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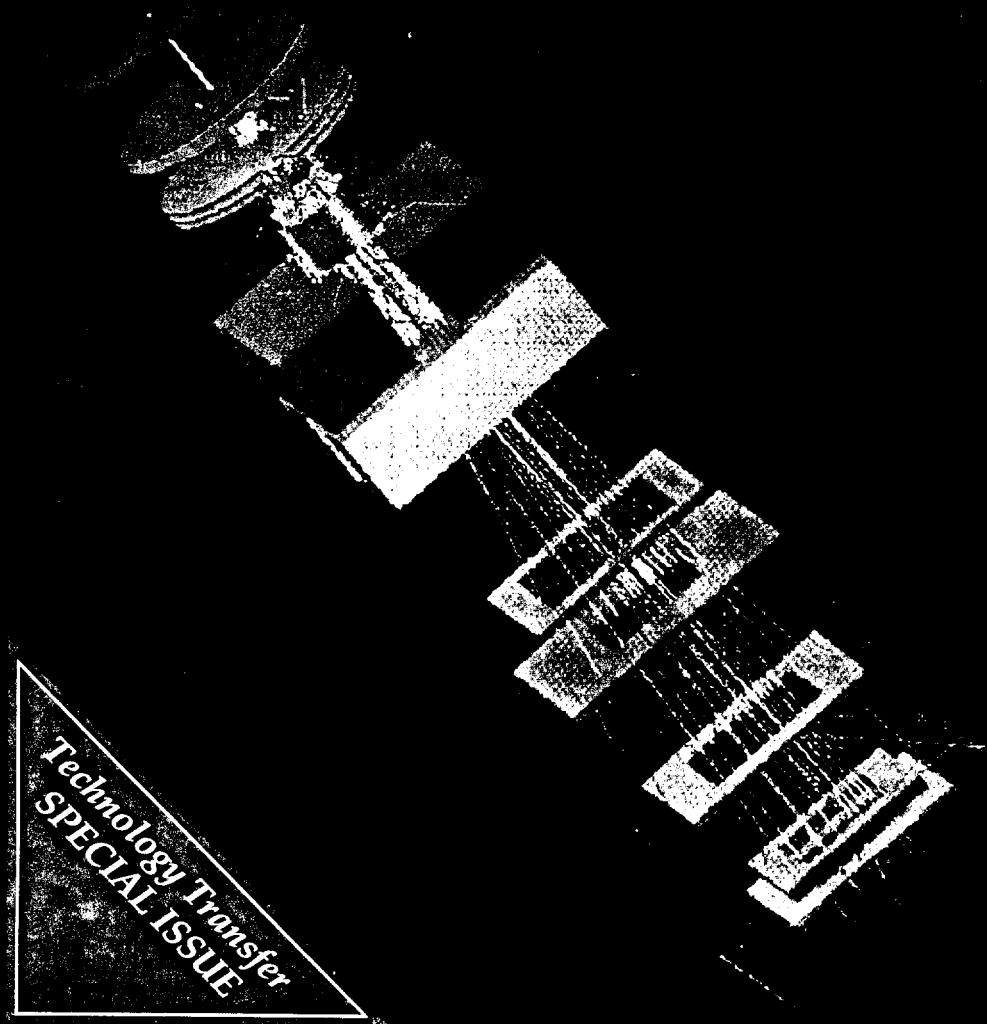

Technology Transfer
SPECIAL ISSUE

0022086

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

SPRING 1993 VOL. 23, NUMBER 1

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Cover: An EGS4 computer simulation of a cancer-therapy accelerator operating in the electron mode. An initial group of 100 electrons (blue lines), each of 20 MeV, strike a scattering foil (dark blue and green), then pass through an ion chamber. Some x rays (yellow lines) are produced, and the beam is shaped by a succession of collimators. This simulation was created by Alex Bielajew and George Ding of the National Research Council of Canada.

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FROM THE EDITORS' DESK

AS THE UNITED STATES reexamines its priorities on different fronts, the federal funding of basic research has come under increasing fire. How can the nation afford to spend so much on pure research, many ask, when it faces such daunting problems? Faced with such questions, scientists engaged in basic research must convince the rest of society both of the worth of pure science and of its economic utility. We have therefore put together this special issue of the *Beam Line*—on the subject of technology transfer in high energy physics—to answer this question.

As Frederick Reines notes in his lead essay, the desire to understand Nature often generates completely unanticipated benefits for society. By pushing the envelope of understanding to its limits, scientists create a multitude of new opportunities, new beginnings, that are all but impossible to predict. They do basic research not because they know the answers but because they seek them, and in seeking them they find totally new ways of doing useful things.

Two excellent examples of such serendipitous benefits from high energy physics are given in the next two articles, by John Ford and Judy Jackson, on the development of medical accelerators and superconducting magnet wire. In both cases, unanticipated spin-offs of the accelerator-builders' trade have become crucial components of billion-dollar industries now making major contributions to modern medicine. Accelerator technology, the detector technology of the experimentalists, and the mathematical methods of theorists have all spawned productive new commercial enterprises in a variety of high technology fields.

But critics complain, and often rightly so, that it is not enough to do basic research and to hope that its applications somehow find their way into U.S. industry. This "trickle-down" approach no longer seems adequate, as competitors in other countries get better at applying the fruits of our own research. One possible solution, intentionally working more closely with industry, is a common theme of the articles by Arthur Bienenstock and George Caryotakis, who indicate how the benefits of such cooperation can flow in *both* directions.

This technology transfer issue closes with a portrait gallery of individuals trained in high energy physics who have gone out into the "real world" and made their mark in such diverse practices as medical physics, management consulting, and microprocessor design. Skills and attitudes they learned while working in this field have helped them make the highly valuable kinds of contributions that the U.S. economy needs to remain strong.

We hope that our readers will come away from this special issue of the *Beam Line* with a better understanding of the complex interaction between high energy physics, high-technology business, and the society they both serve.

Michael Riordan
David Hitlin

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WHO NEEDS SCIENCE?

by FREDERICK REINES

Curiosity about the natural world, pursued for its own sake, has always been a wellspring of innovation.

THE CAVE DWELLER WHO DISCOVERED that the scourge of fire could be tamed—that it could be used at the cave's entrance for protection against beasts of prey, to cook food, for warmth, and to replace darkness with light—made a profound contribution to the survival and well-being of the human race. The original mastery of fire may well have been motivated by sheer curiosity, a desire to understand and thereby control the natural world, rather than any plan to benefit humanity. It seems impossible that the first fire tamer could have foreseen all the practical advantages of the hearth and forge while carrying home that first flaming branch.

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Science not only provides the knowledge required to realize existing goals, it helps us to recognize that new goals are possible.

That same curiosity about the natural world is perhaps the primary motivation of scientists today. It is my impression that this exercise of creative curiosity became fashionable when its fruits were recognized to improve humankind's condition.

Science has continued to provide the understanding that technology fashions into tools that have fed us, clothed us, housed us, nurtured our physical health, transported us, given us virtually instant communication—in short, provided a variety of material benefits far beyond the dreams of our ancestors. One priceless aspect of this Promethean gift was the leisure it provided to observe, to contemplate, to understand and to develop abstract ideas about, among other things, the interrelationship between fire and life.

