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Research Overview 1992

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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accelerator and fusion research division

1992 Summary of Activities

Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, CA 94720

December 1992

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Foreword

Nineteen ninety-two was a busy, productive year of research and planning in anticipation of future projects. The Induction Linac Systems Experiments, the logical next step on the road to a heavy-ion "driver" for inertial fusion energy, received a Determination of Need from the Department of Energy—a key vote of confidence and an optimistic note on which to submit a proposal this year for a 1995 construction start. Meanwhile, our research in magnetic fusion energy progressed further with a design for an accelerator proof-of-principle experiment. The resulting accelerator, at larger scale, would be at the heart of the neutral-beam plasma heaters might be used in the International Thermonuclear Experimental Reactor (ITER). Both ITER and heavy-ion drivers are important elements in the DOE's National Energy Strategy, and we are pleased to be able to contribute to their advancement.

The Advanced Light Source (ALS), a national user facility designed to be at the forefront of synchrotron-radiation research well into the 21st century, is being completed and commissioned by stages in preparation for the beginning of operations in spring 1993. The first beam will soon be injected into the storage ring; meanwhile, the "Beamline Scorecard" shows that, of the 11 beamlines planned for the period through 1995, three insertion-device and two bend-magnet beamlines are expected to be in use for data-taking during the first year of ALS operations. The availability of high-brightness ultraviolet and x-ray beams from the ALS is anticipated eagerly in a broad variety of research communities, including materials science, chemical dynamics, and structural biology. To expand the use of the ALS, a Beamlines Initiative was proposed to the DOE. The initiative includes four more of the insertion devices that enhance synchrotron-light production, along with their associated beamlines, plus completion of second-floor laboratory and office space.

Approval of the proposed Beam Physics Facility was among the highlights of our Exploratory Studies Program. The facility, whose design has been finalized, will use the high-quality 50-MeV electron beam from the ALS injection linac for a diverse experimental program during the periods when the storage ring is full and the injector would otherwise be idle Of the many possible experiments, the first will be a plasma focus and a scheme for generating femtosecond X-ray pulses with Compton scattering against a laser beam. We also further refined two proposed initiatives: PEP-II, a "B factory" at the Stanford Linear Accelerator Center, and an infrared free-electron laser for the Chemical Dynamics Research Laboratory.

Our program in superconducting magnets concluded the SSC Magnet Industrialization Program, in which representatives of private industry worked alongside LBL personnel to learn how to build the LBL-designed collider quadrupoles for the Superconducting Super Collider. Research and development aimed at materials and magnets for the future resulted in a world record for field strength in an accelerator-type magnet (a central field of just over 10 teslas), and among our new lines of inquiry is an effort to develop much-stronger magnets.

Not all the news was good, as we learned that DOE support for the Bevalac heavy-ion accelerator complex would end midway through fiscal year 1993. Plans are being made and implemented for the optimum redeployment of Bevalac personnel (the ALS is one of the facilities already taking advantage of their expertise). We are also looking at ways to make the best use of this heavy laboratory space and to perform the decommissioning in a safe, environmentally responsible, and cost-effective manner. Yet even as the end draws near for this venerable and enormously productive accelerator, the spinoffs from its development and operation continue; most prominently, we have been involved in the design of a proton-therapy initiative put forth by the University of California-Davis Medical Center.

AFRD researchers continued receiving awards and peer recognition in 1992, including the R&D 100 awards, *Research and Development Magazine's* recognition for the year's 100 most significant technical innovations. Three longtime collaborators in the Bevalac biomedical program—AFRD's Tim Renner, along with Bill Chu and Bernhard Ludewigt of the Life Sciences Division—won with the Raster Scanner Beam Delivery System. Ian Brown of AFRD's magnetic fusion energy program, together with Robert MacGill, Michael Dickinson, and James Galvin of the Engineering Division, earned another R&D 100 for the DC Broad-Beam, High Current Metal Ion Source. Meanwhile, a Federal Laboratory Consortium Technology Transfer Award went to Wayne McKinney of the ALS Experimental Systems Group in recognition of his efforts, in collaboration with industry, to develop and characterize supersmooth metal surfaces for synchrotron-radiation optics.

