GHz) and high accelerating gradients (100 MV/m). Recent reacceleration experiments have successfully demonstrated bunched beam transport through two reacceleration induction cells and three traveling-wave extraction cavities for a total rf output of over 200 MW. The phase and amplitude were shown to be stable over a significant portion of the beam pulse.

The technical challenges for making TBAs into real-world power sources lie in the dynamics of the drive beam, which is quite high in current (hundreds of amperes) and must propagate over long distances. In particular, the beam break-up (BBU) instability through the long multi-cavity relativistic klystron two-beam

accelerator (RK-TBA) is known to be severe. While BBU suppression techniques have been successfully demonstrated for a few cavities, a scenario with acceptable BBU control over many traveling-wave cavities must be constructed. Similarly, the longitudinal stability of the rf bunches over a multi-cavity RK-TBA must be demonstrated. In addition to technical feasibility, a case for economic attractiveness is no less essential for the viability of the RK-TBA as a power source.

With these general considerations in mind, we performed a conceptual study, including physics and engineering designs and "bottom-up" cost analysis, for a new version of the RK-TBA that has acceptable longitudinal and transverse beam stability, as well as low cost and high efficiency. This RK-TBA is designed as a power source for a linear collider with 1.5 TeV center-of mass collision energy, representing the upgrade phase of the NLC.

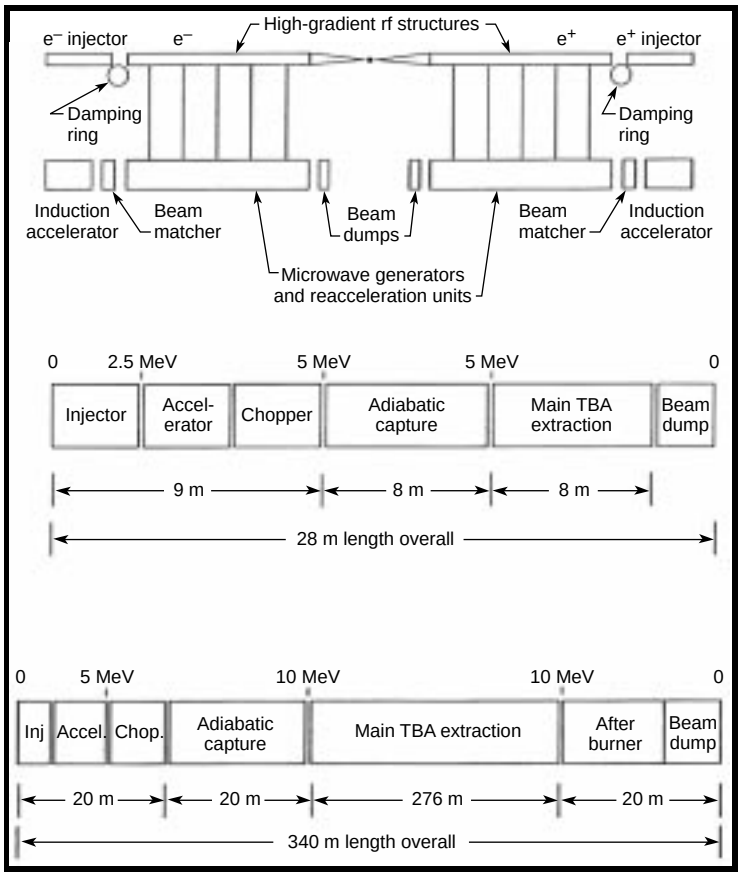

Figure 3-4*. In the Two-Beam Accelerator, a high-current, low-energy drive beam is used for generating rf power that is applied to a high-gradient acceleration structure, where a low-current load beam is accelerated to high energy. Relativistic klystrons would generate the rf power in the example we are studying for possible NLS applications, although we have also done research on wiggler-based TBAs. The point design for the RK-TBA of the NLC is also shown, as is the far shorter RK-TBA proof-of-concept prototype that we would like to build and operate here at Berkeley Lab.*

RK-TBA Design and Specifications

To generate an unloaded gradient of 100 MV/m in the NLC high-gradient structures, the RK-TBA must supply 360 MW of rf power at 11.4 GHz every 2 meters of the main linac's length. The output rf field is specified to have a 100-ns linear risetime followed by a 200-ns flat top. The repetition rate is 120 Hz. To power a 1.5-TeV 22.8-km-long collider (two 11.4-km arms), we propose 76 RK-TBA units, each 300 m long, operating at an average drive beam energy of 10 MeV, with an average current of 600 A over the duration of the pulse, and a reacceleration gradient of 300 kV/m.

The front end of each RK-TBA unit consists of a 1.5-kA injector, followed by an rf chopper at 2.5 MeV and then an "adiabatic capture" unit in which the chopped beam (average current 600 A) is accelerated to 10 MeV and further bunched with idler cavities in preparation for injection into the main RK-TBA. To enhance the efficiency of the RK-TBA system, an "afterburner" at the end of the main RK-TBA continues to extract rf power through 12 successive output cavities before depositing the spent beam (average beam energy below 3 MeV) at the beam dump. The overall conversion efficiency of drive-beam power to rf power of each RK-TBA unit is 90%.

The new RK-TBA design is based on the technology of the long-pulse (few microseconds) induction machines that have been studied over the last 18 years for heavy ion fusion applications. The magnetic material used in this design is Metglas, a metallic glass product that can accommodate a large magnetic flux swing—nearly 3 tesla—before saturation. The induction cores can therefore be made quite compact. Nonaccelerator applications of this material over the last few years have led to dramatic reductions in the cost of Metglas. The small Metglas cores, when combined with low-field (800 gauss) permanent magnets for quadrupole focusing, and small beam pipes (5-cm diameter), have led to a compact induction cell design whose transverse diameter is about 34 cm — much smaller than any of the previously known induction cell designs.

The pulse power for the induction cells comes from a low-voltage system. The induction cores consist of small 20-kV units, powered by pulse forming networks (PFNs) switched by thyratrons. Power is fed into the PFNs via dc power supplies and command-resonant charging (CRC) systems. The low-voltage design avoids the use of step-up transformers, which have high losses. The main losses in the system are associated with core currents in the induction cells. The overall efficiency of the pulse power system (from wall plug to drive beam) is estimated to be 40%.

The rf extraction cavities are located every 2 meters. Present designs center on traveling-wave structures with three inductively detuned rf cells, with an inner radius of 8 mm. Two iris waveguide structures in the last cell are matched for power extraction. Longitudinally, beams will debunch because of space-charge and rf-induced energy spread. To counter these debunching effects, the rf output cavities are inductively detuned. This is accomplished by making the phase velocity of the three-cell traveling-wave structure faster that the velocity of the particles. The particle bunch lags behind the deaccelerating crest of the wave, and the energy loss becomes phase dependent, with the particles at the bunch tail losing the least energy. Kinematics cause the tail to catch up with the head of the bunch, which is followed by synchrotron oscillation in stable rf buckets. PIC simulations with a coupled cavity circuit model show stable propagation through 150 cavities. For comparison, cavities with no inductive detuning are shown to result in particle debunching after a few cavities.