IT HAS BEEN SAID, with some justification, that our knowledge of the material and animate world has outstripped our wisdom regarding our relationship to our environment and to one another. Why not, some suggest, declare a moratorium on science and catch up in our understanding of the mental processes that take place inside the human head? After all, say these proponents of a scientific slowdown, human beings are not able to cope with the already mountainous and ever-increasing mass of new knowledge and its material consequences. Is it not time to pay closer attention to our social institutions—to be more concerned with matters of morality, how to live together in peace and mutual respect, and how to advance the human condition?

We have the makings of a paradox: the very tools provided by the scientific enterprise, which have liberated a significant fraction of the human race from the bondage of a totally consuming struggle to stay alive, which have provided the time to wonder about the role of the human being in the Universe, have also led to ever more complex problems of survival. Our ancestors survived or perished pretty much alone or in small groups. They hadn't the means to exhaust the resources of the Earth—it seemed infinite. We now live in a world in which hunger or famine or the lack of raw materials in one part has an almost immediate impact on the rest. We can be—and most frighteningly are—busily engaged in the exhaustion of the finite world's non-renewable resources. Science and technology have made the world demonstrably finite and made us aware of the inequities in the human condition and the wide disparities in material affluence.

It would be illusory and a simplification of the most dangerous kind to pretend that our material word is other than finite—to imagine that the magic of science can make it otherwise. However, science and technology can tell us a great deal about what we have at our disposal and the limitations imposed by the laws of nature. Given some physical problem, for example, the optimal way to heat a house, we can use the principles of physics to seek solutions. In this case, science tells us that it requires far less energy to heat a home by means of an inverse engine called a heat pump than by a fire on the hearth in the living room.

ONCE SOCIETY HAS formulated a goal, then science and technology may provide us with various options leading towards attainment of that goal. But science not only provides the knowledge required to realize existing goals, it helps us to recognize that new goals are possible. Indeed, social goals are like moving targets; success breeds ever higher aspirations. For instance, if we knew

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The expansion of possibilities that arise from the pursuit of science do not come on command. They derive from the often serendipitous results of the creative curiosity of educated people.

how to obtain unlimited energy from fusion, the reaction that has fueled the sun for billions of years, society would formulate new goals to take advantage of the new-found resource. In the meantime, our wisdom would expand, and stimulate the creation of further goals.

However, the options, the new solutions, the expansion of possibilities that arise from the pursuit of science do not come on command. They derive from the often serendipitous results of the creative curiosity of educated people. When we unleash this curiosity by supporting science, practical benefits arise in unanticipated ways.

A dramatic illustration of this truth is the synchrotrons and storage rings that accelerate electrons and positrons to extremely high energies. These great machines were built to probe the structure of elementary subatomic particles and learn more about the architecture of the atomic nucleus. They have been a spectacular success, as shown by the discovery of totally unexpected particles.

But even less in the minds of the scientists who built these machines was the fantastic utility of a by-product called synchrotron radiation, which became a powerful tool to study hitherto inaccessible problems in condensed matter—that is, liquids and solids. One of the problems studied was the mechanism of nitrogen fixation so important in the manufacture of fertilizer. Imagine a search for the structure of elementary particles leading to better ways to grow food!

This example of the unexpected, unforeseen and indeed unforeseeable result of scientific research can be multiplied a thousand times. We have no better way to advance knowledge than to give maximum support to those creative souls among us who want to know the answers to such "academic" questions as, "Why does the sun shine?" "How do electrons behave in semiconductors?" "What are the ultimate constituents of matter?" Even "What questions are in fact meaningful to ask?"

Questions such as these, asked when no conceivable practical consequence was foreseen, have led to the extensive knowledge and myriad benefits upon which our present day society depends. The goal of understanding for the sake of understanding has been the wellspring from which countless innovations have emerged.

IN SUM, science is vital to people's needs, inextricably linked with our search to understand ourselves and our place in the Universe. Unlike the finite planet on which we live, this quest for understanding is unending; there is no boundary, no evident limit to the intellectual adventure of which science is such an intriguing, noble, and beautiful part. Science, a means to practical tools, is at the same time an activity of transcendent intrinsic merit. It has given us a gift of unlimited value: an endless frontier.

Today, as our leaders face the agonizingly difficult decisions about how to invest our limited resources, it seems worthwhile to remember an exchange attributed to Michael Faraday, a pioneer in the harnessing of electricity. The story goes that a member of Parliament, following a demonstration of the new miracle, asked about electricity, "What good is it?" Faraday responded, "Sir, of what good is a newborn babe?"

It is tempting and, in fact, may be temporarily expedient to sacrifice scientific programs for seemingly more pressing needs. However, if we really care about the long-term solutions to our needs, we will need more science, not less.

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LITTLE LINACS FIGHT CANCER

by JOHN FORD

Linear electron accelerators are used in medicine to treat millions of cancer patients every year.

THERE ARE FEW EXAMPLES of the social benefits of spin-off technology from frontier physics research as dramatic as the linear accelerator. Today, the mainstay technology for megavoltage radiotherapy is the microwave-powered electron linear accelerator or "linac," which was originally developed at Stanford University in the 1940s and 1950s. There are some 3500 medical linacs in operation around the world— about half of them in the United States. Radiotherapy, the treatment of disease by ionizing radiation, is reserved almost entirely for cancer treatment, but within this disease category it is a widely used means of therapy.

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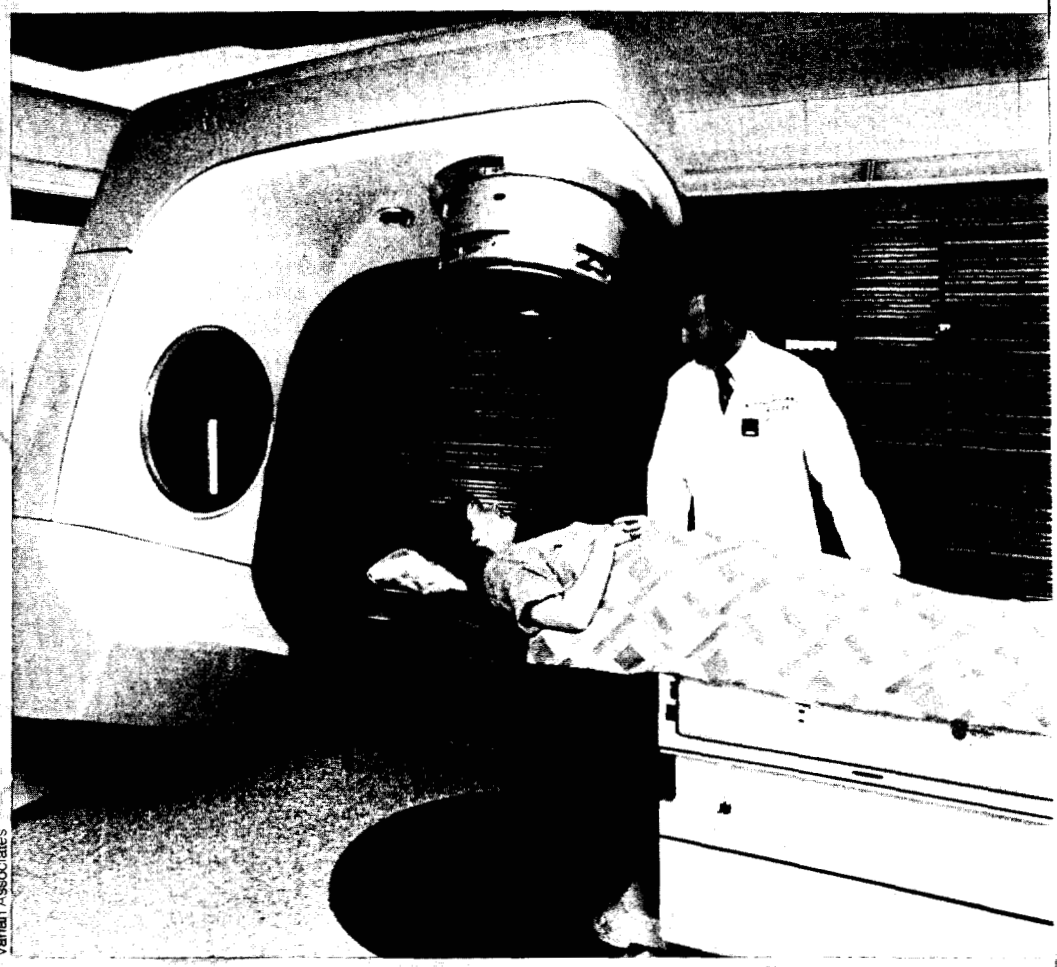
A radiation-therapy facility that makes use of a small linear accelerator for the treatment of cancer. The accelerator is housed in the rotatable gantry.