Behind all these plans and achievements are the people of AFRD. Their 1992 accomplishments, including the highlights described in this report, were made possible by a unique combination of skill, creativity, and hard work. These qualities have made me proud to serve as their leader, and I am confident that the permanent director, when appointed, will inherit a forefront scientific organization worthy of the LBL tradition.

Richard A. Gough
Acting Director,
Accelerator and Fusion Research Division
December 1992

Accelerator and Fusion Research Division Staff

Richard A. Gough, Acting Division Director

Staff Senior Scientists and Faculty

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Roger Bangerter
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Olivia Wong
Katherine Williams†
Judy Zelver

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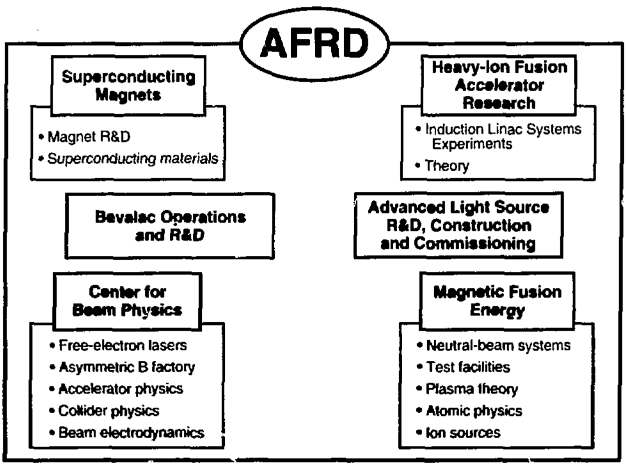
* Department of Physics, UCB
† Retired

AFRD: Diversity with a Common Theme

THE ACCELERATOR AND FUSION RESEARCH DIVISION is not only the largest scientific division at LBL, but also one of the most diverse. Major efforts include

- Investigations in both magnetic and inertial fusion energy.
- Design, construction, and commissioning of the Advanced Light Source, a state-of-the-art synchrotron-radiation facility.
- Theoretical and applied studies of accelerator physics.
- Research and development in superconducting magnets for accelerators and other scientific and industrial applications.
- Operation of a heavy-ion accelerator complex, the Bevalac, for nuclear science and biomedical research.



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These efforts share a foundation in the physics and technology of beams of ions, electrons, and photons. This introductory section gives an overview of AFRD's fields of inquiry and their relevance to current issues in science and technology. Later chapters go into greater detail on each topic.

Fusion Energy: Beginning the Next Explorations on Two Frontiers

As the industrialized world contemplates its dwindling fossil-fuel supplies and the environmental costs of energy production, nuclear fusion looks ever more appealing. Potentially one of the most efficient of all physical processes that release energy, it is also attractive from a pragmatic viewpoint. The fuel (the hydrogen isotopes deuterium and tritium) could be readily obtained, and the reactions would not leave the long-lived, highly radioactive waste products associated with fission. But controlled, self-sustaining fusion on a power-plant scale remains decades away.

The work being done today addresses two fundamental problems. One is how best to get the reaction started; a temperature of about 100 million degrees Celsius is required before random thermal interactions force the nuclei close enough to each other to fuse. (The nuclei are all positively charged and therefore repel each other; to make them fuse when they meet, the temperature must be kept high, meaning that they move fast and collide hard.) The other problem is how to make the product of density and confinement time must reach a very high value known as the Lawson criterion. Researchers in AFRD are organized into two groups corresponding to different basic approaches to these problems.