A key design feature of this particular RK-TBA is that the betatron period is exactly equal to the spacing between adjacent output cavities. This "betatron-node" scheme leads to minimal beam offset at the rf cavities. Excitation of the HEM_{11} mode at 14 GHz is drastically reduced as a result. Transverse dynamics have been modeled with a beam-

breakup code that includes both cumulative and regenerative effects: it shows BBU growth is acceptable, less than 4 e-folds. The cavity parameters for these simulations were obtained from the codes URMEL and MAFIA. For a 8-mm radius cell, a natural de-Qing of the dipole mode occurs because of the coupling to the TE_{11} mode in the beampipe. The betatron-node scheme imposes constraints on the accuracy of the focusing fields and beam energy. Sensitivity studies to this point indicate that without feedback, the field errors must be less than ±1% and energy variation from head to tail must have comparable accuracy.

There is another low-frequency BBU mode, associated with the induction gaps, that must be controlled. The relatively low current of 600 A, combined with the Landau damping that occurs naturally because of the energy spread in the rf buckets, again kept the simulated BBU growth below 4 e-folds in a 300-m long RK-TBA subunit. To achieve this low growth, the induction gaps were designed for maximal dipole de-Qing, using the induction-cavity design code AMOS.

A first engineering and costing exercise for the full RK-TBA system has been performed. The electrical design includes all components starting from the ac power distribution system, through the dc power supplies, the CRC system, the pulse forming networks, and the induction cores. Racks and installation, as well as instrumentation and control, were included in this exercise. Costs were estimated with a “bottom-up” approach (that is, starting from individual components and adding them up to arrive at the entire system), assuming mass production procedures for fabrication and assembly. Our preliminary cost estimate for the TBA-based power source for a 1-TeV center-of-mass linear collider is less that $1 billion. This estimate does not include conventional facilities, or any institutional overhead. The overall efficiency of the system (“wall plug” to rf) is estimated to be 36%.

A preliminary design report for our systems study has been completed. On the basis of this design, a joint proposal between LBNL and LLNL was submitted to DOE for a seven-year RK-TBA project that will build and test a 28-m prototype. The prototype will be sited at LBNL in the RTA Test Facility. To date, half of the electron gun has been prepared and is currently being tested. The facility will test many of the critical issues of cost, efficiency, and beam dynamics of an RK-TBA system. Should the power extraction test prove successful, the RTA could be mated to the NLC Test Accelerator at SLAC to power the NLCTA high-gradient structures to 100 MV/m. The proposed RTA work is a component of the collaborative effort by SLAC, LBNL, and LLNL, is incorporated in the NLC ZDR and was reported at the 1996 DPF Snowmass Workshop and Study.

Reported by Simon Yu (Berkeley Lab) and George Westenskow (LLNL)

Free-Electron Lasers and Radiation Sources

The Free-Electron Laser and Radiation Source Group carries on the Center’s long-standing interests in sources of radiation via relativistic beams. This largely theoretical group studies subjects of characterization and manipulation of photon and particle beams, and generation of intense photon beams from

infrared to gamma rays for wide-range of applications. In particular, the following topics are under investigation:

- High gain FEL theory
- Initiation, growth, saturation, transverse and longitudinal coherence of Self-Amplified Spontaneous Emission (SASE)
- Characterization of the qualities of particle and photon beams via the Wigner function and entropy
- Radiative laser cooling of relativistic heavy ions beams
- Radiative laser cooling of electron beam via Compton scattering
- Transition undulator radiation
- High-average-power FELs for research and industrial applications
- Intense X-ray FELs as “fourth generation light sources”
- We have been providing theoretical/numerical leadership to the SLAC Linac Coherent Light Source (LCLS) project.
- A major new activity of the Group is to bring about a high power FEL project at LBNL for future satellite power beaming applications.

Free-Electron Laser R&D

We have been steadily expanding our analytical and numerical capabilities for reliable predictions of high gain FEL operation in the short wavelength region. We have developed the most complete and accurate solutions of 3D FEL theory thus far. These solutions take into account energy spread, emittance and betatron oscillation of the electron beam, and diffraction and guiding of the photon beam. Powerful interpolating formulas based on these solutions are obtained and being used world-wide for the study, design and optimization of high gain FELs, in particular, those based on the SASE principle. Furthermore, the unique solutions of the higher-order FEL eigenmodes provide the tool for a quantitative analysis of transverse coherence of SASE. It is found from this study that the well-known criteria for diffraction-limited or transversely coherent undulator radiation, which requires the beam emittance to be less than the wavelength divided by 4, can be violated by a large factor for SASE without significant reduction in transverse coherence. These results have significantly advanced our understanding of SASE, the backbone of the fourth generation light sources, and their implications are important for the development of linac-based X-ray FELs. In addition to the development of 3-D FEL theory, a theoretical framework for handling the startup and exponential gain behavior, taking into account the slippage and the effect of finite pulse duration has been formulated.

Over the years we have accumulated various simulation codes to study different aspects of the FEL behavior. In particular, the simulation code GINGER has been refined and upgraded to permit calculation of the harmonic generation, startup from noise, undulator interruptions, oscillator FELs, etc. These capabilities have enabled us to play a leading role in the LCLS collaboration in the theory/simulation area.

Experimental FEL Studies

Jonathan Wurtele of the CBP is a collaborator in the BNL FEL experiment at the ATF. The experiment uses a tunable microwiggler, the MIT Microwiggler, which provides a 0.45 tesla on-axis field over 70 periods of 8.8 mm each and is notable for its extensive tunability and a novel tuning regimen through which rms spreads in peak amplitudes has been reduced as low as 0.08%. Preparations are currently underway for runs at 34 MeV (1.064 um) and 48 MeV (532 nm) at ATF. In support of the efforts to commission an FEL at these wavelengths, we have calculated the gain for a small number of passes and have shown how the radiation frequency shifts from the spontaneous emission peak to the peak gain frequency with increasing pass number. This theory indicated that the previous beam used at the ATF had too few pulses to lase.

In the past year, we have developed a novel technique for characterizing the properties of a 50 MeV electron beam directly from the microwiggler's spontaneous emission. Experimental work in this area is typically limited by poor resolution and the difficulty of distinguishing between numerous inherent spontaneous emission broadening mechanisms such as energy spread, beam divergence, off-axis electron propagation, beam trajectory errors and collection angle effects. In particular, energy spread and electron beam divergence are difficult to separate because two-parameter fits to the data do not always produce a unique solution and resolution is diminished when the contribution of natural linewidth is large. The MIT Microwiggler offers unique opportunities for such an application through its compact size, extensive profile tunability, adjustable field strength, long length and period, which makes the emissions particularly sensitive to beam parameters, and sets the wavelength of emission in the visible (532 nm at approximately 50 MeV), where a wide variety of optical diagnostics is available. The response of the spontaneous emission-based technique to beam parameters was demonstrated with a systematic series of experiments at the Accelerator Test Facility.