Varian Associates

Radioactive implants are used in some cases (about 5 percent), but most often the radiation dose is administered by a powerful external source. Over the last twenty years the electron linear accelerator has become the dominant device, replacing betatrons and Cobalt-60 machines. Treatment with energetic photon (from 4 to 20 MeV) and electron beams (from 4 to 22 MeV) is commonplace. Compact, highly sophisticated linear accelerators are now found in university medical centers, community hospitals and private outpatient facilities.

The statistics of cancer are impressive. Approximately one in every four persons will develop a cancer at some time in his or her lifetime. This incidence rate is increasing mainly because of the rise in life expectancy. Age is the single largest risk factor for cancer; for white males in the United States, for example, the incidence rate increases sixteen times from the second to the fifth decade of life and another five times from the fifth to the seventh decade.

In Western Europe and other developed countries, approximately 50 percent of all patients diagnosed with cancer are treated with ionizing radiation, either as the primary method or as an adjunct to surgery or chemotherapy. In the United States, which enjoys the largest number of modern treatment machines per capita, the referral rate is even higher (closer to 60 percent in some medical communities). Many would argue that this higher referral rate is closer to the ideal, given what is known about the efficacy of the various treatment methods. In a society with health-care services comparable to the United States or Western Europe, the average person has a one in eight chance of being treated on a linear accelerator in his or her lifetime. The odds increase significantly with age. Although it is not generally recognized, the value to society of the linear accelerator is immense.

CLINICAL RADIOTHERAPY

Within a few months of Roentgen's discovery of x rays in November 1895, they were being used for medical diagnosis, and some biological effects of these new rays were observed. By 1900 the destructive effects of radium on human skin were known. But it was also soon realized that radiation had a more destructive effect on diseased tissue than on normal tissue. By fractionating the exposure, researchers learned that the difference was quite extraordinary and that radiation could have marvelous curative properties. With the twentieth century began the clinical science of radiotherapy, which after nearly a hundred years is growing in importance as result of new and exciting technology.

Radiotherapy owes its success to the differential killing of cells. Normal cells are endowed with robust repair mechanisms. Cancer cells have compromised repair mechanisms. Radiotherapy takes advantage of this difference by applying the radiation in fractionated doses over an extended time period. Between each fraction the normal cells repair and repopulate, while the diseased cell colony is attenuated. Some healthy cells are inevitably sacrificed in the process, as they are with surgery or chemotherapy. Any tumor can be destroyed with a sufficiently high radiation dose. Radiation therapy fails when the

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The Dynamics of Cancer

THE WORD *cancer* is derived from the Latin word for crab, so described by the ancients because advanced tumors are often surrounded by radiating engorged veins that have the appearance of the legs of a crab. And like the tenacious grip of a crab, the disease does not let go.

Tumors, or neoplasms (new growths), are either benign or malignant. Benign tumors generally develop slowly, often ceasing growth at some point. They remain encapsulated, grow by expansion, and normally don't pose a health problem except where they might exert pressure on a neighboring structure. In general, benign tumor cells continue to resemble normal cells.

Malignant tumors behave in a decidedly more antisocial manner. Growth is variable and often rapid. These tumors are usually not encapsulated, and their growth is by infiltration, destroying neighboring structures. Succeeding generations of these malignant tumors also become different from normal cells, exhibiting increasingly wild unregulated behavior. Malignant tumors shed cells and emboli that can penetrate both the lymphatic system and the blood vessels. Lymphatic disease is regional, but tumor cells transported through the vascular system can start new colonies, or "metastatic" tumors, in distant organ systems. Close to 75 percent of all cancer victims die from the effects of metastatic disease.

Cancer is characterized by progressive infiltration and is considered fatal if not treated. There are unusual cases of what has the appearance of permanent spontaneous remission, where the patient's immune system rallies to defeat the disease; but these cases are statistically rare and are sometimes interpreted as miracle cures, which has the unfortunate effect of propagating quackery.

A tumor may spring from one transformed cell. The growth of a tumor-cell colony is roughly exponential, since the time between cell divisions (doubling time) is almost constant. If the growth is perfectly exponential, then the logarithm of cell number plotted against time gives a straight line. A more refined picture might show a longer initial doubling time as the tumor colony struggles to escape the attack of the immune system and recruits supporting tissue systems such as the needed vasculature. The curve then bends upward, showing a higher constant slope until the tumor begins to outstrip the supporting tissue and blood supply. The doubling time then increases, and the growth curve bends over. At this point the tumor is of a size that is clinically detectable, about 1 gram in mass with about a billion cells acquired by 30 doublings. Although the doubling rate is then slightly diminished, the dramatic effects of exponential growth become very apparent, with only ten additional doublings necessary to reach a generally lethal tumor mass of one kilogram.

These growth dynamics give most cancer its characteristically long apparent "latency" period, followed by a sudden manifestation of the disease with rapid progression. The 12-week doubling time for squamous cell carcinoma of the bronchus can produce symptomatic lung cancer in seven years. Prior to the tumor-growth phase there can also be a long pre-cancerous induction period.

Metastatic tumors have similar growth dynamics, although the doubling times may be modified by differing host response and the fact that the metastatic cells may be more anaplastic than the original primary tumor cell. The most regrettable property of many tumors is that they are metastatic before they become clinically detectable.

There is a tendency to think of cancer as a single disease. The term actually refers to an entire category of disease rather like the phrase "bacterial disease" or "viral disease." There are more than one hundred known tumor-causing diseases with differing pathology and epidemiology. The physician oncologist—who may be an internist, surgeon, chemotherapist, or radiotherapist—faces an extraordinarily difficult subject, with all the complexity of the different types of cancer multiplied many times by the complications of the individual patient histories and particular patient responses.

Cancer may develop as a result of all sorts of stresses including viral infections. Exposure to certain chemicals is also known to induce cancer. Some of the most potent cancer-causing chemical agents, or chemical carcinogens, are found in tobacco smoke, and smoking is, by far, the biggest cancer problem. There are many other promoting factors such as diet, infections, hormones, genetic factors, and sometimes even anatomical defects.

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normal tissue tolerance is reached before the tumor is destroyed.