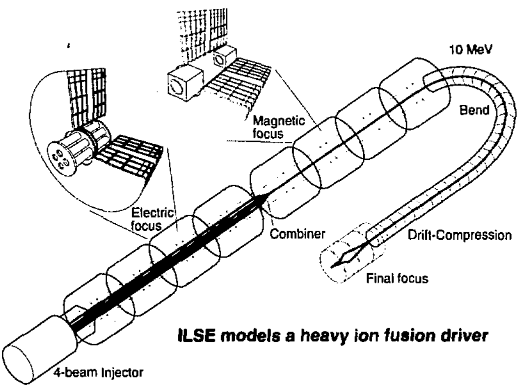
Magnetic fusion, the more familiar scheme, uses a magnetic field of great strength and rigorously maintained geometry to confine a continuously reacting plasma and keep it away from the reactor walls. In the largest of today's tokamak reactors, magnetically confined deuterium plasmas (and, in one experiment at the Joint European Torus, a deuterium-tritium plasma) have been heated to temperatures at which fusion reactions took place. The best of these brief "shots" have released about 80% as much energy as was required to heat the plasma, or about 10% of the energy that would be needed for ignition (self-sustaining fusion). In the tokamak projects, which tend to be very large and, increasingly, international, Lawrence Berkeley Laboratory has played a major supporting role. The effort focuses on development of neutral-beam injector systems that pump large quantities of energetic hydrogen or deuterium atoms into a tokamak, thereby helping to heat the already-hot plasma to thermonuclear temperatures.

This presents interesting scientific and engineering challenges: the atoms must initially be ionized, or given a charge, so they can be accelerated, but then they must be neutralized so they can penetrate the tokamak's magnetic field. AFRD's **Magnetic Fusion Energy (MFE) Program** supports magnetic-fusion experiments by developing ion sources, accelerators, and neutralizers. The group developed the Common Long-Pulse Source, a standard neutral-beam plasma-heater for U.S. fusion experiments, and released it into commercial production in the mid-1980s. They are now following up that achievement by designing ion sources and accelerators for next-generation tokamaks such as the proposed International Thermonuclear Experimental Reactor (ITER). To maintain larger plasmas at higher temperatures for longer periods, the neutral-beam systems that may be required in these reactors will have to be based on a different technical concept. The designs of a proposed proof-of-principle accelerator and of a test facility for it are being refined by the group.

The other approach is inertial fusion energy, which begins not with a plasma but with a spherical target of deuterium-tritium fuel. The target is hit from many directions at once with beams of laser light or energetic particles. This energy bombardment heats and compresses the target enough to induce fusion; the reaction is over so quickly that the balance of forces from all sides is enough to provide containment and satisfy the Lawson criterion. The process would be repeated several times per second in a power plant.

Heavy ions (as opposed to lasers or lighter ions) appear to be the best candidates for the repetition rate, reliability, and efficiency that would be needed in a power plant. In AFRD, the **Heavy Ion Fusion Accelerator Research (HIFAR) Program** theoretically and experimentally evaluates the possibilities for using heavy-ion beams as drivers for inertial-confinement fusion.

Since 1982, they have been progressively scaling up systems that transport and accelerate beams of heavy ions. The group recently concluded a multiyear experimental program with MBE-4, a four-beam induction linac designed to provide basic data on beam control from which information useful in the design of a fusion driver can be extrapolated. The next step, now in the engineering design phase and about to be proposed for a 1995 construction start, is ILSE, the Induction Linac Systems Experiments. ILSE will contribute further knowledge toward the goal of a full-scale driver.



ILSE models a heavy ion fusion driver

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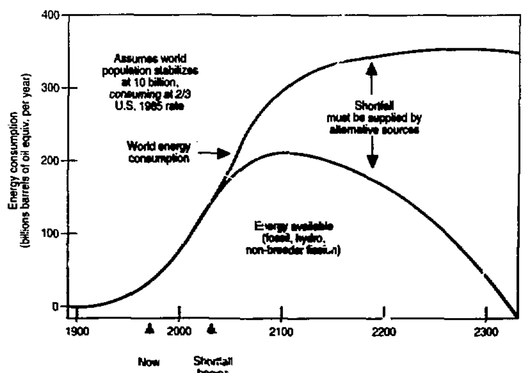
The population of the world and the per-capita energy demand are both growing, so a shortfall is expected sometime in the next century. New sources of energy, such as fusion, will be needed to fill the gap. It will take time to meet the technical challenges of developing these new sources, so early and vigorous R&D would be prudent; therefore the National Energy Strategy calls for a fusion demonstration in the 2025 time frame. The HIFAR Program's ILSE apparatus and the MFE Program's negative-ion accelerator and test facility for ITER neutral-beam injection are among AFRD's proposed contributions to the attempt to harness fusion power. Other programs involving AFRD can also contribute directly or indirectly to alleviating the energy shortfall; an example is the proposed Chemical Dynamics Research Laboratory, with its implications for combustion efficiency. (Energy-shortfall graph courtesy LLNL)