The setup for spontaneous emission studies of the electron beam is simple and efficient. The spatial profile of spontaneous emission into a Cerenkov cone is recorded using a narrow bandwidth interference filter and a CCD camera. The radius of the cone depends on the interference filter central wavelength and electron beam energy, while the cone width is determined by energy spread and divergence broadening, and the number of periods in the wiggler. Systematic measurements of the cone width over a range in beam energy, energy spread, tuning parameters and wiggler field strength have been performed. Simple analytic expressions for the contribution of natural linewidth, energy spread and divergence were derived, and it was found that by looking at large angles, a figure for beam divergence could be extracted directly from a single shot measurement.

The technique developed in non-perturbative beam characterization is useful for estimating beam emittance and for matching the beam into the wiggler and provides direct, instantaneous feedback during beam tuning and optimization. It can therefore be applied to FEL research and also far more general applications.

Linac Coherent Light Source

We have done significant analysis and numerical modeling for several different conceptual FELs proposed both at LBNL and at other institutions. Our most extensive effort has been

in support of the LCLS which is being studied by a consortium of institutions including SLAC, UCLA, LBNL, LLNL, and University of Milan. The LCLS proposes to use part of the SLAC linac, at energies up to 15 GeV, with high peak current (5 kA), low emittance (1-2 p mm-mrad normalized) in a long (50-100 m) undulator to produce very high brightness, coherent X-ray emission in the 1.5-15 Å wavelength range. We have developed a powerful system optimization tool, and carried out a comprehensive multi-dimensional parameter optimization necessary for making a proper choice of undulator and electron beam parameters, and for developing a strategy for a phased approach from a longer wavelength operation toward the ultimate goal at the short wavelength.

We used the time-dependent, 2-D (r-z) FEL simulation code GINGER to examine the start up of the LCLS FEL from shot noise (i.e., random bunching) naturally present in the input electron beam and also the development of longitudinal coherence as the radiation grows exponentially with distance down the undulator. We have also investigated the usefulness of various modifications such as making the first part of the undulator resonant with the 3rd subharmonic (e.g., 4.5 Å compared with the desired output at 1.5 Å) whose exponential gain length is shorter. The second half of the undulator, which would remain resonant at 1.5 Å, uses the third-harmonic bunching produced by the first undulator as an enhanced “seed” for continued exponential growth. We have also investigated the advantages and disadvantages of inserting various drift spaces in between undulator sections; explored the possibilities of using electron beam in the FEL as an effective X-ray lens to control the angular divergence of the X-ray beam it is generating; and found that the inclusion of time-dependent effects significantly reduces the gain from what would be found in a monochromatic signal.

High-Power FEL for Beaming Power Up to Satellites

In the past we have been actively working on designs of user optimized FELs, in an effort to bring an FEL user facility at LBNL. This effort was best summarized in a comprehensive conceptual design report of an infrared FEL we produced several years ago for the proposed chemical dynamics research laboratory. Although the project has not been materialized for the lack of funding, having recognized the possible unique applications of high average power FELs for research communities and industries, we have been continuously pursuing various schemes of FELs based on highly efficient, multi-turn, recirculating linacs.

More recently we have studied such a high power FEL for beaming power from ground to solar cells on orbiting satellites. A multi-institution collaboration is established to further clarify the R&D issues leading to a preliminary design report. The works that have been done so far in this group include the following. A numerical simulation code was developed to study the energy loss instability of the accelerator system, which is crucial for the multi-turn, recirculating accelerators. Following extensive modifications to GINGER to model oscillator FELs, we have used it and a 1-D time-dependent code to model the “electron output coupling scheme” which was proposed as a path to a high average power FEL.

The scheme involves a relatively standard oscillator FEL whose major purpose is to bunch the electron micropulses followed by a single-pass amplifier undulator (the “radiator”) in which the bunched beam would radiate copious amounts of coherent power without limitations due to mirror damage. In a series of papers, we investigated the requirements for stable mode operation of the oscillator, especially in an optical klystron configuration, and the expected extraction efficiency of the output radiator, with and

without tapering of the undulator. Depending upon the exact beam parameters chosen, we found that relatively high cavity losses and careful detuning will probably be necessary to produce output bunching parameter at a level of 0.3 to 0.5. Extraction efficiencies much above a few percent will require relatively long (> 5 m) radiator undulators.

Reported by Kwang-Je Kim and Ming Xie

Generation of Femtosecond Bursts of X-rays in a Storage Ring

Ultrashort pulses (less than 100 femtoseconds in duration) of X-rays (1Å and shorter in wavelength) will be a valuable research tool in probing ultrafast processes in condensed matter physics, chemistry and life sciences—if they can be produced. One scheme of producing such a source of radiation, originally conceived at the Center, involves Thomson-scattering a short visible laser pulse orthogonally off an electron beam that has low (but relativistic) energy . Experiments have already been carried out in the Center's Beam Test Facility, and the results are reported in the section on Experimental Beam Physics. The success of this experiment in achieving the expected flux in a micropulse is encouraging. We await the successful use of these generated x-rays in a first experiment on time-resolved studies of phase transition on the surface of silicon. In anticipation of future needs for such a source, we have focused on how to improve upon the average flux to the level of 10^9 x-ray photons per second.

Such an extrapolation seems plausible in a scheme with a bunch of electrons stored in a storage ring and periodically interacting with a short pulse (100 femtoseconds) of visible laser photons stored in an optical cavity with a regenerative amplifier inside , as shown in Figure 3-5. Although a typical electron bunch in a storage ring is tens of picosecond long, only a short portion of it (100 femtoseconds) retains the memory of having interacted with a short visible laser pulse for a brief period. This interaction "tickles" the beam, so to speak, and induces a systematic energy modulation on the beam over a 100 femtoseconds only out of its full length. For a 2 GeV beam as in the ALS, interacting with a terawatt-peak-power, 0.8-µm-wavelength laser, the modulation amplitude could be as high as 10 MeV or higher.

