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Accelerator and Fusion Research Division
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Foreword

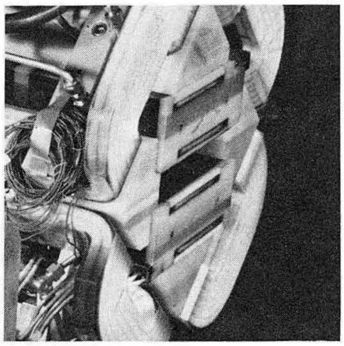
"Nothing happens unless first a dream."
—Carl Sandburg

The Exploratory Studies Group is dedicated to advanced investigation of accelerators and electromagnetic radiation. Its primary mission is to explore the next steps in the development of particle accelerators and storage rings, which are important both for high-energy physics and for the wide range of disciplines now turning to synchrotron-radiation sources and free-electron lasers. Our research is therefore deeply committed to LBL's institutional goal of becoming a center for the generation and use of coherent and incoherent electromagnetic radiation of exceptional brightness and for generic research on the future development of accelerators.

A significant fraction of our effort is dedicated to general accelerator-physics research for facilities on the immediate horizon, but a vital part of our activities comprises research into exotic future possibilities for charged-particle production, accumulation, acceleration, and storage. Accordingly, we are involved in three general areas of study: (a) research, development, and design for the Superconducting Super Collider, the next collider anticipated for high-energy physics research in the U.S.; (b) accelerator-physics research for the Advanced Light Source, the 1–2 GeV synchrotron radiation source now under construction at LBL; and (c) generic high-energy accelerator-physics and photon-beam research that looks far into the future, envisioning facilities that would employ new techniques of particle generation and storage. In the context of this last topic, we are carrying out a variety of studies. The subjects include next-generation TeV-scale linear colliders; facilities that would allow fundamental particle-physics research at lower energies ("B factories," for example); systems and components for high-brightness particle beams; and fundamental limits on acceleration and beam luminosity.

In addition, we are deeply committed to the education and training of physicists who will play a crucial future role in accelerator-related sciences, and we continue our international involvement in accelerator research through collaborative and advisory interaction with other institutions and laboratories around the world. The following pages provide a flavor of our multifaceted activities during 1988.

Swapan Chattopadhyay
Group Leader, Exploratory Studies
May 16, 1989



5.

EXPLORATORY STUDIES

. . . laying the foundations for future research in particle accelerators . . .

NOT ONLY BY ASSISTING in the research and development tasks now at hand, but also by laying the foundations for future research in particle accelerators, the Exploratory Studies Group functions as a key element of AFRD. Support for the Advanced Light Source (ALS) figured importantly in both of these roles. In assisting the design and implementation of the ALS, we have shed light upon fundamental issues of accelerator physics that will also apply to other third-generation synchrotron-light facilities and to damping rings for future high-energy linear colliders.

Topics of special relevance to the high-energy-physics community also figure prominently in our research. We added to our contributions toward the proposed Superconducting Super Collider (SSC), while at the same time looking beyond it. The multibillion-dollar SSC, whose 20-TeV proton collider rings will be more than 50 miles in circumference, seems to represent the geographical and financial limit of synchrotron technology. Physicists have therefore turned toward electron colliders in their long-range plans. Circular electron accelerators encounter a practical energy limit around a few hundred GeV due to synchrotron-radiation losses, so linear accelerators will be needed.

Accordingly, we are working with the Lawrence Livermore National Laboratory (LLNL) and the Stanford Linear Accelerator Center (SLAC) to explore new technologies. These efforts are focused on a futuristic linac called the two-beam accelerator, or TBA, which might derive its microwave power from a free-electron laser (FEL) or a relativistic klystron (RK). If the TBA fulfills its early promise, it might be used in a new class of efficient and relatively compact electron-positron linear colliders envisioned for the early 21st Century.

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In addition to these efforts at the energy frontiers, 1988 also saw the opening of a new area of inquiry for us: specialized accelerator facilities where important topics in particle physics could be explored at lower energies. Among the possibilities is APIARY (Asymmetric Particle Interactions Accelerator Research Yard), a "B factory" that could be based on the PEP ring (Positron-Electron Project) at SLAC. In APIARY, fundamental CP-violation studies and general B-meson physics would be advanced by creating B mesons and their antiparticles in electron-positron collisions that have a moving center of mass. The motion would spatially separate the decay products of the short-lived mesons, making detection simpler than if the center of mass were fixed.

A constant component of our efforts is theoretical study of beam dynamics in accelerators. Significant advances have been made in mathematical and theoretical techniques for analyzing nonlinear dynamics of storage rings and other machines.

Production of high-brightness beams of electrons and photons has been another theme of our research. Our investigations centered on bright electron sources and coherent radiation sources such as FELs.

Accelerator Physics for the ALS

In a ceremony on July 28, 1988, ground was broken at the site of the ALS, a third-generation synchrotron-light source. Of course, that symbolic beginning was preceded by a great deal of design and evaluation. Although our work has primarily focused on the immediate needs of the project, we have investigated many basic physics issues involving electron storage rings with numerous insertion devices. This research is highly generic and is relevant, for the most part, to any third-generation source, as well as to compact damping rings envisioned for high-energy linear colliders.

Linear and Nonlinear Effects

In facilities like the ALS, the dynamic behavior of particles is dominated by nonlinear fields generated by the strong sextupole magnets that correct chromatic aberration. The effects of these strong nonlinearities are exacerbated by two other phenomena: random quadrupole and sextupole errors in the lattice of bending and focusing magnets, and linear and nonlinear effects from the undulators and wigglers in the ring.

The 1988 work concentrated primarily upon the way insertion devices limit the dynamic aperture of the ring. (Dynamic aperture may be thought of as the effective bore of an accelerator; if the beam goes beyond the dynamic aperture limit, it can no longer be controlled and used.) We have developed two new computer codes, GEMINI and FUTAGO, that work together as shown in Figure 5-1 in modeling single-particle dynamics under the influence of various linear and nonlinear phenomena. Not only the normal lattice parameters but also user-entered values for imperfections, such as component misalignments and higher-order components of the magnetic fields, can be taken into account. Further details on these codes may be found in the "Mathematical Techniques in Particle Dynamics" section later in this chapter.