The most important mechanism for killing cells involves the formation of free radicals in the cell nucleus and depends on the presence of oxygen. Unfortunately tumors often outgrow their blood supply and become hypoxic. Hypoxic tumor cells can have only a third the radiosensitivity of well-oxygenated tumor cells; it is often these cells that cause the treatment to fail. Various strategies have been used to overcome this limitation, but this problem remains one of the most important challenges in radiation therapy. One strategy has been to use other particles such as neutrons, for which cell killing is independent of free-radical formation. For a number of reasons this approach is not promising.

In the first half of the twentieth century, radiation was used successfully to treat a number of different pathological conditions in addition to cancer. But researchers, physicians, and patients were often unnecessarily exposed, and often grossly overexposed, out of carelessness and ignorance. Radiation was quickly recognized as itself a carcinogen, and its use was soon restricted and better regulated. Thus radiation is at present almost entirely reserved for the treatment of cancer. For that reason the term radiotherapy is being replaced by *radiation oncology*, and radiotherapists are more often called radiation oncologists, a term that also recognizes the broader range of care provided to the cancer patient.

Surgery has the advantage of being an anatomically specific treatment. Chemotherapy has the advantage of being a systemic treatment that could in principle deal with metastatic disease. With the exception of a few uncommon diseases such as leukemia, lymphoma, and testicular tumors, metastatic disease remains incurable. Often a tumor is near a critical organ, or it has infiltrated surrounding critical structures, making surgical excision impossible. Chemotherapy may be ineffective or limited by its overall toxicity. In many cases post-operative radiation therapy is given after surgery to destroy regional lymphatic disease. Limited use of electron-beam therapy has been made to give an extra dose to a tumor while the patient is undergoing surgery.

In a society with health-care services comparable to the United States or Western Europe, the average person has a one in eight chance of being treated on a linear accelerator in his or her lifetime.

Radiation therapy is possible because limited areas of the body can tolerate some 10 to 30 times the lethal whole-body radiation dose (which is, however, somewhat difficult to define). The lethal whole-body dose is relatively low because certain organs are exquisitely radiosensitive. Because bone marrow is the first system to be destroyed by radiation, it determines the maximum survivable whole-body dose. The tolerance of a given volume of tissue is dependent on the tissue types present, its vasculature, the volume irradiated, the dose fractionation, and other patient-specific factors that are not well understood.

The tumor-control probability curve is an S-shaped curve that rises somewhat symmetrically about the 50 percent point. It is essentially zero below 5 times the lethal whole-body dose, and for many tumors with 30 fractions in six weeks it is above ninety percent in the range of 10 to 20 times the lethal whole-body dose. The probability for unacceptable complication is also a similar S-shaped curve, usually positioned on the dose axis to give radiation oncologists the agonizing problem of balancing the chance for cure against the chance for a lethal or serious complication. (This balancing act sometimes becomes the subject of litigation.)

There are two basic objectives for radiotherapy: cure or palliation. If there is a chance the patient will be free of disease after treatment, then a curative strategy is followed. If the disease is incurable, then the objective is to prolong life and alleviate symptoms, reducing pain and disability. Since it is difficult to justify complications for palliative therapy, doses are generally reduced to 80 percent of curative levels. Often the choice between an aggressive curative treatment or palliation is not clear-cut, and the decision involves counseling between the radiation oncologist, patient, and family.

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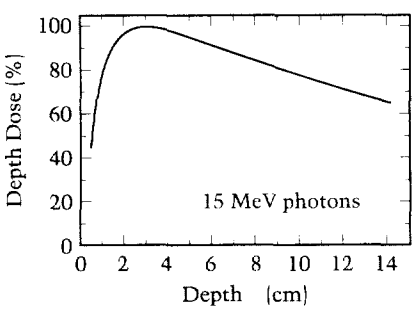
The Physics of Radiotherapy

EXTERNALLY PRODUCED photon beams, or x rays, have the widest application in radiotherapy (perhaps 80 percent or more). In the early 1970s electron-beam therapy became routine, and it is now used in 10 to 15 percent of the cases. The biological effect of high energy photons and electrons results from the swarm of electrons produced in the tissue. Therefore energy absorbed per unit mass of tissue (Gray = joule/kilogram) is used to quantify absorbed dose. A typical curative dose might be 60 Gray in 30 fractions given in six weeks.

For photon beams, divergence and attenuation reduce the radiation flux in tissue, but the electron swarm builds up to equilibrium from the skin surface. These two effects produce a dose function that builds to a maximum and then falls off with increasing depth. Backscatter of these electrons produces a significant dose at the patient surface, which can range from 15 percent to essentially 100 percent of the maximum dose. The depth of maximum dose increases with energy.

For electron beams, the effects are similar except that the primary electrons eventually slow down and produce very high ionization per unit length as they reach their maximum range. Beyond the depth of maximum dose the electron dose plummets precipitously and nearly linearly into an x-ray contamination tail that is only a few percent of the maximum dose. High energy electrons lose energy at a rate of about 2 MeV/cm in water, which is quite similar to soft tissue. Bone is about 1.8 times the density of water, so the energy loss per unit distance in bone is about twice that in water.

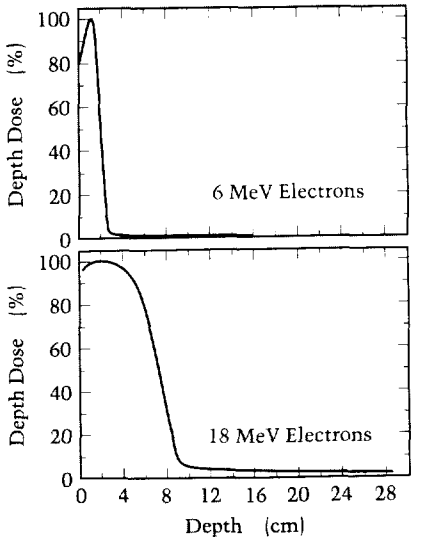


A beam of 15 megavolt x rays filtered for uniformity up to a 35 by 35 cm field at isocenter produces a characteristic depth-dose curve with a maximum at 2.7 cm and clinically useful dose beyond 10 cm.

For energies below 1 MeV, the maximum dose is deposited essentially at the skin surface. Most lesions, however, are relatively deep-seated, and therefore it is helpful to use higher energy photon beams, which have greater depth dose. It is not helpful to have the maximum dose beyond the patient midplane, and the highest energy clinical photon beams have been produced by betatrons operating at 45 MeV. Today there is little interest in photon energies beyond about 25 MeV, and practically all the old high-energy betatrons have been retired.

Electron beams are advantageous when the target volume is relatively superficial and underlying structures need to be spared. An example is a chest-wall lesion that must be treated without damaging lung tissue, which is particularly radiosensitive. As the energy increases from 4 MeV to 20 MeV the dose curve takes the shape of a plateau with the skin dose nearly 90 percent of maximum dose. Beyond 20 MeV the fall-off region stretches out, with the electron depth-dose function resembling that of a high-energy photon beam. The advantage of sparing tissue at depth is lost. The useful electron energy range is considered to be between approximately 4 and 20 MeV.

Proton and heavy-ion beams produce a relatively low constant depth dose that ends in a narrow spike. Thus the dose can be highly localized, which in principle would allow higher tumor doses and relatively lower normal tissue doses. But tumors are best visualized as uniform volumes of varying shapes with tentacles of disease reaching out in various directions. These cells and cell clumps scattered beyond the obvious tumor boundary are called micro-extensions. It is therefore important to have dose margins, and the high degree of localization is not as useful as it might first appear.