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Advanced Light Source: Seeing the Future in a New Light

The discovery of the x-ray in 1895 revolutionized not only the work of physicians, but also that of physicists. In two decades of excitement that helped set the stage for today's knowledge of the atom, they studied the interaction of x-rays and matter. The results and the investigators—Roentgen, Compton, Laue, the Braggs—are familiar from freshman physics and from the roll of Nobel laureates.

After that heady beginning, the scientific and industrial uses of x-rays continued to progress, growing very subtle and sophisticated. Nonetheless, a backlog of interesting and potentially useful x-ray work began to accumulate, including studies of processes at interfaces and surfaces; microscopy and holography; and the probing of chemical reactions. The conventional means of producing x-rays, which involves striking a material with a beam of electrons, could generate tremendous power, but the backlogged ideas needed qualities other than sheer power: tiny, intense beams, perhaps of just one precise "color," perhaps coherent, almost like a laser beam.

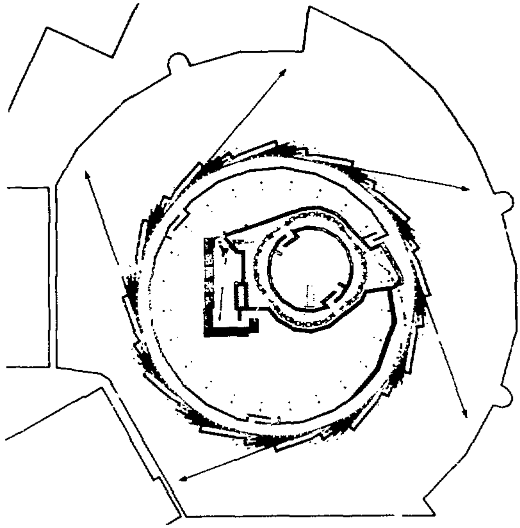
The solution was found in the late 1940s in what seemed to be a completely unrelated realm: the electron synchrotron. When a magnetic field makes an electron beam change direction, photons are given off. This effect was at first considered a nuisance for robbing power from the beam and heating the accelerator and the experimental apparatus. But beginning in the 1950s, scientists began to realize that this nuisance had desirable qualities—that x-rays of unparalleled intensity could be obtained. The pioneers of synchrotron-radiation work obtained this radiation "parasitically" from electron accelerators meant for high-energy physics.

In the 1970s, there appeared a second generation of synchrotron-radiation sources: a generation of electron storage rings* whose reason for existence was the production of synchrotron light. AFRD advanced this new field by developing practical versions of magnetic devices called "wigglers" and "undulators" that could further manipulate an electron beam, producing radiation with selectable bandwidth and coherence.

During the early and mid-1980s, AFRD began designing a third-generation synchrotron-radiation facility. The hallmarks of the third generation are high-quality electron beams (small source diameter and low transverse energy), along with a ring design that lends itself, both mechanically and in terms of maintaining beam quality, to the insertion of numerous wigglers and undulators. In 1986, the groups within the **Advanced Light Source** project officially began the detailed design of the ALS a national user facility that is expected (presuming upon a successful Operational Readiness Review) to be fully commissioned and ready for users in 1993. By the end of fiscal 1992, the staged construction and commissioning activities were nearing a major milestone: injection of an electron beam into the storage ring. Meanwhile, work continued on design and fabrication of insertion devices and beamlines. Development of the user program continued, with LBL and outside researchers designing experiments and equipment to take advantage of this bright new source as they enter the second century of the x-ray.

* In a storage ring, a variation on the general theme of the synchrotron, a large number of accelerated particle bunches go around a "racetrack" millions of times for repeated re-use, as opposed to being delivered once to a fixed target.

The multiple straight sections in the ALS can each accommodate a magnetic insertion device to enhance synchrotron-light production. The bending magnets in the arc sections (shown during an early phase of installation in late 1991) produce useful synchrotron radiation as well. The high-brightness beams of ultraviolet and soft-x-ray light from the ALS are of interest to a wide variety of researchers in fields ranging from structural biology to the fabrication of next-generation computer chips.