Single-Particle Dynamics and Insertion Devices

From its conception, the ALS has been designed for a relatively large number of magnetic insertion devices (the final design calls for as many as 11 to be accommodated). The effects of so many insertion devices, singly and as a group, cannot be viewed simply as minor perturbations; they are expected to influence the beam's behavior significantly.

It was clear from previous work that the insertion devices would have both linear effects (primarily breaking of lattice symmetry, resulting in phase changes between the chromatic sextupole magnets) and nonlinear effects (including beam

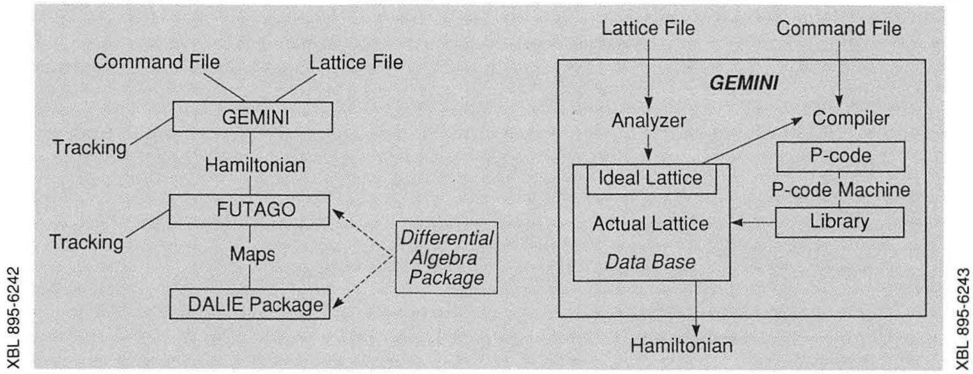

Figure 5-1. The GEMINI and FUTAGO programs can be used independently or together; the left diagram shows their relationship. The diagram at right shows the interworkings of various components of GEMINI.

distortion and amplitude-dependent tune shifts). To understand and quantify these effects, we have undertaken systematic analyses.

Among the findings was that, for a given peak magnetic field on axis, the nonlinear effects are more pronounced for insertion devices with shorter periods. (This has been borne out by particle tracking in computer simulation, using an algorithm that separates nonlinear effects from linear ones.) For instance, an undulator of 9-cm period may be regarded as a predominantly linear device, with its nonlinear effects reduced to the level of minor perturbations, whereas an undulator of 3.65-cm period has linear and nonlinear phenomena comparable to each other. Nonlinear effects do not lend themselves to practical correction; designers must minimize them or build in tolerance for the consequences. The linear phenomena, however, might well be corrected with the various quadrupole focusing elements in the ring.

To explore the various means of correction, we hosted a workshop on "Storage Ring Beam Dynamics with Undulators and Wigglers" in May 1988. One of the topics brought up at the workshop, which we subsequently explored in depth, was "perfect compensation" of the linear effects. We found several schemes for achieving or closely approximating perfect compensation by matching various parameters of the lattice.

Figure 5-2 summarizes the efficacy of perfect compensation (accomplished by whatever means) in an idealized model of the ALS lattice. As expected, we found that the effects of a long-period device, such as U20.0, become essentially invisible

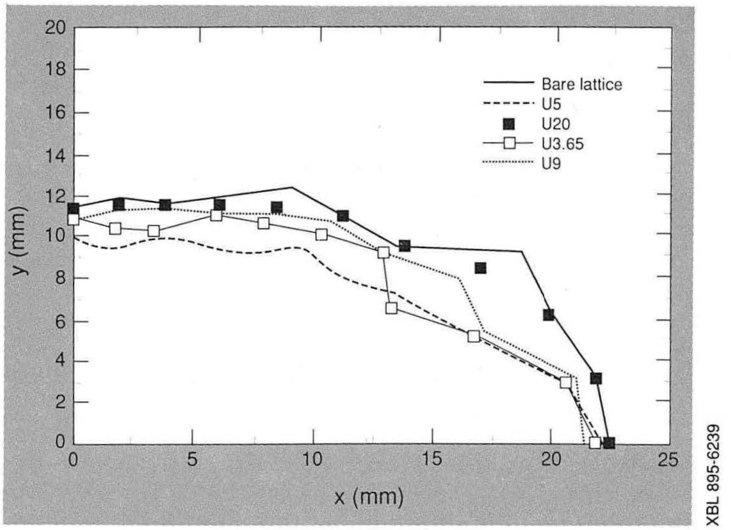

Figure 5-2. The effects of long-period insertion devices upon the dynamic aperture of the ALS ring are primarily linear and could be cancelled out almost entirely through the technique of "perfect compensation." Shorter-period insertion devices have significant nonlinear effects that cannot be corrected, but perfect compensation of their linear effects would be helpful nonetheless.

to the lattice; that is, the device does not compromise the dynamic aperture of the bare lattice. Perfect compensation is also helpful for shorter-period insertion devices, such as U5.0, even though they have significant nonlinear effects. All the perfect-compensation approaches we studied would require adding more quadrupole magnets to the lattice or varying the locations of existing quadrupoles.

However, there are a number of easier ways to compensate partially for the linear effects of an insertion device, including local tune adjustment and matching of the Twiss parameters α_x and α_y. Furthermore, given the significance of the uncorrectable nonlinear effects from the many short-period insertion devices, there remains a question of whether the benefits of perfect compensation are worth the added equipment costs and the intrusions upon the limited straight-section length. We examined a case of eight undulators of various periods and found that the dynamic aperture (although diminished) was acceptable without any attempt at perfect compensation.