Top: 6 MeV electrons spread by a system of scattering foils give a uniform field up to 35 by 35 cm at isocenter and a typical depth-dose curve with some "skin sparing," then a sharp peak and rapid fall-off, with very little x-ray contamination beyond the expected range. Bottom: 18 MeV electrons similarly spread by foils allow very little skin sparing, then a broad peak followed by a more gradual fall-off, with some x-ray contamination beyond the expected range.

The interaction of photons and electrons with tissue is well understood in terms of photoelectric processes, Compton scattering, pair production, etc. Because of the complications encountered in actual practice, dose calculations are based on formulae derived from both theory and empirical data. Today treatment-planning dose calculations are done using computer programs, such as the Stanford Linear Accelerator Center's EGS program. It has taken several years to develop algorithms that handle inhomogeneities such as bones and air cavities. Much effort is now being directed toward developing algorithms that can determine and present detailed three-dimensional dose distributions from exotically shaped beams.

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As with much of life, medical choices generally involve a careful weighing of risks. Both short-term and long-term risks such as radiocarcinogenesis are considerations. To a cancer patient undergoing radiotherapy, the risks attributable to radiation certainly seem very small compared with the risks of not being treated. What is often not appreciated is that the risks from radiation therapy are often much smaller than the risks posed by alternative therapies. Surgery can involve very profound risks, and chemotherapy agents can in some cases pose far greater risks of carcinogenesis.

Fear of nuclear weapons and the politics of the Cold War have served to heighten the public's concern over radiation, often beyond the point of rationality. It may be that radiotherapy is applied with too much conservatism in some cases. Over the last few years radiosurgery techniques have emerged in which narrow intersecting beams of radiation have been used to cure blood-vessel malformations in the brain that are very risky to remove by conventional surgery. Radiation therapy may also emerge again as an option for certain autoimmune diseases.

A radiotherapy clinical team usually consists of a radiation oncologist, typically a board-certified specialist; a medical physicist, perhaps a dosimetrist; registered radiation technologists who set up the patients and operate the equipment; nursing staff; and often a social worker. A radiotherapy department can operate with a high patient-to-staff ratio; the current recommended patient load is 25 to 30 patients per day per accelerator. No expensive consumables or pharmaceuticals are generally used, and radiotherapy is a relatively inexpensive technique.

MEDICAL ACCELERATORS

The range of devices developed to produce clinically useful radiation beams is certainly a tribute to man's ingenuity. Until the 1950s, the physician's need for depth dose paralleled the physicist's quest for higher energies. The technology spinoff from physics to radiotherapy was rather direct. As the era of the super accelerators began, the requirements diverged—with the medical accelerator designers concentrating on compactness, stability, energy variability, clinical beam generation, mechanical versatility, ease of use, maintainability, and affordability.

Through the 1950s many technologies were available: high-voltage power supplies, Van de Graaff generators, resonant transformers, betatrons, linacs and irradiators using high activity radioisotopes such as Cobalt-60 made possible by reactors. Throughout the 1960s there was a sorting out of technologies, with the compact microwave-powered electron linear accelerator the clear winner. Within this category there have been an impressive range of designs brought to the market.

The first medical accelerators were produced in England and used a traveling-wave accelerator guide powered by a magnetron. Space is at premium in a medical machine, and as early as 1949 a method was described for recirculating the output power of the accelerator by means of a hybrid ring rather than dissipating it in a water load. Theoretically the power can be doubled, with the beam energy increased by a factor of 1.4, but the ideal gain cannot be realized because the power pulse is finite, about four microseconds.

For photon beam therapy, it is very helpful to put the target that produces the x rays in a rotating gantry such that the beam axis always passes through a common point called the isocenter. The patient lies on a treatment couch, which also has an axis of rotation through the isocenter, and is positioned with the isocenter in the middle of the tumor volume. Beams from all directions intersect at the tumor to concentrate the dose. Because of the accelerator length this design usually requires a magnet to bend the electron beam onto the target. The magnet turns out to be quite useful for energy discrimination, especially for multiple-energy machines.

During the 1960s commercial bent-beam, traveling-wave machines began to appear. These early units were more complicated to operate than Cobalt-60 machines and did not win immediate acceptance despite superior beam performance. At first blush, standing-wave accelerators would not seem to have an advantage. Even though the field is doubled in some cavities, alternate cavities are not excited. However this structure was found to be advantageous if the excited cavities were arranged more tightly along the beam axis. There are two strategies to accomplish this end: make the node cavities thin, or move them off axis. The latter strategy yields the side-coupled standing-wave accelerator.

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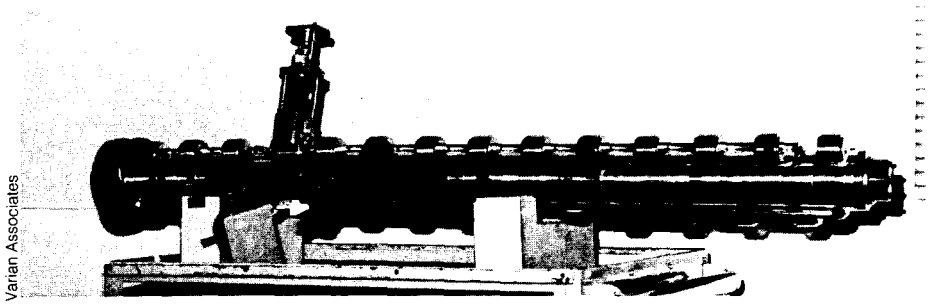

Varian Associates

This side-coupled standing-wave accelerator with an "energy switch" allows for the generation of high-output, stable x-ray modes at widely separated energies, thus providing the full range of treatment capability. This copper structure, about four feet long, was developed in the mid-1970s. It operates at S-band frequencies, around 3000 MHz, as do practically all medical linacs.

Developed at Los Alamos National Laboratory in 1967, this accelerator made a valuable contribution to radiotherapy. The first application was a machine introduced in 1968 using a vertically mounted accelerator tube achieving 4 MeV electrons in 30 cm. This machine was simple and compact, and it finally provided an acceptable alternative to the reliable and inexpensive Cobalt-60 unit. The shunt impedance per unit length for this accelerator was 72 megohms/meter compared to 58 megohms/meter for traditional traveling-wave structures.

Side-coupled standing-wave accelerators have been refined with shunt impedance as high as 120 megohm/meter, corresponding to a maximum accelerating gradient of about 30 MeV per meter. Such accelerators now find the widest application not only because of higher energy gradients but also because they can be better stabilized. Most machines providing energies higher than 10 MeV are klystron-powered side-coupled standing-wave types. A magnetron-powered double-pass accelerator using a reflector magnet was also introduced but enjoyed only limited commercial success.

Medical accelerators use short bunchers that are optimized at only one power level. This has been a disadvantage for machines offering widely separated photon energies. The very large traveling-wave machines of the mid-1960s used a short accelerator section coupled to a longer section by an attenuator and phase shifter. By maintaining constant power in the buncher section these machines could produce the high current needed to generate x rays at widely separated energies. But such complex circuitry proved too costly for the emerging medical market.

In the late 1970s the variable side-coupled standing-wave accelerator was introduced. This design has one variable geometry coupling cavity (called an energy switch) beyond the buncher and provides high output x-ray modes with widely separated energies. Importantly, this allowed for high output at 6 megavolts, where the electron-to-photon conversion efficiency is relatively low. This modality finds the widest application in radiotherapy.