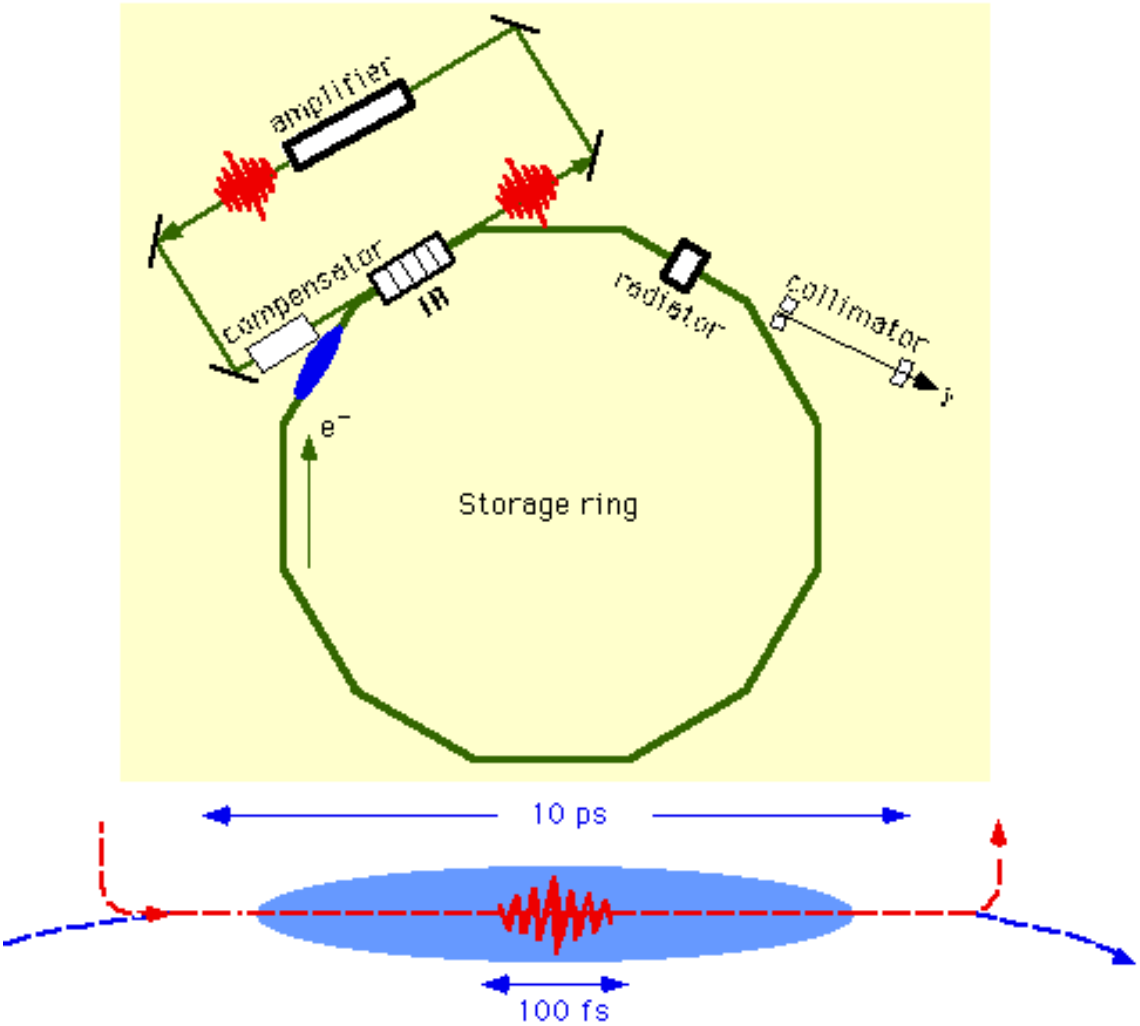

Figure 3-5*. The scheme of an electron storage ring in conjunction with a regenerative laser ring resonator in a configuration that allows generation of femtosecond x-ray bursts.*

The dispersive magnetic lattice of the storage ring can then be used to discriminate spatially, in the direction transverse to beam motion, the 100 femtosecond slice against the rest of the beam (Figure 3-6a). This beam then is allowed to radiate through a special radiator where the "discriminated" slice will radiate differently from the rest of the beam. A specially designed beam line (with choppers, etc., to chop out and synchronize the multiple interactions of the electron and laser pulses) will then deliver femtosecond bursts of x-rays to users (Figure 3-6b). The average flux of femtosecond x-ray bursts expected would be 10^9 per second with a spectral brightness close to that of the usual synchrotron radiation sources. The scheme looks promising enough that we have actually designed a laser path along the ring and the vacuum chamber. The modification to the back-port of a specially selected undulator straight section has already started.

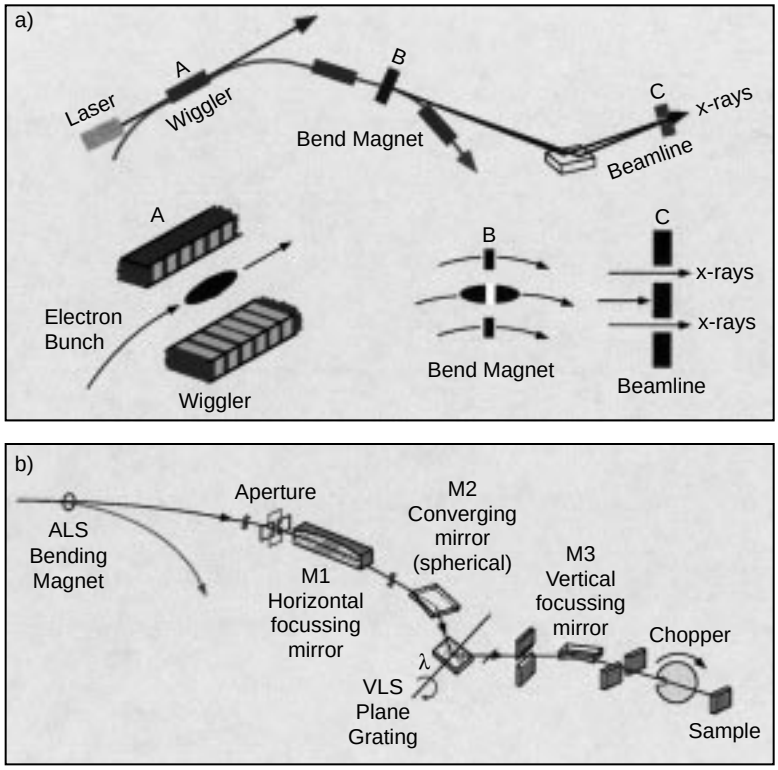

***Figure 3-6**. (*a, upper*): Magnetic discrimination of the energy-modulated femtosecond longitudinal slice in the transverse plane. (*b, lower*): special beamline for the femtosecond x-rays from the ring.*

Entropy of Particle and Photon Beams

We have investigated the entropy of a particle beam, relating it to the more familiar concept of emittance as a measure of its disorder. These concepts can be generalized to the case of photon beams, the entropy in this case being related to the density operator. We study in detail the case where the photon beam is a stochastic superposition of coherent Gaussian beams. The goal of the study is to understand the qualities of the particle and photon beams from a fundamental point of view.