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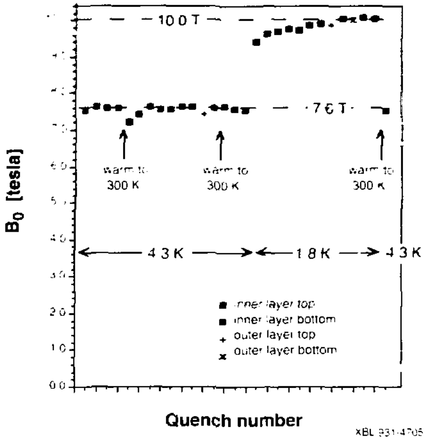
Magnets for the SSC and Beyond

The Superconducting Super Collider, the most ambitious of particle accelerator projects, will have a pair of underground storage rings, 52 miles in circumference, in which protons circulate in opposite directions. The two beams, each with an energy of approximately 20 TeV, will cross and collide in several "interaction halls." High-energy physicists need such energies to put hypotheses about the basic structure of matter to experimental test. SSC energies should be the hunting grounds for particles that have been postulated but never observed and measured, such as the top quark and the Higgs boson. Perhaps its users will even find particles, phenomena, or parameters that do not fit today's theories—an exciting prospect that has been a hallmark of accelerator-based physics.

The design and construction of such a large facility have occupied researchers from many laboratories. AFRD's **Superconducting Magnet Program** has played a key role in the SSC effort for several years, concentrating on the design and manufacture of the superconducting wire and the cable made from it, and on design and testing of the quadrupole magnets used in the collider-ring lattice. These magnets have to meet exacting performance specifications, especially in terms of magnetic-field uniformity. They must also be extremely reliable in order to give users the high experimental statistics needed at the frontiers of high-energy physics. Much effort has gone into optimizing seemingly minute design details that would affect performance under those conditions. Anticipating the need for private industry to mass-produce the SSC's thousands of magnets, we embarked upon a Magnet Industrialization Program to transfer the technology for building them. In 1991 and 1992, engineers from Babcock and Wilcox and from Siemens worked alongside us to build collider quadrupoles.

While working in support of the SSC's immediate needs, we have also looked toward the future. With one of our experimental high-field dipole magnets, D19, we set a world record for field strength in accelerator-style magnets: 10.06 T centrally and 10.4 T near the side of the bore. We also began work on D20, an accelerator-style magnet that uses a different type of superconductor (which requires innovative construction techniques) and should achieve fields considerably greater. Other work included cabling-machine development, which anticipates requirements for different cable designs in our program. We also continued exploring the science and technology of superconducting materials and magnets in many other ways. Our ongoing materials program is working with private industry on superconductor that incorporates "artificial pinning centers" for better performance, and is also involved in development of "high-temperature" superconductors into magnetic materials that are useful in a macroscopic engineering sense. Better ways of designing accelerator magnets are also of interest, as are potential nonaccelerator uses of high-field magnets, such as nuclear magnetic resonance equipment. The program is rooted in the technology of advanced accelerators, a community that it continues to serve, but its work also has the potential for direct and indirect payoff in several other fields that could benefit from cheaper and better superconducting materials.

LBL has been one of several laboratories working to support the magnet R&D needs of the SSC. *Recent achievements include* development of quadrupole (focusing) magnets for the collider rings, such as the magnet shown here being inserted in its *cryostat, and transferring the technology to the private sector* through our SSC Magnet Industrialization Program. Meanwhile, looking beyond the SSC, we achieved a world-record magnetic field in an accelerator-type magnet with the experimental dipole D19. And we are testing innovative mechanical designs and superconducting materials in the ongoing attempt to make magnets stronger, more efficient, cheaper, and more reliable. The "Artificial Pinning Center" wire shown in this photomicrograph, produced by one of our industrial collaborators, is just one example.