Output performance for medical accelerators ranges from 2 to 4 Gray per minute at isocenter (one meter from the target) for x rays with the lowest output at low energy, and from 2 to 10 Gray per minute at isocenter for electron beams. The currents needed for x-ray beams can produce extremely high doses in the electron therapy mode. This is a hazard in medical accelerators, and in a few cases has led to fatal accidents with machines that magnetically scan the electron beam. In total, however, the safety record of medical accelerators has been extraordinarily good, thanks to the careful design and exacting procedures that exist today.

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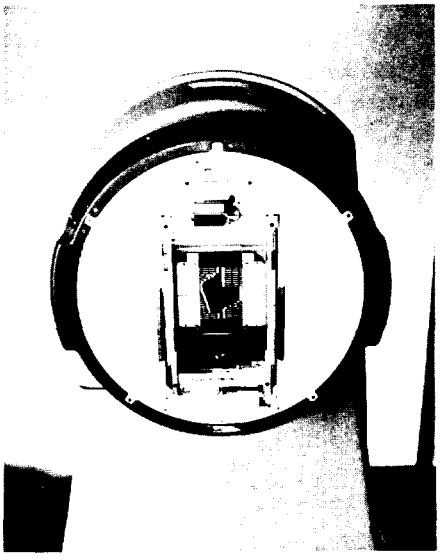
Medical accelerators are unrivaled for economy and cost effectiveness, which is a tribute to the designers and manufacturers. Single-energy x-ray machines sell for about $500,000, and very advanced units for less than $1,500,000. Compared to other capital medical equipment of technical complexity even approaching that of the medical linear accelerator, these machines are a bargain. With useful lifetimes of 15 years or more, they are an incomparable value.

THE FUTURE

Within the last ten years computer-controlled medical accelerators have become the standard. Computers can better manage and present machine data and can automate many housekeeping routines. Although the medical community was skeptical at first, computerized machines have proven to be more reliable and easier to operate. More importantly, computer-controlled accelerators are capable of preprogrammed movements of the gantry and collimators to produce specialized dose distributions. This has opened up a new technology called "dynamic beam delivery" which can significantly concentrate the tumor dose and spare more healthy tissue.

Computers are also used to drive a new device called a multileaf collimator, which can conform the beam to the two dimensional projection of the tumor volume as seen from the accelerator target at a particular angle of gantry rotation. Such a device can be operated dynamically.

Dynamic beam delivery and conformal therapy promise improved local control of tumors. If we invoke the "one half rule of thumb for radiotherapy statistics," we see how important this is: Half of all the cancer patients (slightly in excess of 900,000 people per year in the United States) are referred for radiotherapy. Half of these patients are palliative due to metastasis; the other half are potentially curative, and for half of them we fail to control the primary tumor. Therefore better local control with radiotherapy could save another one-eighth of the people stricken with cancer each year, or more than 100,000 human beings in the United States alone.



Multileaf collimator conforms the radiation to the "beam's eye" view of the tumor volume at any accelerator gantry angle. This MLC fits below the standard collimators for maximum versatility.

This may not be the whole story. Research now suggests that strategies for controlling metastatic disease may depend critically on the simultaneous control of the primary tumor. Therefore, many more patients could benefit from better local control with future progress in dealing with disseminated disease.

For the reasons cited, continued technical development of radiotherapy offers great potential benefit. But much greater benefit could be derived in the short term by simply finding ways to make the present medical accelerators available to the developing world. The shortage of medical accelerators on a global basis is appalling. In developing countries medical accelerators are operated with very high patient loads. It is not unusual for such machines to treat more than 1000 different patients per year operating sixteen hours, or more, a day. At an average of 20 fractions per patient, this translates into a patient load of 80 per day. Basic care generally involves a minimum of two irradiations per patient per day, which is difficult at such a high daily patient load.

Radiotherapy is entering a new, exciting era with the advent of dynamic and conformal therapy, three-dimensional treatment planning, and new imaging technologies—and there are demands for improved accelerators, higher x-ray dose rates and special configurations. New medical technologies such as immunotherapy are not likely to replace radiotherapy, particularly for the gross disease so often seen in the clinic. The little linacs will continue to play an exciting role in medicine.

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by JUDY JACKSON

Building Fermilab's Tevatron accelerator brought science and industry together in a partnership that took superconducting technology

DOWN to the WIRE

THE FIRST SPOOL of superconducting cable had an airline ticket and a seat of its own on the Boston-to-O'Hare flight early one summer afternoon in 1974. Robert Remsbottom, in the seat beside it, didn't let the cable out of his sight. There wasn't another such spool on Earth. The Fermi National Accelerator Laboratory would use that spool of cable and thousands more (most traveling with lesser accommodations) to build the first superconducting synchrotron, the world's highest-energy particle accelerator—and to save five million dollars a year on the Laboratory's electric bill. In the process, Fermilab brought experts in superconductivity like Remsbottom together with physicists, engineers, materials scientists and manufacturers in a collaboration that fast-forwarded the infant superconducting magnet industry to a full-grown role in the billion-dollar world market created by magnetic resonance imaging.

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As the United States wrestles with how best to use results from basic scientific research to strengthen our country's economy and lead to a better way of life, "The Case of the Superconducting Wire" shows plainly both the power and the pitfalls of the arranged marriage between Science and Industry—and the remarkable, even unexpected, progeny they sometimes produce. Almost 20 years ago, Fermilab's procurement from industry of large quantities of material manufactured using just-emerging technology raised critical questions for government, science and private industry: How do we reconcile the undeniable requirement to control costs in taxpayer-supported national laboratories with the indisputable need for businesses to earn a reasonable profit? How do we balance the free flow of scientific information with the protection of technological know-how?

OVERNIGHT, A NEW MARKET

"Technology transfer" suggests the orderly flow of information from the laboratory bench to the factory to the marketplace. Pure scientist makes important discovery, passes it on to applied scientist who uses new knowledge to develop technology for new products, creating new markets, better economy, new jobs. Like all real-life human endeavors, technology transfer is more complicated and less orderly. Fermilab's advancing research in high-energy physics, for example, required large quantities of superconducting wire and cable, creating overnight a market for products that didn't yet exist. It was this "demand pull," rather than a particular new discovery, that sent technological development and large-scale production zooming up the learning curve. Meeting this demand created an industry with the capability to supply a commercial market—driven by the important new medical diagnostic tool called magnetic resonance imaging (MRI)—that no one had foreseen at the start. To build the Tevatron, the world's first superconducting particle accelerator, Fermilab used 135,000 pounds of niobium-titanium-based superconducting wire and cable between 1974 and 1983. At the project's start, annual world production of these materials was a few hundred pounds. Fermilab brought together a collaboration of scientists and manufacturers who improved the properties of the superconductor and developed a large-scale manufacturing capacity. Today, annual production has climbed to 200,000 pounds, about half of which finds commercial applications, principally for MRI.

MILLIONS OFF THE ELECTRIC BILL

From its beginning, physicists planning Fermilab (called the National Accelerator Laboratory until 1974) west of Chicago had conceived of using superconducting technology to achieve an accelerator energy level of 1 trillion electron volts (1 TeV). But the people who met in 1967 to plan the Laboratory realized that it was not yet technically feasible to build superconducting magnets of accelerator quality. Instead, they designed a machine to achieve 400–500 GeV using only conventional magnets. The first 200 GeV proton beam passed through the Main Ring on March 1, 1972. That September, with the Main Ring well on its way to an energy of 400 GeV, Director Robert R. Wilson established an informal working group to begin investigating technical issues involved in building the next-generation accelerator, the Doubler.*

Renowned for his parsimony, Wilson thought Fermilab's power bill was too high. It was high in 1972, when the first beams passed through the Main Ring, and it got higher. By 1976, the Laboratory's consumption of electric power had nearly doubled—and the electric bill had shot up by a factor of six to nearly $10 million a year. Using superconducting magnets would take much less power than conventional magnets and cut Fermilab's electric bill by an estimated $5 million a year, while at the same time doubling the energy of the accelerator.