Other Synchrotron Radiation Investigations

In addition to modeling single-particle dynamics in the storage ring, we performed complete dynamics analyses of the booster synchrotron and the injection linac. We also investigated the effects of undulator radiation inside the rf waveguide formed by the beam tube and examined the effects of the resulting wakefields. And, we refined earlier calculations of the angular distribution and energy spectrum of photon flux from the ALS bending magnets and insertion devices.

To further our understanding of the generic properties of high-brightness synchrotron-radiation sources, we participated in experimental accelerator-physics studies at various facilities. They included PEP in a low-emittance multibunch mode that has been envisioned for synchrotron-radiation experiments, as well as BESSY, a 750-MeV synchrotron-radiation source in West Berlin which was recently equipped with its first undulator. These studies have led to a better understanding of the dynamic effects of insertion devices and of multibunch effects in storage rings.

SSC Support

The scope, complexity, and importance of the SSC project have drawn upon the resources of virtually the entire U.S. accelerator-physics community. We have been heavily involved in this project for several years. Our 1988 efforts included design of a new lattice for the SSC main rings, a significant advance that is nonetheless compatible with the overall structure set forth in the SSC Conceptual Design Report (CDR). And we proposed a new lattice design for the series of progressively more-energetic boosters that will inject protons into the main rings.

We also studied the optimum method for controlling the beam-crossing angle at the interaction points. In the process, we modified the SYNCH computer code to simultaneously fit the requirements for closed-orbit matching and for minimizing dispersion.

Main-Ring Lattice

The lattice design published in the CDR (March 1986) had several shortcomings, which we have addressed in a proposed new design. It differs from the CDR design primarily in the phase advance through each cell in the lattice. By increasing the phase advance from 60° to 90° (with a corresponding reduction in the number of cells) we obtained a number of advantages. Toleration for imperfections in the magnetic fields has been increased, and a more-compact apparatus for suppressing beam dispersion can be used.

We also redesigned the lattice in the straight sections that will contain the experimental areas. The new design eases tune matching between the injection and collision optics. It also has a constant phase advance between neighboring straight sections, thus reducing chromatic aberration. Further, large beta functions are restricted to the quadrupole triplets; this is desirable because the magnet length increases with the beta function, a lattice parameter.

Injector Studies

A new design for the lattices of the SSC's three injector synchrotrons has been completed and compared with the specifications of the CDR. The parameters of the injector complex are matched, so the SSC can be filled to 94% of its theoretical bunch capacity. Dispersion is substantially reduced, compared with the CDR design, and is zero in the straight sections.

We also completed single-bunch tracking studies of the lattice, including the effects of the space-charge force, chromatic sextupoles, synchrotron oscillation, and expected systematic and random errors in the dipole magnets. We concluded that the CDR magnet design allows adequate dynamic aperture for all three boosters, and that the space-charge effect in the low-energy booster—the first in a series of three booster synchrotrons—has no significant detrimental effect if the booster is tuned properly. (The low-energy booster is especially critical; because of the lower energy of the beam, space-charge effects are proportionately more important than in the other boosters.) Further, we found that the thresholds of single-bunch instabilities in all three injectors are high enough to be of little concern. Figure 5-3 shows the tune distribution of particles in the low-energy booster at injection energy, including the effects of space charge.

Further SSC Beam Dynamics Studies

In other investigations in support of the SSC, we designed an injection girder (transport-and-matching section) that could be used to connect the linac to the Low Energy Booster; this was a part of the injector complex that had not been designed in detail. And, we showed that a "three-lump" correction scheme, previously devised for systematic multipole errors in the superconducting dipoles, would also be effective against random errors.

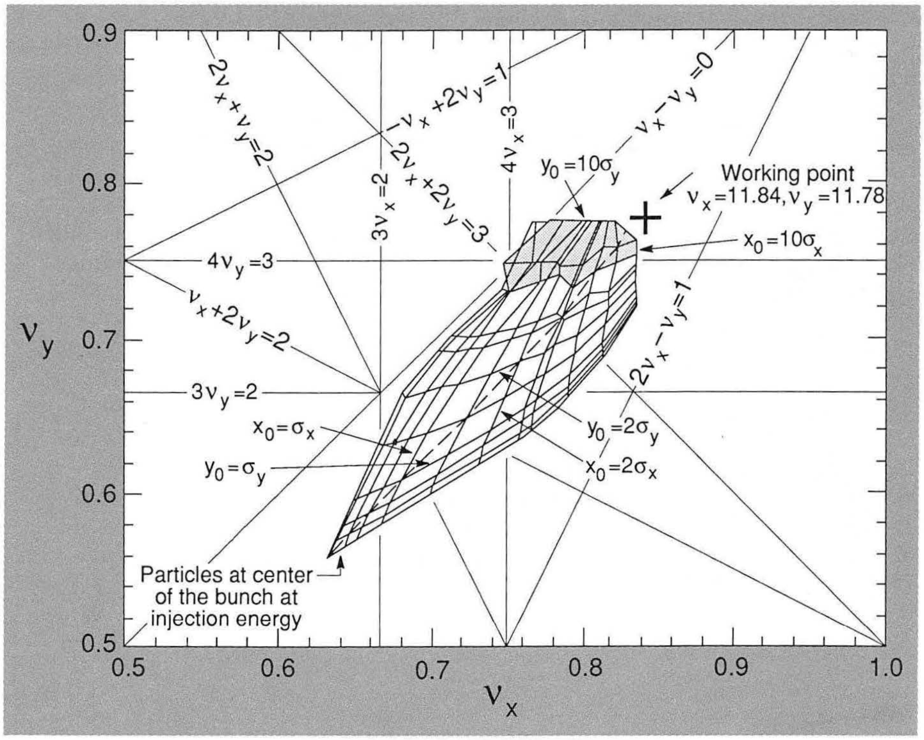

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Figure 5-3. Computerized simulation produced this plot of tune distribution of protons in the SSC Low Energy Booster during injection. Note the significant distortion of the otherwise uniform shape at large amplitudes (highlighted area) due to space-charge effects.