Reported by Swapan Chattopadhyay, Alexander Zholents, Max Zolotorev, and Kwang-Je Kim

Experimental Beam Physics

During the past two years, the Experimental Beam Physics Group has continued to work on experiments involving the interaction of high intensity lasers with

particle beams and plasmas with an aim towards the development of novel radiation sources, high performance laser based beam diagnostics, as well as new accelerating and focusing mechanisms involving the use of plasmas. The group has designed, constructed and operated the Center for Beam Physics' Beam Test Facility (BTF) at the Advanced Light Source. The BTF was designed in 1993 and commissioned in 1995 by the Center for Beam Physics. A transfer line from the linac carries the electron beam into an adjacent, shielded cave equipped with diagnostic instrumentation for electron and photon beams and with a femtosecond, terawatt laser system built by the Materials Sciences Division on the top of the shielding. Because the linac does not need to operate for synchrotron radiation users except to fill the storage ring, it is conveniently available most of the time for BTF use.

Femtosecond X-rays

A first experiment successfully completed at the BTF during the 1995-1996 period was on the scattering of a high intensity photon beam off relativistic electrons. In collaboration with the Femtosecond Spectroscopy group of the Material Science Division, the group successfully generated the world's shortest hard x-ray pulses using 90˚ Thomson scattering of a terawatt laser pulse off a relativistic electron beam as shown in Figure 3-7. This novel geometry allows production of femtosecond x-ray pulses using a tightly focused but temporally long electron bunch. The transit time of the light through the beam determines the length of the scattered light pulses and this time can be matched to the laser pulse length in the femtosecond range by focusing the electron beam to a narrow waist in the interaction region.

Another aspect of the 90˚ geometry is that transverse and longitudinal phase space distribution measurements of the electron bunch become possible. The laser acts as a microprobe for the electron beam and the x-rays carry the signature of the beam properties. Such a technique will become increasingly important for measurement of detailed electron bunch properties in high quality accelerators.

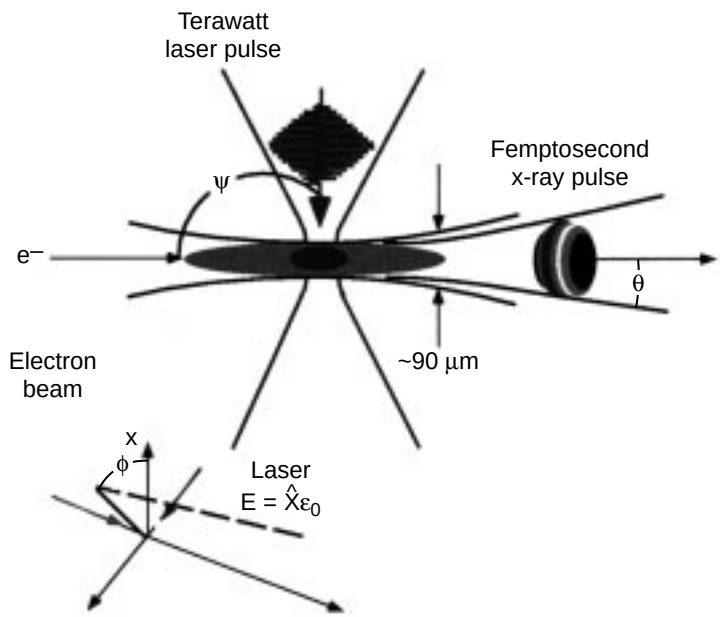

Figure 3-7*. Orthogonal Thomson scattering configuration for producing femtosecond x-rays.*

For the experiment, the group used the 50-MeV electron beam from the ALS linac consisting of electron bunches of 1.3 nC charge and with a 20-ps FWHM duration. The femtosecond laser system comprised a Ti:Al_2O_3 laser followed by a chirped pulse amplification system (pulse stretcher, preamplifier and amplifier powered by a Q-switched YAG laser, and pulse compressor) as shown as Figure 3-8. The laser output consisted of 60-mJ pulses lasting 100-fs (FWHM) at a wavelength of 800 nm. The measured interaction area was 90 μm in diameter.

These parameters result in an x-ray flux close to the measured value of about $5x10^4$ photons/second at a wavelength of 0.4 Å. Measurements of the x-ray beam profile as imaged on a phosphor screen with a CCD camera yielded a beam size consistent with the expected beam divergence of 1/g (Figure 3-9). Analysis of the obtained far-field image provided a single shot measure for the electron beam divergence of essentially a 200-300 fs slice of the 25-30 ps long bunch. Transverse and longitudinal scanning of the laser beam across the electron beam yielded the spatial and temporal structure of the electron bunch. Subtle chromatic aberrations in the transport line, which were not picked up by an optical transition based diagnostics due to resolution limits, were observed with the laser probe and corrected by adjusting the magnetic transport lattice. Spectral measurements with a germanium detector at various observation angles agreed closely with theoretical calculations, indicating that the theory can be used as a guide for predicting performance under various experimental conditions.