These magnets use less power than conventional magnets, because superconducting materials do not resist the flow of electric current when they are cooled to temperatures a few degrees above absolute zero.

**The superconducting accelerator at Fermilab has had more names than a character in a Russian novel. First it was generally called the "Doubler," or sometimes the "Energy Doubler," in recognition of the goal to increase accelerator energy from 500 to 1000 GeV. Later, during the 1974 gasoline shortage, it was called the "Saver," or the "Energy Saver," to emphasize the savings in power it would make possible. Physicist Peter Limon remembers attending a meeting devoted to long and heated debate of the relative merits of "Doubler/Saver" and "Saver/Doubler." Its current name, the "Tevatron," reflects its status as the first 1 TeV accelerator.*

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Above: Charles Laverick, left, Argonne National Laboratory, and William Fowler of Fermilab during a 1974 conference on applications of superconductivity.

Because electric current that flows through superconducting wire doesn't lose energy to resistance, magnets made with such wire use less electric power to achieve the high magnetic fields required by particle accelerators. It does take energy to cool the magnets, however, so the net reduction in power use is less than 100 percent.

Shortly after Heike Kamerlingh Onnes discovered superconductivity in 1911, he also discovered the bane of superconducting materials: quenching. This phenomenon occurs when a superconducting material reaches a certain critical current, temperature or magnetic field; it suddenly "goes normal," that is, returns to its nonsuperconducting state, releasing its stored energy—and sometimes melts. His discovery of this phenomenon also quenched Kamerlingh Onnes's enthusiasm for the practical uses of superconductivity. It was not until the late 1960s that superconducting technology reached the stage where it began to interest the builders of particle accelerators.

BETWEEN MAGIC AND WITCHCRAFT

Many have credited Wilson with a genius for bringing the right people—with the right skills and knowledge—together at the right time in order to accomplish scientific goals that were, to say the least, challenging. He never used this talent to better effect than in the design and building of the Doubler.

In the mid-1970s, when physicists and engineers at Fermilab began trying to design and build superconducting magnets, the technology of manufacturing superconducting wire and cable was still "exotic," as Leon Lederman, who became Director of Fermilab in 1978 after Wilson resigned, has written. "Somewhere between magic and witchcraft," is where University of Wisconsin metallurgist David Larbalestier places it.

Using his own brand of magic, Wilson brought together his available sources of expertise in superconducting technology for the task of designing and making the wire and cable. Fermilab physicists William Fowler, Paul Reardon and Russ Huson and metallurgist Bruce Strauss had gotten their feet wet in superconducting technology by building magnets for the 15-foot bubble chamber. John Purcell, a physicist from Argonne National Laboratory brought to the project his experience in building its 12-foot bubble chamber.

The Applied Superconductivity Laboratory at the University of Wisconsin gave Fermilab another entree into the field of superconductivity. Attracted partly by the wire-fabricating facilities designed by specialist Remsbottom, Larbalestier had come to Wisconsin from Britain's Rutherford Laboratory, where he had worked on superconducting materials in the effort to understand how they work at a microscopic and molecular level. "Larbalestier was our mentor in superconductivity," says retired Fermilab Associate Director J. Ritchie Orr. "He made it his business to understand how it really worked."

Sixty years after Kamerlingh Onnes's disheartening discovery,

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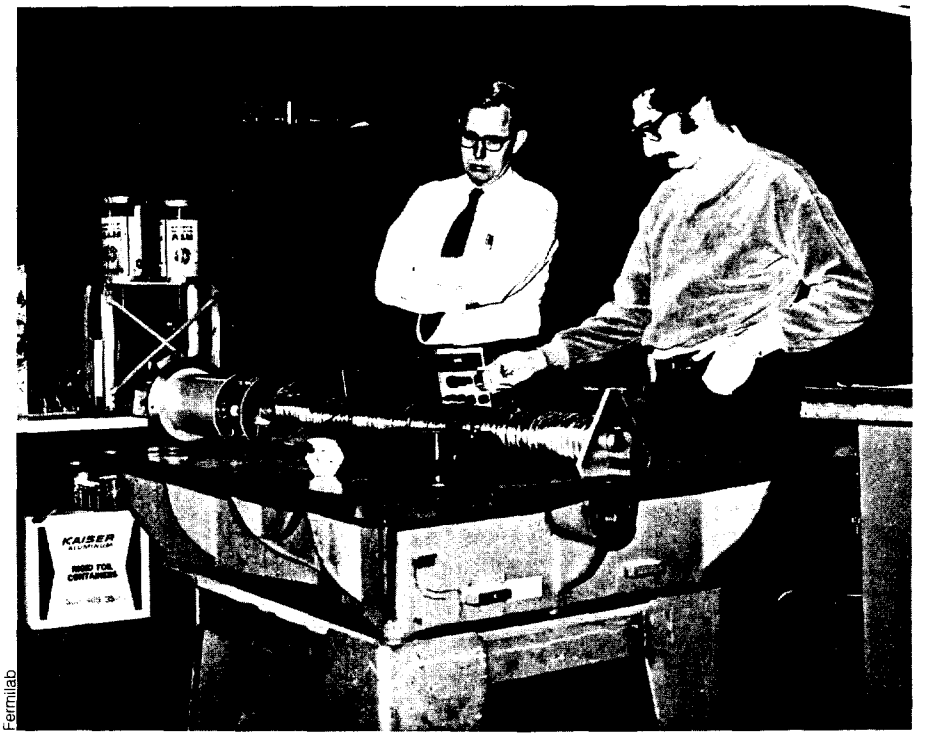

Fermilab

Engineer Willard Hanson and metallurgist Bruce Strauss test an early superconducting magnet.

quenching still caused problems for magnet builders at Fermilab, explains physicist Alvin Tollestrup, who, along with Orr and Fermilab physicists Richard Lundy and Helen Edwards, received the 1989 National Medal of Technology for their contributions to the Tevatron. A superconducting magnet uses coils of cable made of strands of superconducting wire to induce a magnetic field. The performance of a magnet made of such wire—its ability to reach and maintain a prescribed magnetic field without quenching—depends on many factors but fundamentally on the critical current of the superconductor, that is, on the amount of current the wire can conduct, at its operating temperature and field, without quenching. Thus, says Tollestrup, the object of making superconducting wire is to achieve workable wire—that bends easily, for example, and has precise dimensions—with a high critical current.

IT'S NOT SO EASY

The would-be wire maker must combine the right alloy of the right superconducting materials in the right configuration with a conventional conductor, such as copper; then find the right methods of heating and drawing the materials into wire, in order to achieve the requisite critical current and mechanical properties that will allow the wire to be formed into cables. Finally, those materials and methods must be adapted for mass-production of wire of uniform quality. The problem to solve in cabling the wire is to find the right number of strands of wire, in the right configuration, with the right materials on the surface of the strands and on the cable itself to achieve the highest critical current and appropriate mechanical properties so that it can be wound into magnet coils.