Other Accelerator Studies

Members of our group have been working with Fermilab on possible upgrades for their Tevatron, the first accelerator to exceed 1 TeV, and on problems related to other accelerators for nuclear science. We also undertook initial studies of an infrared FEL, which might be built here at LBL in a location where advanced experiments in chemical dynamics could be performed by taking advantage of beams from both facilities. And, we made some advances in mathematical techniques for analyzing particle dynamics.

Machine Investigations

Among the possible upgrades for the Tevatron facility is a new proton-antiproton collider, operating at 1.8 TeV per beam, in the existing tunnel. We have completed a feasibility study of such a collider from the lattice standpoint. At a 1988 study meeting in Snowmass, CO, we and others performed a preliminary lattice design involving 8- to 9-T dipoles. Except for some modifications to allow beam extraction at the higher energy, the lattice is much like that of the existing Tevatron and has comparable linear optical properties. We also designed a new interaction region that permits electrostatic beam separation during multibunch operation; this innovation could be incorporated in either the present Tevatron or an upgraded version.

We contributed to the performance verification of RHIC, the Relativistic Heavy Ion Collider proposed for construction at Brookhaven National Laboratory. RHIC, with its TeV/nucleon equivalent fixed-target energies, would extend the line of research originated at LBL's Bevalac.

The physics and the engineering feasibility of an infrared FEL were also prominent subject of our research. The IRFEL we studied would have a wavelength in the 3–50 μm range. Wavelength stability is highly important, especially for chemical-dynamics studies; this IRFEL would have a stability ($\Delta\lambda/\lambda$) of $\pm 1 \times 10^{-4}$ or better. The instrument would preferably be built near the ALS, positioned so that beams from both facilities could be fed into the same experimental area for two-wavelength "pump-probe" studies.

Mathematical Techniques in Particle Dynamics

Accurate computer simulation of large and small periodic rings requires the use of tracking codes that can treat lattices realistically, taking into account random and systematic errors, closed-orbit correction schemes, and so forth. We have developed an exact recursive algorithm, based on differential-algebraic and Lie-algebraic techniques, that implements canonical transformations, eliminating secular terms in the motion of particles. It can be used for motions of arbitrary complexity and can treat higher-order error terms and nonlinear terms to an extent limited only by the power of the computer on which it is used. The algorithm is implemented in the computer codes GEMINI and FUTAGO.

The algorithm also treats problems in phase spaces and parameter spaces of arbitrary dimensionality, limited again only by the capabilities of the computer. First it extracts the formal power-series map for one period of the ring from a complex tracking code by using differential-algebra techniques. Then it analyzes the final map by expressing it in terms of Lie generators. The scheme is modular and removes the need to account for local *s*-dependent perturbation. Further, production and analysis of the map are independent. This powerful approach is already yielding crucial results for the SSC and the ALS that could not have been obtained by the other methods available today.

APIARY: B-Factory Studies

Recently the high-energy physics community has become increasingly interested in "B factories," which would produce $B\overline{B}$ pairs for fundamental studies of CP violation and rare B-meson decays. Numerous schemes for $B\overline{B}$ production in electron-positron collisions have been advanced in the literature. They fall into four categories:

- *Symmetric equal-energy colliders based on two identical storage rings*

- *Symmetric equal-energy linear colliders based on two identical linacs*
- *Hybrids involving a ring and a linac*
- *Asymmetric (heteroenergetic) colliders with one relatively high-energy ring and one lower-energy ring (9 × 3 GeV, for example), an idea conceived at LBL.*

The last category offers some intriguing advantages. In particular, of all schemes that would provide enough experimental statistics in one to three years to permit confident statements about results, it has one of the lowest luminosity demands. Furthermore, because the center of mass of the collision moves in the laboratory frame of reference, the decay products are separated in space and time, making detection easier.

Independently and in collaboration with SLAC, we have studied this idea from the accelerator and detector viewpoints. The conclusion is that an asymmetric B-factory using the high-energy PEP ring at SLAC would be scientifically and economically attractive. Our plan for a B factory is called the Asymmetric Particle Interaction Accelerator Research Yard, or APIARY.

APIARY Physics Design Study

We have nearly completed a study of the physics design of a 3-GeV storage ring for APIARY. This design features a common magnetic-optics focusing scheme for both the high- and low-energy beams at the interaction point. (The collision optics may call for superconducting and/or permanent magnets in the interaction-region straight section.) A tentative site plan, showing two possible low-energy rings, is shown in Figure 5-4.

The design also satisfies the "Asymmetric Energy Transparency" condition that makes the two beams behave symmetrically in the transverse phase space, despite the energy asymmetry, while undergoing beam-beam interaction, radiation damping, and quantum fluctuations. To satisfy this condition, we have to take advantage of the damping characteristics of wigglers (short-period magnetic insertion devices); the design calls for horizontal and vertical wiggler magnets sharing radiation among themselves in both planes.

The high-energy PEP ring could be used virtually as is, or could be given a variety of upgrades for better performance. Allowing for a modest tune shift of 0.05 due to beam-beam interaction, and taking impedance limitations on currents in the two rings into account, one can obtain a collision luminosity of 2×10^{33} cm^{-2} s^{-1} without any exotic technologies and without major modifications to PEP. Presently, the PEP luminosity is limited by several factors, some more amenable to correction than others. They include restrictions on beam current from ring impedance, limits on the amount of synchrotron radiation the PEP vacuum chamber can absorb safely, and the effects of coupled motion of multiple electron bunches.

PEP has a formidable 120-cell rf system (24 cavities with 5 cells each) characterized by substantial higher-order modes. In addition to limiting the total beam current via impedance, these modes generate multibunch coupled motion. The coupled motion could be controlled with a high-powered feedback system. A more comprehensive upgrade, perhaps involving 20 single–cell superconducting cavities operating at 352 MHz like those used in CERN's Large Electron-Positron collider, would cost more but would give substantially greater benefits. In particular, it would greatly reduce beam impedance, thereby raising the current limit (more electrons could be packed into each bunch) and would also reduce coupled motion.