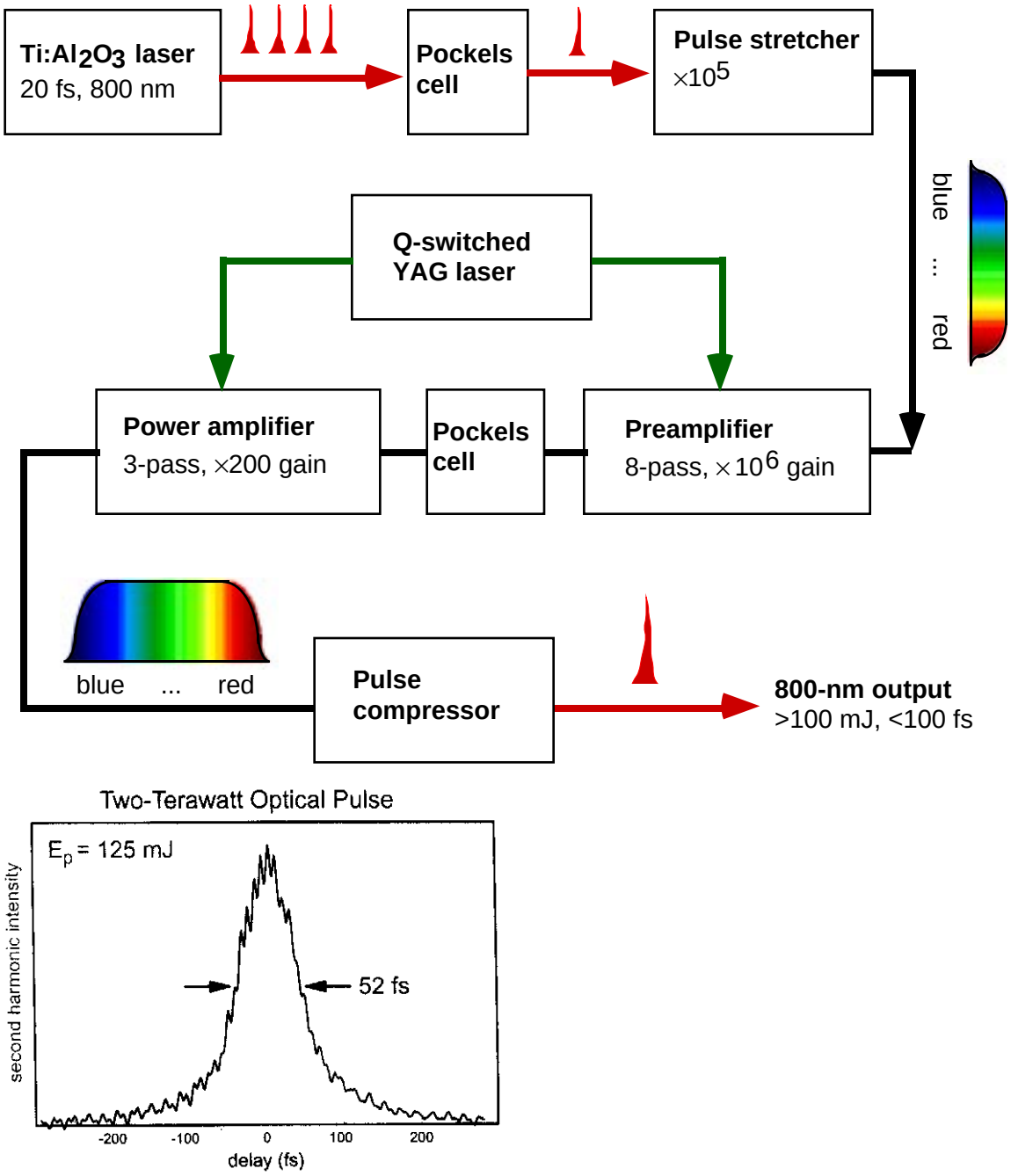

Figure 3-8*. The femtosecond terawatt laser system that will be used in this experiment was developed by LBNL's Material Sciences Division (Femtosecond Laser Spectroscopy Group)*

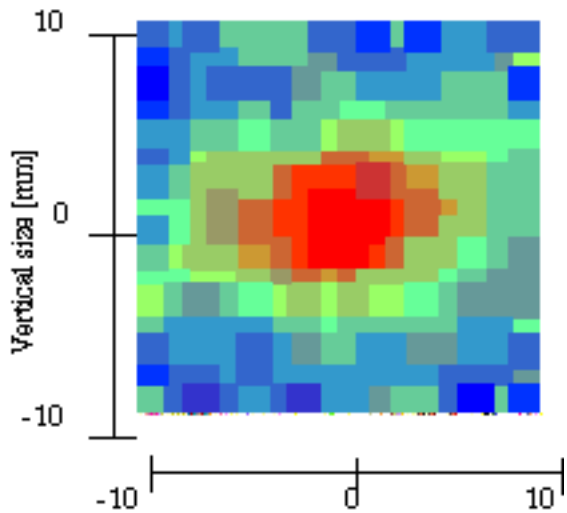

Figure 3-9*. False color CCD image of the spatial profile of a 30 keV x-ray pulse on the phosphor screen, which is located 80 cm from the IP.*

The brightness of about 2 x 10^5 photons / sec · mm^{-2} · $mrad^{-2}$ in a 15% BW achieved in the first experiments is sufficient for static x-ray diffraction from strong scatterers (a few minutes to obtain a rocking curve). But the long-term goal is to carry out time-resolved EXAFS and other studies of structural dynamics, on the fs time scale, of the atomic motions that underlie such phenomena as phase changes, chemical reactions, and surface processes. Substantial but realizable improvements (primarily in linac technology), such as higher repetition rate, reduced bunch length, and lower emittance, together with a boost in laser pulse energy, could increase the x-ray brightness to nearly 10^{11} photons / sec · mm^{-2} · $mrad^{-2}$ in 3% BW, enough for experiments of this type.

In future experiments, the group will attempt to shorten the x-ray pulses to as little as 50 fs by focusing the electron beam more strongly. Also on the agenda is to attempt pump-probe experiments with laser excited samples to observe the time evolution of Bragg-diffraction peaks and hence changes in long-range order.

Plasma Lens

The second experiment which has become operational at the BTF is a parametric study of plasma lens focusing. In this experiment, the 50 MeV electron beam is focused into a plasma column which is typically about 1 mm high and 1–2 cm long and has a density of 5 x 10^{12} to 2 x 10^{14} cm^{-3}. The plasma is produced through two-photon ionization in tripropylamine (TPA) using a frequency quadrupled Nd:YAG laser beam(266 nm radiation) which is focused to a line using cylindrical optics. The advantage of this technique is the fact that the plasma density can be controlled either through the chamber fill pressure (linear dependence) or through the laser intensity profile (quadratic dependence). For example, by tailoring the laser beam profile at the focus, plasmas with longitudinally (direction of the

electron beam) varying density profiles can be created. Detailed interferometric measurements of the plasma density have been carried out using 94.3 GHz in-quadrature microwave interferometry, which gives both phase and amplitude of the microwave beam simultaneously.

A schematic of the diagnostic is shown in Figure 3-10 with results from a scan of plasma density versus TPA fill density for a fixed incident laser intensity of 91.8 MW/cm^2 This technique makes it possible to probe sub-critical and also super-critical. Plasmas were produced with thickness less than the collisionless skin depth, allowing the evanescent microwave fields to tunnel through the plasma.

The electron beam profile is measured using optical transition radiation produced when the electron beam passes through a thin aluminized mirror. The beam spot is imaged with about 12 micron resolution onto a 16 bit CCD camera or a picosecond streak camera system, which are mounted about 8.5 m away from the interaction chamber. The beam current is monitored using an integrating current transformer mounted together with the mirror on a movable carriage inside the vacuum chamber. This system allows, through time integrated measurements of the electron beam size versus longitudinal position, a direct calculation of the beam's Twiss parameters as shown in Figure 3-11.