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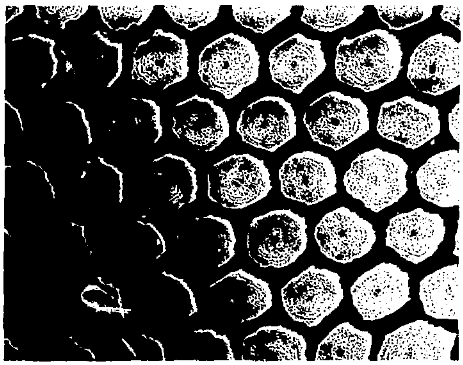
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Center for Beam Physics: "Nothing Happens Unless First a Dream"

The **Center for Beam Physics*** is a key element in several of the division's diverse activities, assisting with immediate programmatic needs and—as indicated by the Carl Sandburg quotation at right—also laying foundations for future research. A highlight of the program's 1992 accomplishments was the design of the Beam Physics Facility. This new facility that makes double use of the ALS injection linac during the long periods when the ALS storage ring is full and the injection complex is therefore idle. In one of the two experiments currently planned, the 50-MeV electron beam will be crossed with a visible laser beam in an attempt to produce femtosecond x-ray bursts through 90 Compton scattering. The other experiment will test new ideas for plasma focusing of an electron beam.

One of the Center's areas of involvement is the proposed Chemical Dynamics Research Laboratory, a new initiative by LBL's Chemical Sciences Division that is designed for synergy with the ALS. In 1992, the Center's researchers refined their concept for an infrared free-electron laser (IRFEL) that features tunability, high power, and fine resolution. By combining the IRFEL's powerful, tunable output with beams available from the ALS, chemical lasers, and molecular-beam sources, the CDRL could offer unprecedented opportunities for studying pure and applied reaction dynamics and a variety of topics in materials and surface science. In this new design, the proposed IRFEL uses superconducting accelerating cavities to achieve greater energy stability in the electron beam (and thus in the photon beam) and to achieve continuous-wave rather than pulsed operation.

High-energy physics also figured prominently in this divisional center's efforts. Another major initiative, which is being spearheaded by the Stanford Linear Accelerator Center with collaboration of LBL and Lawrence Livermore National Laboratory, is PEP-II, an energy-asymmetric B-meson "factory" based on the existing PEP storage ring at the Stanford Linear Accelerator Center. Creating B mesons and their antiparticles in electron-positron collisions that have a moving center of mass, an idea originated by LBL Deputy Director Pier Oddone, will spatially separate the decay products, making detection simpler than it would be if the center of mass were fixed. This will enable high-energy physicists to study charge-parity violation and rare B-meson decays.

The Collider Physics group within the Center continued collaborating in basic and applied research for the generation of high-energy accelerators beyond the SSC. Their efforts focused on a futuristic electron linac called the two-beam accelerator, driven by microwave power from either a free-electron laser or a relativistic klystron. Other contributions to high-energy accelerators come from the Beam Electrodynamics Group. Their research emphasizes electromagnetic analysis and various radiofrequency "gymnastics" to ensure proper beam behavior—a set of skills that have contributed to a variety of projects in recent years, including the ALS and the Tevatron, and are now being brought to bear on the B factory.

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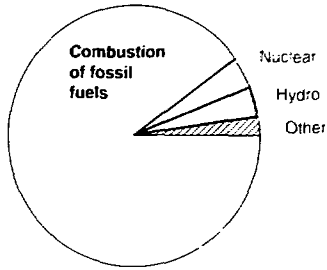
*Formerly the Exploratory Studies Group

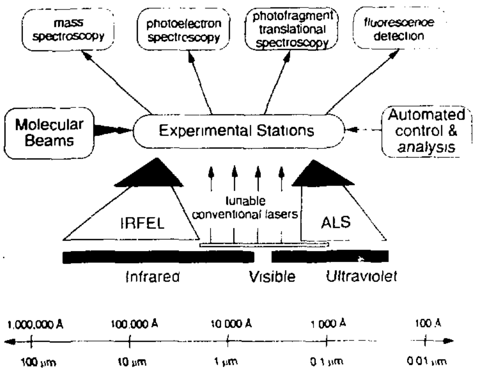
The United States currently gets more than 90% of its total energy from combustion, so even small improvements in combustion efficiency could have tremendous benefits. The proposed CDRL is part of the Combustion Dynamics Initiative, a joint undertaking with sites at LBL and Sandia National Laboratories in Livermore, CA. The CDRL will offer an unprecedented opportunity to bring together various technologies for probing energetic, transient chemical reactions at a very fine level of detail. The community of potential users is putting together a broad program of pure and applied studies, ranging from reaction dynamics to applied work that might ultimately help increase engine efficiency or reduce air pollution. Shown here is the spectral coverage that would be available to CDRL users with the proposed superconducting IRFEL.