Large increases in luminosity would also call for a more-capable vacuum-chamber cooling system or, better yet, a new vacuum chamber. (A luminosity of 1×10^{34} cm^{-2} s^{-1} would produce 8 MW of synchrotron-radiation power; the present vacuum chamber and cooling system can only handle 3 MW.)

Figure 5-4. APIARY could be built at SLAC with the addition of a 3-GeV storage ring (in either of two physical sizes) near the existing PEP storage ring. Because of the energy asymmetry, the center of mass of the collision moves in the laboratory frame of reference; thus the decay products are separated in space and time, making detection easier.

Two-Beam Accelerators and Bright Electron Sources

Of the many ideas that have been proposed for the electron-positron colliders of the next century, the Two-Beam Accelerator (TBA) appears to be one of the most promising. Conceived at LBL, it is now being investigated (in several alternative configurations) for major research programs at many of the world's accelerator laboratories. As construction and operating costs and sheer physical size begin to pose practical limits for present accelerator technologies, the 200-MeV/m gradients possible in a TBA become increasingly attractive.

Two-beam acceleration begins with a high-current, relatively low-energy electron beam (3-kA, 10-MeV, for example) from an induction linac. This beam is applied either to an undulator-based FEL or to an RK, *producing microwave power on the order of 1 GW in a very small structure, perhaps 1 m in length. The microwaves, in turn, are coupled to an adjacent high-gradient acceleration structure.*

A TeV-caliber acceleration structure would be 5–10 km long, according to theoretical and experimental findings. (By contrast, a 1-TeV linac with a gradient comparable to that of today's state-of-the-art electron linac, the Stanford Linear Collider, would be about 60 km long if it could be built at all.) Designs for FEL-based and RK-based TBAs are being developed by LBL researchers, in collaboration with colleagues from LLNL and SLAC.

FEL-Based TBA

In 1985, a successful demonstration of efficient, high-power microwave production from an FEL was conducted at LLNL, using an experimental undulator designed and fabricated by the LBL-LLNL-SLAC team (Figure 5-5). The FEL produced more than 1 GW of peak power at 35 GHz with an efficiency of better than 35%. During initial tests, we explored the microwave breakdown limits of the "septum coupler" that extracts the microwaves from the FEL, and we tested a short prototype of a high-gradient accelerator (HGA). The experimental program was suspended in 1986, however, because the accelerator we were using was rebuilt and subsequently became unavailable for this application.

In 1987, a high-quality, 10-cm-long, 34-cavity HGA was fabricated to LBL specifications by the Haimson Research Corp. (Figure 5-6). We arranged to test it at the Massachusetts Institute of Technology, using a research version of a cyclotron auto-resonance maser instead of an FEL as a power source. These tests, scheduled for 1989, will probe the breakdown threshold of the HGA at 33.31 GHz and power levels of 20–50 MW, and are expected to demonstrate acceleration gradients of 200–300 MeV/m.

In the meantime, theoretical studies of the original FEL/TBA concept revealed a number of possible problems. Most of them were solved fairly easily, but achieving adequate system phase stability proved to be a formidable challenge. If the phase of the incoming microwaves at an HGA power-input port is not correct,

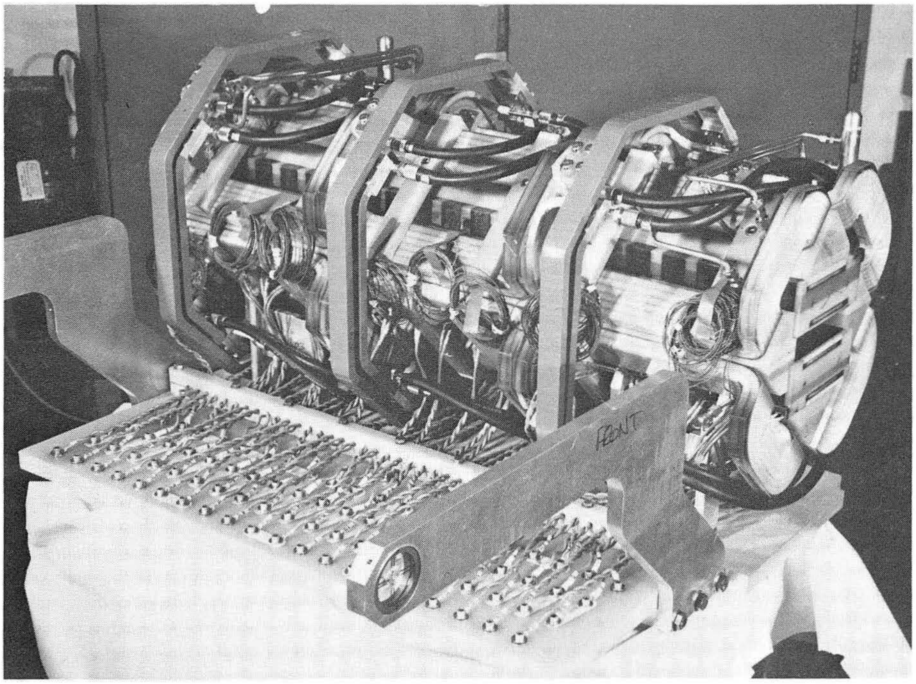

Figure 5-5. The free-electron laser used for TBA research in 1985 and 1986 at LLNL. The 1-m-long wiggler provided an impressive demonstration of high-power microwave output (1 GW of peak power at 35 GHz with an efficiency of better than 35%) and was used in early tests of a high-gradient accelerating structure.