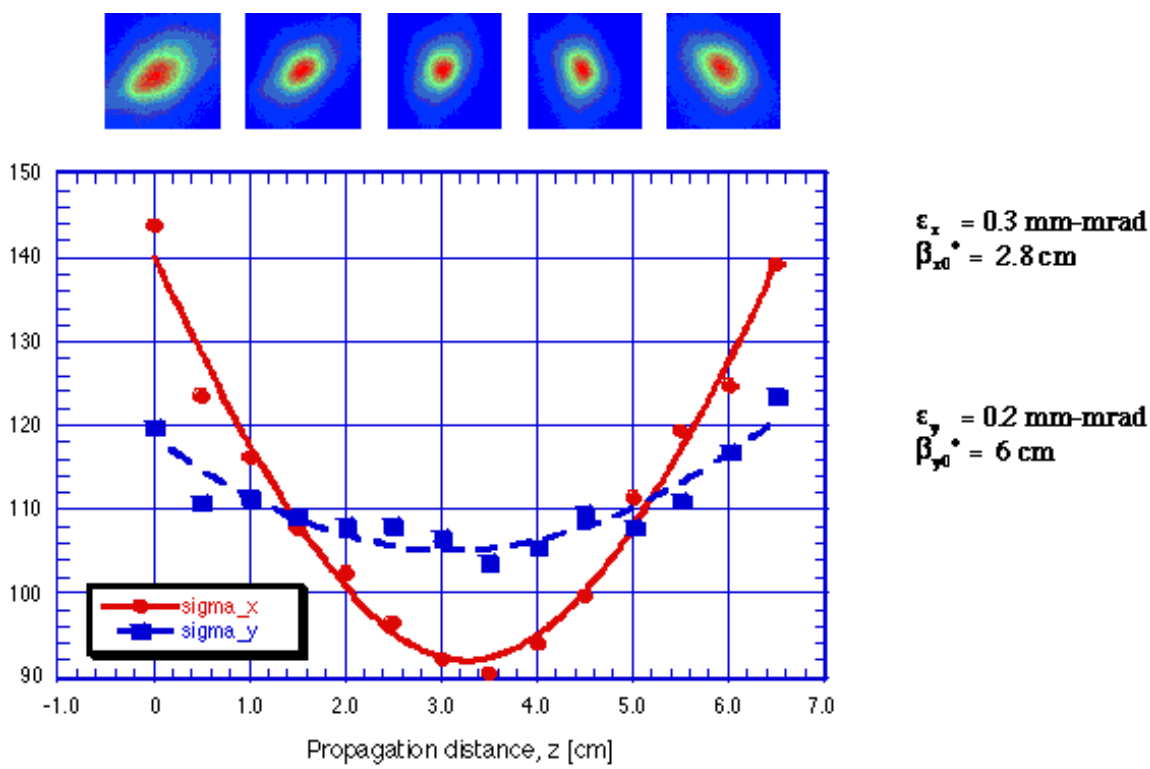

Figure 3-11*. Electron beam size (horizontal and vertical) measured with OTR as a function of propagation distance. The solid lines are quadratic fits for beta-function and emittance.*

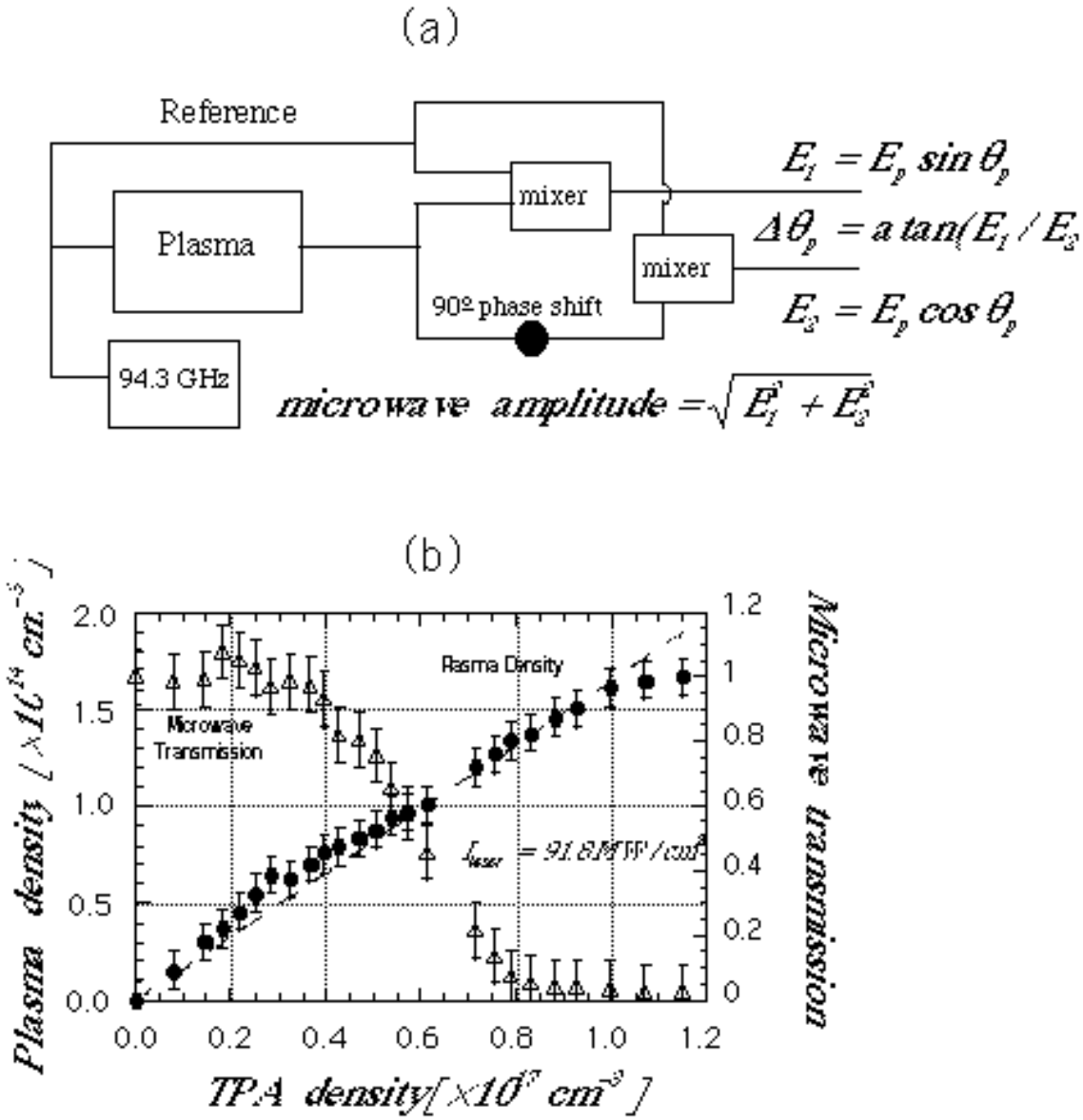

Figure 3-10. *(*a, upper*) Schematic of the 94.3 GHz microwave interferometer. (*b, lower*) Plasma density and microwave transmission as a function of TPA density.*

First observation of the electron beam focusing after propagation through the plasma was made in June 1996, only 20 minutes after turning all systems on. Figure 3-12 shows a typical scan of beam size versus longitudinal position with laser off and on. In addition to laser induced ionization, measurements have indicated electron beam impact ionization to be an important effect when using TPA. Since the initial results, detailed studies are ongoing on various regimes of operation of the plasma lens (i.e. overdense, current cancellation, and

underdense regime) to evaluate the ultimate focusing strength, temporal lens dynamics, beam matching into the plasma, beam induced ionization etc.. The expertise gained in this experiment is also being applied to a proposed plasma wakefield acceleration experiment at SLAC where a 30 GeV beam will be injected into a 1 m long plasma, for demonstration of net acceleration of 1 GeV in 1 m.