U.S. ENERGY CONSUMPTION



This picture will not change appreciably in the foreseeable future

CDF/LBL Technical Facilities



Electromagnetic spectrum wavelength

The Long Shadow of the "Bevalac Era"

After nearly four decades of service, which resulted in scientific productivity not even dreamed of by its original builders (and which entailed many an ingenious upgrade), operations at the system of two accelerators known as the Bevalac are expected to stand down for the last time in early 1993.

The older of the two, the Bevatron, was the most energetic proton synchrotron of the early 1950s. It was there that Segre and Chamberlain discovered the antiproton, an achievement that won them the Nobel Prize. After two decades of contribution to the "particle explosion" that revolutionized subatomic physics, the accelerator was thought to be nearing the end of its career, but thanks to an imaginative idea, some of its brightest days were still ahead. The idea was to feed the Bevatron with the beam from the nearby SuperHILAC heavy-ion linear accelerator, which itself was well known as the discovery tool for several transuranic elements. When the SuperHILAC-to-Bevatron transport line was completed in 1974, the result was a unique system that could accelerate heavy nuclei to GeV-per-nucleon energies. An early-80s upgrade called the Uranium Beams project, which included a third ion injector at the SuperHILAC, a new vacuum liner in the Bevatron, and a computerized control system, enabled acceleration of any naturally occurring element. In 1983 the Bevalac set a total-energy record, which still stands, by accelerating uranium to 960 MeV/n.

This high-energy, heavy-ion capability gave rise to the "Bevalac era" in nuclear science—an era of great advancement in science and technical discovery, an era when the behavior of nuclear matter at extremes of temperature and pressure first came under concentrated scrutiny. Biomedical research and treatment of patients with particle beams, another field pioneered at LBL, also became an important part of the Bevalac's programs.

The Bevalac-era interest in nuclear matter under extreme conditions has engendered a variety of programs elsewhere, including a major new initiative at Brookhaven National Laboratory called the Relativistic Heavy-Ion Collider. Charged-particle radiotherapy is also beginning to come into its own—a privately funded proton facility at the Loma Linda University Medical Center recently joined several governmentally sponsored efforts worldwide. Ironically, the Bevalac itself could be supported no longer in an era of tightly constrained research budgets.

The Bevalac will live on in a variety of ways. Spinoff technologies from the constant effort to use and improve the Bevalac have included novel ion sources, beam-delivery systems for medical treatment, dosimetry technologies, and an easier-to-make version of an accelerator called a radiofrequency quadrupole. Three generations of scientists came to the Bevalac to study the nature of matter and the behavior of irradiated cells. Most important, the Bevalac will live on through its contributions to knowledge: numerous individual discoveries that, when taken together, compose a theme of finding the unexpected. This has been a leitmotif of accelerator-based physics, and is an auspicious legacy for the machines and experiments of today and tomorrow that owe so much to the Bevalac.

An aerial photograph, with the beam path superimposed, shows how a geographical coincidence inspired a singularly successful idea. The Bevalac's combination of energies and ion species have ensured it a long and scientifically productive life. The 39-year-old Bevatron and the 35-year-old SuperHILAC, separately and together, have been tremendously productive to science. Some of the findings have been quite unexpected and extremely important (nuclear antimatter, strange particles, and resonances at the Bevatron; five manmade elements at the HILAC and SuperHILAC; and nuclear compressibility at the Bevalac, to name a few). Hundreds of LBL and visiting researchers have worked at these machines, and more than 80 students have written doctoral dissertations on related research. The challenge now is to identify facilities and funding for the vast amount of work that has yet to be done.