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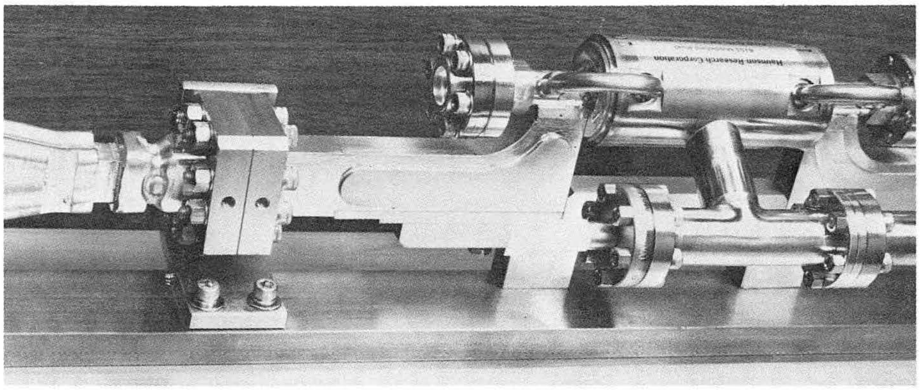

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Figure 5-6. The latest high-gradient accelerating structure has 34 cavities and operates at 33.3 GHz. Extreme manufacturing precision is required in such devices; this one was machined to tolerances of ±1.25 μm. Acceleration gradients of 200–300 MeV/m are expected in tests at power levels of 20–50 MW.

the electron bunch will not receive the expected acceleration; it appears that small errors in undulator field strength, FEL beam energy, and especially FEL current can cause unacceptable phase deviations. In 1988 we found that choosing the correct physical configuration and operating parameters for the FEL (and for the reaccelerator that re-energizes the electron beam after it goes through the FEL) might result in steady-state, alternating-gradient longitudinal focusing. This can apparently make the phase of the microwave beam less sensitive to small, unavoidable variations in accelerator parameters. Engineering efforts aimed at developing hardware concepts and operating techniques for the TBA are also in progress. Figure 5-7 shows a simple, inexpensive permanent-magnet wiggler designed to produce 17-GHz microwaves (a nearly optimum frequency for a TeV-class TBA) from a 3.5-MeV, 3-kA electron beam.

Another promising development, diagrammed in Figure 5-8, is a permanent-magnet separator for extracting microwaves from the FEL. In this device, the electron beam would be "jogged" about 10 cm off center by three small permanent-magnet dipoles. This displacement would permit the microwaves to be reflected out of the beamline and conveniently divided into four equal-power HGA feeds. This separator would be 50–70 cm long for a 10-MeV electron beam.

A cost study of FEL-based power sources for linear colliders confirmed the desirability of a beam reaccelerator, which has been part of the various TBA concepts from the beginning. A 1-TeV collider using FEL-based TBAs would cost roughly $1 billion; we estimate that reaccelerating the FEL drive beam three times instead of building multiple accelerators would save on the order of 25% of the cost of the apparatus, or about $250 million.

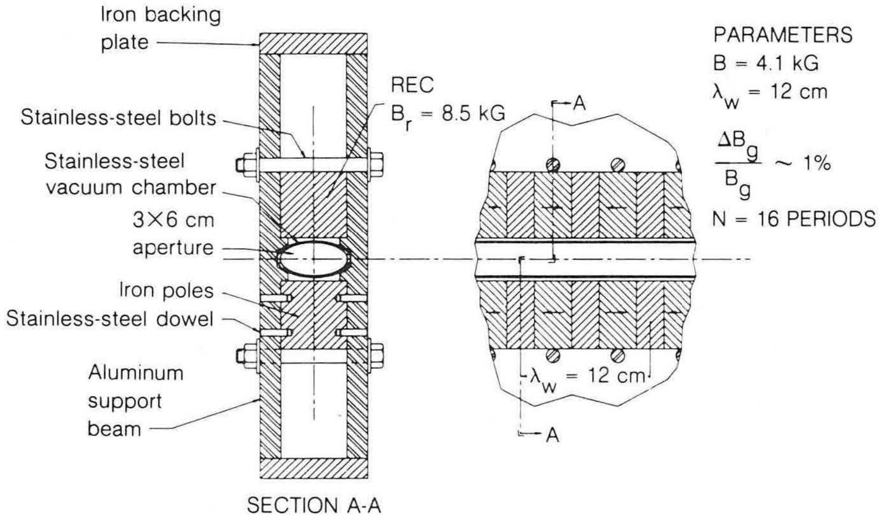

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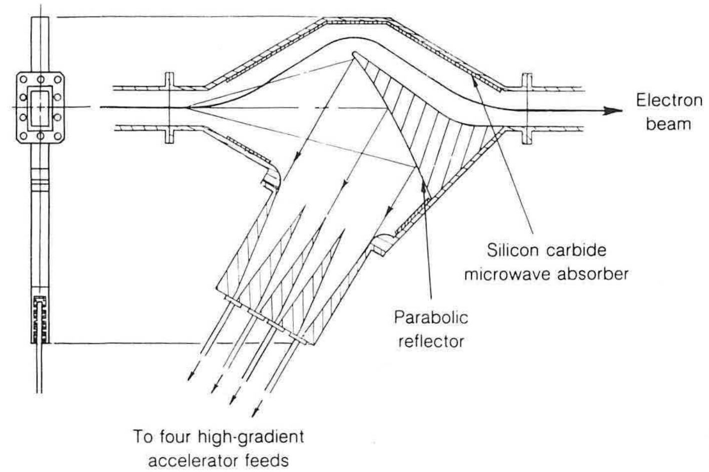
Figure 5-7. A 2-m-long permanent-magnet wiggler based on this design could turn a 3.5-MeV, 3.0-kA electron beam into 5.0 GW of microwave power at 17 GHz—a conversion efficiency of approximately 44%. Such a wiggler would be both practical and relatively inexpensive to manufacture.

Figure 5-8. This promising concept for extracting multi-GW microwave power from an FEL is now being studied. Small permanent-magnet dipoles (not shown) would "jog" the electron beam away from the centerline, permitting the microwaves to be reflected from the central region. A 17-GHz extractor would be 50–70 cm long.