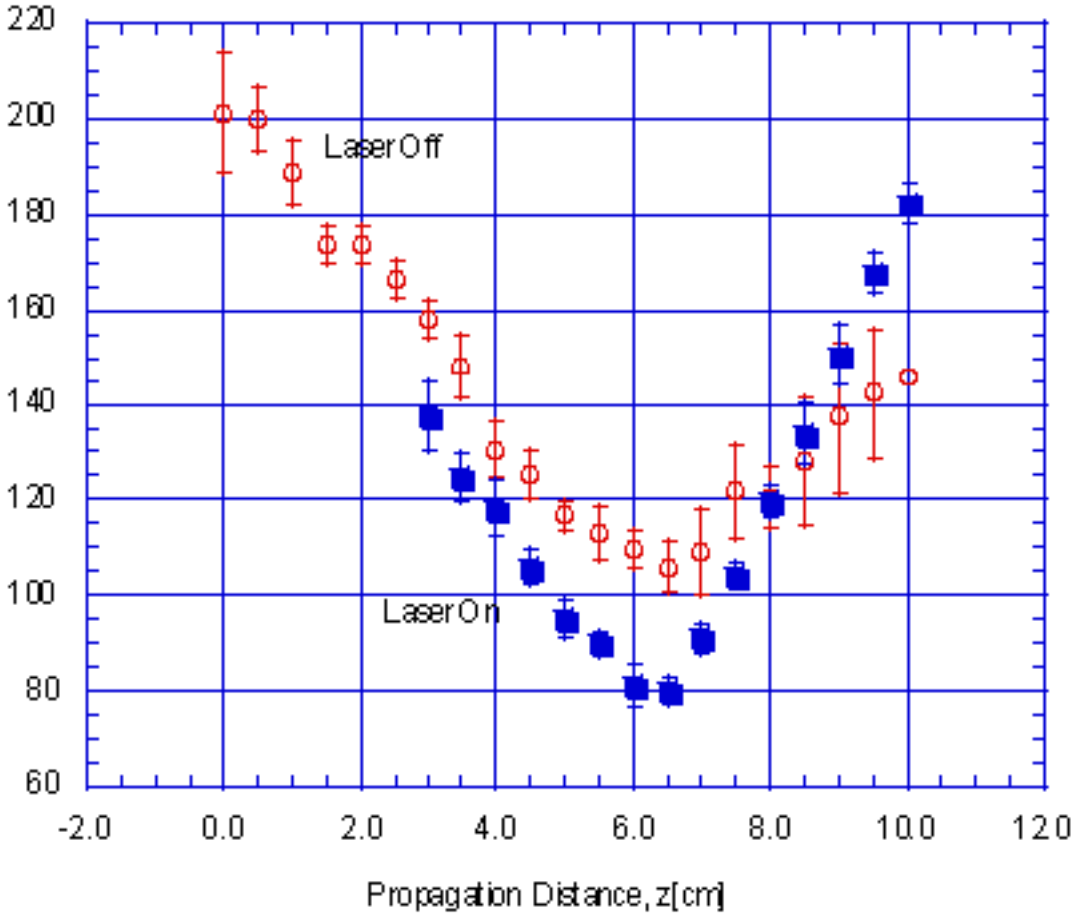

Figure 3-12*. Vertical electron beam size as a function of propagation distance with plasma* (solid squares*) and without plasma (*open circles*).*

l'OASIS Lab: A Testbed for Laser-Plasma-Particle Beam Interactions

In addition to the BTF experimental activities, the Group has been expanding the Laser Optics Laboratory. This lab, which was started in 1992, is now called the l'Oasis laboratory. In addition to the excimer laser, which is used for experiments on laser guided current channels by the Fusion Energy Research Program (see Chapter 1), a multi-terawatt

ultra-short pulse laser system will be available. The new laboratory will serve as experimental testbed for concepts on the interaction of high intensity ultra-high frequency electromagnetic fields with particle beams, plasmas and accelerating structures, towards the development of novel acceleration techniques and associated diagnostics; production of plasma based devices compatible with particle accelerators; development of laser components for optical stochastic cooling experiments; and novel radiation sources.

Construction of the new laboratory was started in January 1996 and completed in April 1996. Lab space in four separate rooms was consolidated; water cooling, electrical power, and laser interlock system were installed. A large laser system is presently under construction for experiments on laser guiding and wakefield excitation in a plasma fiber, as well as laser induced particle trapping for injection into the high gradient wakefields. The aim of the first phase of the experiment is to demonstrate guiding of intense (> 10^{18} W/cm^2), ultra-short pulses (50 fs) in a plasma channel, and excitation of high gradient longitudinal accelerating fields in the channel.

The plasma channels will be produced by a long laser pulse which has been brought to a line focus with an axicon lens. With this technique, pioneered by H. Milchberg et al. from the University of Maryland, 100 ps long pulses with intensities on the order of 10^{14} to 10^{15} W/cm^2 have been guided over distances of up to 70 Rayleigh lengths. In our experiment guiding of laser pulses with intensities relevant for laser wakefield excitation over a distance of 1 - 2 cm will be attempted. In addition plasma density modulations excited by the guided laser pulse in the channel will be measured optically. In the second phase, optical techniques for particle injection will be studied. In collaboration with researchers from the Naval Research Lab, we recently proposed a colliding pulse technique for laser induced trapping of plasma electrons in a laser excited wake. This novel technique, a variant on the LILAC concept, is a promising avenue for the development of an all-optical particle accelerator as it requires about two orders of magnitude lower laser intensity than the LILAC scheme. Implementation of the technique will be readily possible with the laser under construction.

The laser system under development operates at 800 nm wavelength and utilizes $Ti:Al_2O_3$ as the amplifying medium. Ultra-short pulses (typically 25 - 30 fs long) produced by a Kerr lens modelocked oscillator, which operates at 81 MHz and is pumped by an Ar-ion laser, are injected at a 1 kHz repetition rate into a commercially built regenerative amplifier (Spitfire-regen). The Spitfire is pumped by a 1 kHz intra-cavity doubled Nd:YLF laser and has a built in optical stretcher and compressor. The oscillator pulses are stretched about a factor of 10^4 and subsequently amplified after about 20 passes from the nanojoule level to 1.4 - 1.6 mJ. A 95 % reflective mirror sends the laser pulses to a two-pass pre-amplifier followed by a three pass main amplifier. The remaining 5 % is compressed inside the Spitfire and frequency doubled.

The pre-amplifier and main amplifier, presently under construction, are pumped by a frequency doubled Nd:YAG laser system, which delivers about 2 J at 532 nm. The expected final energy after amplification will be about 600 mJ. Half of the energy will be utilized for plasma production and heating. The other half of the energy will be pulse compressed in a scaled-up version of the Spitfire compressor, which has been built and tested to compress the long pulses (300 ps) down to about 40-50 fs long pulses, and then injected into the plasma channel. The frequency doubled weak pulse from the Spitfire will be utilized for a radial plasma density profile measurements using Mach-Zender interferometry.

Based on a theoretical model for wakefield excitation in the plasma channel, we have designed and built a single shot frequency resolved optical gate (FROG) to time resolve, with

femtosecond resolution, how the laser pulse shape and phase are changed through the interaction with the plasma guide.

Experiments are slated to commence during summer 1997.

Reported by Wim Leemans