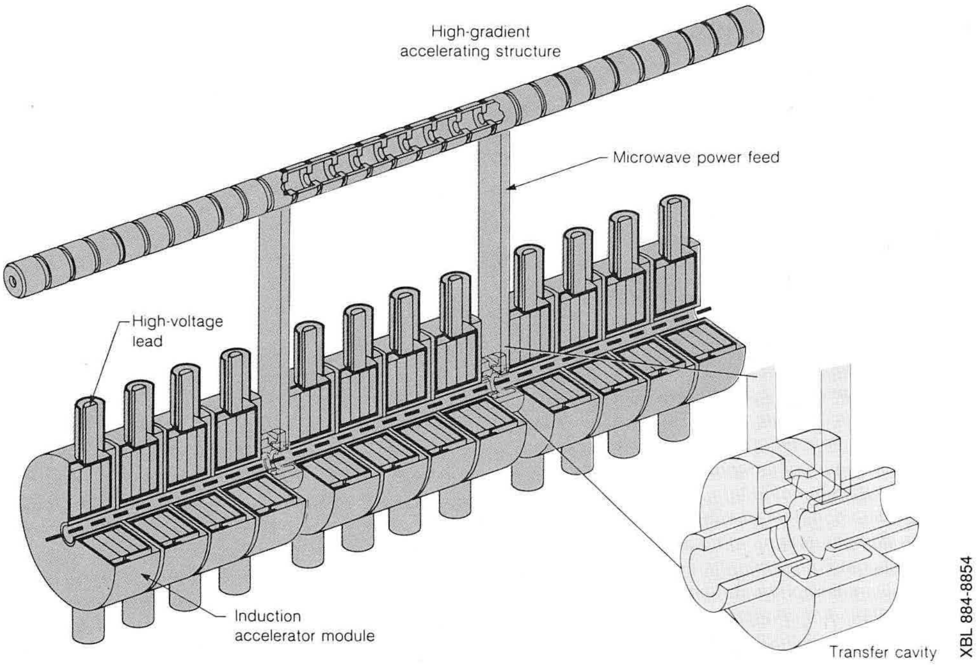
RK-Based TBAs

Recently we have been exploring the possibilities of a TBA that derives its power from a relativistic klystron, an idea originally proposed by W. K. H. Panofsky of SLAC. Figure 5-9 shows the internal structure of such a system. The bunched, low-energy, high-current beam threads it way through a series of standing-wave transfer cavities from which microwave power is fed to the HGA. In collaboration with LLNL and SLAC, we have investigated both this concept and an alternative in which traveling-wave structures are used for output coupling.

A recent series of standing-wave RK experiments at the LLNL Accelerator Research Center was designed to study breakdown and electron-loading phenomena and to investigate ways of improving beam transport. We obtained an output power of 200 MW from a six-cavity, 11.4-GHz RK; when this power was coupled to a 30-cavity HGA built by SLAC, a gradient of 140 MeV/m was produced without breakdown.

In other experiments, which involved single-cavity, standing-wave RKs, it proved difficult to achieve the predicted maximum power output without either microwave breakdown or excessive electron loading (in which the RK fills up with

Figure 5-9. A two-beam accelerator could be powered by RKs rather than by an FEL. In the concept diagrammed below, standing-wave cavities (*bottom*) extract power from an intense, low-energy electron beam, whose energy is then replenished by conventional induction acceleration modules. The microwave power is transferred to a high-gradient accelerating structure (*top*) in which a second electron beam is accelerated to a very high energy. (LLNL artwork)



electrons stripped from its walls by the high fields). One contributing factor was the low repetition rate of the accelerator we used (10 Hz at most), which precluded repetitive high-field conditioning of the devices. A more significant handicap, though, was inherent to standing-wave structures: surface electric fields that, at peak, are much larger than the accelerating gradient.

The surface-electric-field problem was addressed by replacing the standing-wave coupling structures with an 11.4-GHz traveling-wave structure. (For a given accelerating gradient, traveling-wave structures operate with lower surface electric fields.) We have achieved breakdown-free operation at 100 MW thus far; power has been limited by available beam current and by breakdown in the buncher cavity upstream from the RK. During the 1988 experiments, cavities were used for klystron-type bunching; in 1989 we plan to use a microwave-driven beam chopper for bunching. Although less efficient, this bunching method has several important advantages, including greatly reduced sensitivity to beam energy. The assembly, which is about 1 m long, is shown in Figure 5-10.

TBA-Related Studies

A problem that must be addressed in any beam transport system is beam breakup through beamline resonance and positive feedback. When the beam first excites resonant structures along the beamline, it sets up a "transverse wake"—electric and magnetic fields that act on later portions of the beam, causing transverse displacement. This displacement excites even-larger fields, causing even more displacement. If this feedback is strong enough, the beam will be lost. We and our LLNL colleagues have developed computer codes, which run on the Cray computers at the National Magnetic Fusion Energy Computing Center, to model beam breakup in the FEL and RK TBAs and to compute the growth of the displacement.

Beam reacceleration will be an important cost- and energy-saving function in a TBA collider. Accordingly, we have been performing theoretical studies of

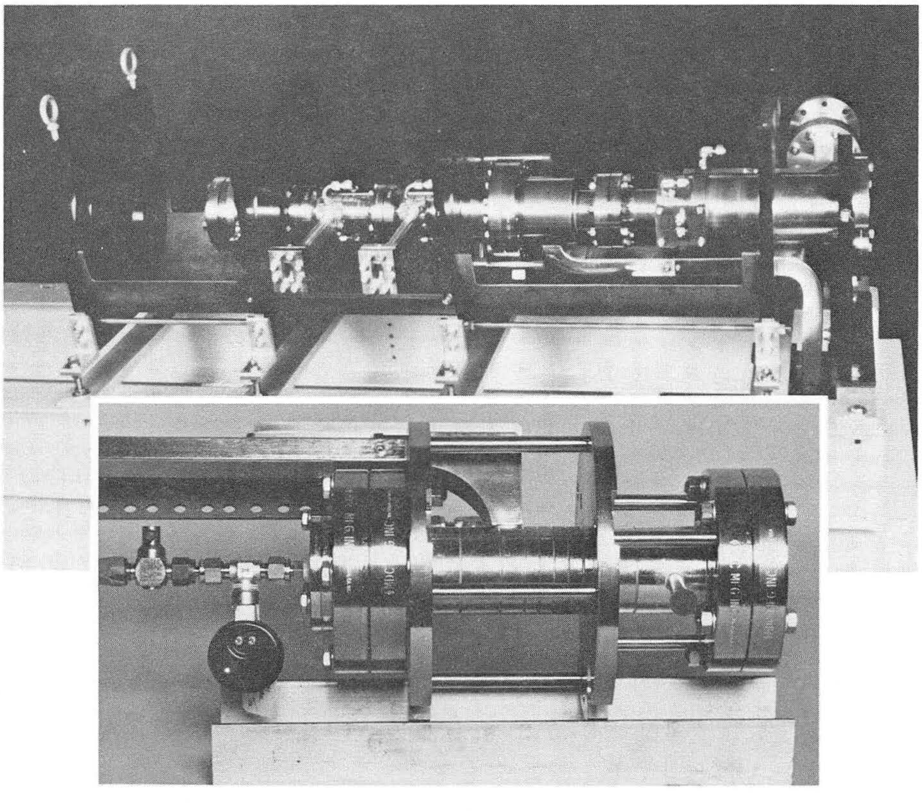


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Figure 5-10. Traveling-wave cavities offer some advantages over standing-wave cavities for RK applications. In particular, for a given accelerating gradient, they operate with lower surface electric fields, thereby raising the electrical-breakdown performance limit. The 1-m-long assembly shown here may be thought of as an efficient electron *de*celerator capable of converting electron-beam energy into microwave energy. *Inset*: a detail of the traveling-wave output coupler. (LLNL photographs)

induction-linac reacceleration of bunched beam. The main obstacle is that a beam "sees" the linac as a cavity that can oscillate. This property may be viewed as longitudinal impedance, i.e., coupling between the beam current and the various cavity modes. This impedance causes energy loss and energy spread in the TBA drive beam. These problems will have to be understood and corrected to enable the eventual development of a collider. In the course of the TBA research and other Exploratory Studies Group investigations, what amounts to a new field—beam-plasma physics—has opened up at the intersection of plasma, beam, and accelerator physics. The number of physically sound concepts, all worthy of further study, has grown beyond the number of researchers available to work on them. Some of the more promising ones are described below.

Plasma Adiabatic Compression. When a relativistic electron beam enters a plasma channel, it is focused to a spot by a radial pinch force. The spot size is determined by the beam emittance and by the betatron wavelength, which is a function of the plasma density. By tailoring the density of a gas through differential pumping, and by ionizing the gas with a laser pulse (as in "laser guiding" at the Advanced Technology Accelerator at LLNL), one could obtain a spot size that could be achieved with magnetic optics only at great expense and with exceedingly close tolerances. A plasma adiabatic compressor might be useful in an electron-positron collider, for instance, where it would focus the beams just before collision.

Ion-Focused Free-Electron Lasing. In an FEL, the gap between two wiggler pole pieces could be filled with a neutral gas, which would be ionized by a laser just before a relativistic electron beam was sent through the wiggler. Because of the stronger focusing of the electron-beam spot, this device would provide stronger coupling to the radiation field than a conventional (hard-vacuum) wiggler and would therefore be more efficient. We have developed parameters for a 50-nm FEL based on this principle, and theoretical work is continuing.

Plasma Compensation. A relativistic electron beam drives return currents through the plasma that tend to cancel the beam's magnetic field. Plasma lenses and conventional ion-guiding techniques rely on space-charge neutralization and do not attempt to neutralize the return currents, whereas plasma compensation does both. It has been suggested as a means of reducing beamstrahlung at the interaction point in electron-positron colliders. (Beamstrahlung is radiation emission by a single particle in the magnetic field produced by the colliding beams.) Plasma compensation has been the subject of extensive analytical and numerical investigation; the key issues to be addressed in the future include the "background problem," or interactions of the compensated beams with the hadrons in the plasma.

Beam-Beam Compensation. There may be advantages in neutralizing space charge and return currents for each beam in a collider by co-propagating oppositely charged beams of equal current. If successful, this would alleviate some collider problems, including beamstrahlung, pair production and other quantum-electrodynamic processes, beam disruption, and tune shifting. Numerical simulation of four-beam collisions is underway, with particular attention to compensation at the interaction points of two possible future colliders: a "B factory" (see the APIARY section of this chapter) and a linear collider at the Fermilab Tevatron.

Bright Electron Source

An ongoing goal of the LBL-LLNL-SLAC collaboration on RK research has been a "1-GeV Test Experiment," a feasibility demonstration of an ultracompact rf linear accelerator (not more than 5 m long) that can produce 1-GeV electron beams of exceptional brightness. A preliminary physics design of a bright electron injector, based on an rf gun with a photocathode driven by a picosecond laser, has been completed at LBL. This gun design is conceptually similar to the design pioneered by Los Alamos National Laboratory (LANL), but is parametrically different and incorporates achromatic magnetic bunching and transport systems, as well as diagnostics. The parameters were chosen on the basis of simple but realistic analytical models, as well as computer simulations, that account for transverse and longitudinal space-charge effects. Table 5-1 compares it to other existing and planned electron guns. Such an apparatus might be useful not only in TBAs for colliders, but also in FELs used as compact coherent light sources (e.g., in x-ray holography) and for research in the propagation of intense beams.

Table 5-1. Characteristics of High-Brightness Electron Guns

	Emittance (m-rad, normalized)	Charge per bunch (nC)	Bunch length (ps)
1-GeV Experiment (11.4 GHz)	3×10^{-5}	1–2	3.5
SLAC gun	1.5×10^{-4}	12	2500
SLAC gun after buncher	$2–3 \times 10^{-4}$	12	15
SLAC gun after mag. compressor	$2–3 \times 10^{-4}$	12	5
LANL rf gun	$0.5–1 \times 10^{-5}$	5–10	60–70 (currently planned for 15)
BNL rf gun (planned)	$3–6 \times 10^{-6}$	1	3–5
Stanford Univ. microwave gun	$1–10 \times 10^{-6}$	< 0.1	4

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