What kind of cable works best in superconducting magnets? Particle accelerators have lived and died by the answer to that question. For years, magnet builders at Brookhaven National Laboratory struggled to build superconducting magnets for the ISABELLE collider using not flat cable but a braid of superconducting wire. Many point to this choice of braided cable as a fatal flaw that led to ISABELLE's demise when the Department of Energy withdrew funding for the project in 1983.

These were problems that members of Wilson's Doubler group took on in the early 1970s. "When it comes to making superconducting magnets," says metallurgist Strauss, "a let's-try-it" approach works better than a theoretical one based on calculations alone. If you think about superconductivity too long, you'll realize it won't work." By early 1975, Fermilab's highly systematic and tightly organized "let's-try-it" approach had made enough progress to fix important wire and cable specifications. The cable would be a 23-strand, flat, twisted "Rutherford cable." The superconductor itself would be an alloy of 53.5 percent niobium and 46.5 percent titanium, proportions chosen to be nonproprietary and in the middle of the range of proprietary alloys of the various wire vendors. (Later research would show that the exact ratio of niobium to titanium was not critical in wire performance.) The work of Fermilab physicists Fowler, Reardon and Donald Edwards, metallurgist Strauss, technical consultant Remsbottom, and others ultimately produced not simply a set of specifications for superconducting wire but a sort of "build-by-numbers" wire-making assembly, the so-called Fermilab Kit.

BY THE TON?

As the needs of the magnet-development program increased, Fermilab researchers began looking for manufacturers who could work with them to supply large quantities

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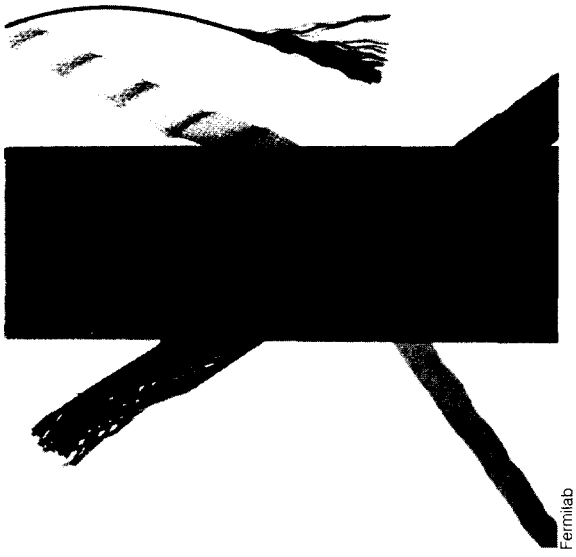

Fermilab

Argonne National Laboratory

Above left: Each wire strand contained 2100 filaments of superconductor. The New England Electric Wire Company wove the wire into 23-strand, flat Rutherford cable which was wrapped in Kapton insulating material. Above right: Paul Reardon, right, at a 1974 conference in Illinois. Opposite left: The "Fermilab Kit" for making superconducting wire comprised a copper can filled with 2100 niobium-titanium rods in hexagonal copper tubes (foreground), capped with a tailpiece and a nose piece. Employees of Intermagnetics General Corporation assemble the kit. Opposite right: A Fermilab machinist winds superconducting cable to form the outer shell of a Doubler magnet coil.

of superconducting wire and cable that would meet the specifications of the evolving magnet design. Having previously served as Fermilab's business manager, Reardon played a central role in putting together the collaboration between the laboratory and the manufacturers of superconducting alloy, of wire and of cable to produce the materials the project required. Orr sees Reardon as another of Wilson's strategic choices, another person with the right skills at the right time, a man with "organizational brilliance and guts. He didn't mind gambling a little with the taxpayers' money when he believed it would mean substantial benefits in the end." Reardon's gambles usually paid off for Fermilab.

Niobium-titanium is an alloy formed at high temperatures by melting in a vacuum with an electron beam. In 1974, when Fermilab first went looking for superconducting alloy, the Teledyne Wah Chang Albany Corporation in Oregon was the major supplier of niobium-titanium in the United States—and the Laboratory was virtually the only buyer. Strauss and Reardon once constructed a bar chart showing that Fermilab had bought 95 percent of all the niobium-titanium ever produced since the beginning of time. Niobium is mined in only a few places on earth—Brazil, Canada and China. In the 1970s China was not a practical source, and the ores with the highest concentration came from Brazil. Most of Fermilab's niobium alloy came from Brazilian ores until climbing export taxes sent Wah Chang to Canadian sources.

In the spring of 1974, Reardon, Strauss and contracts manager Edward West made a trip, legendary in Fermilab lore, to the Northwest to buy niobium-titanium from Wah Chang. "How much is it by the ton?" Reardon is supposed to have asked. Strauss remembers him explaining, "If we order it by the pound, they'll never learn how to make it in quantity." That early decision to buy a large amount of niobium (an initial order of about 15,000 pounds) proved significant in defining the relationships Fermilab established with the companies that made the alloy into superconducting wire.

FROM MINE TO MAGNET

Fermilab requested delivery of the alloy from Wah Chang as straight 24-inch rods, an eighth of an inch in diameter. The rods were the first piece of the Fermilab Kit, which consisted of a "billet" of 2100 niobium-titanium rods inserted into hexagonal oxygen-free, high-conductivity copper tubes with round bores, all packed into a 10-inch diameter copper "can." Nose and tail pieces were welded onto the can. The niobium-titanium rods came from Wah Chang. The Small Tubes Products Company made the hexagonal copper tubes.

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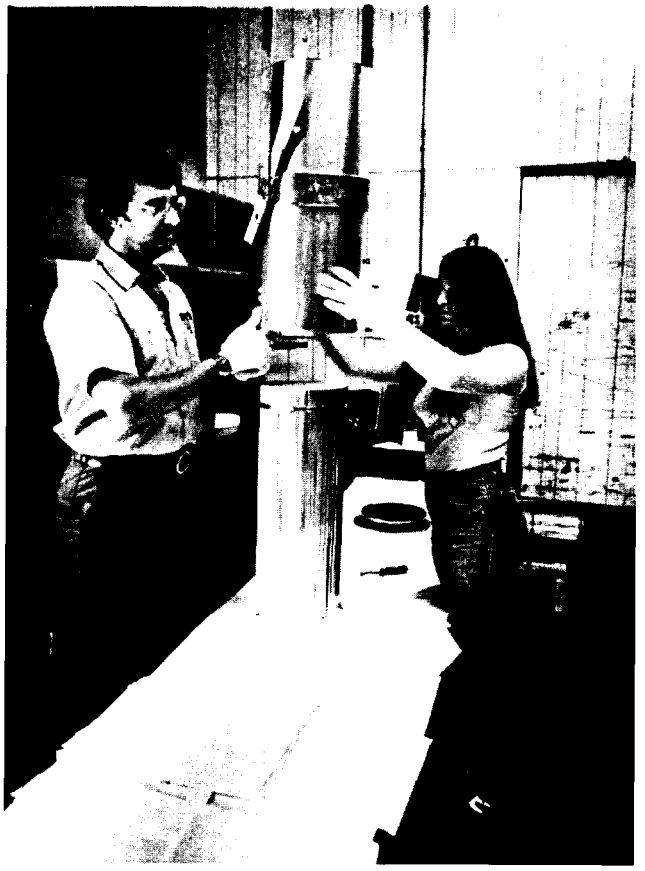

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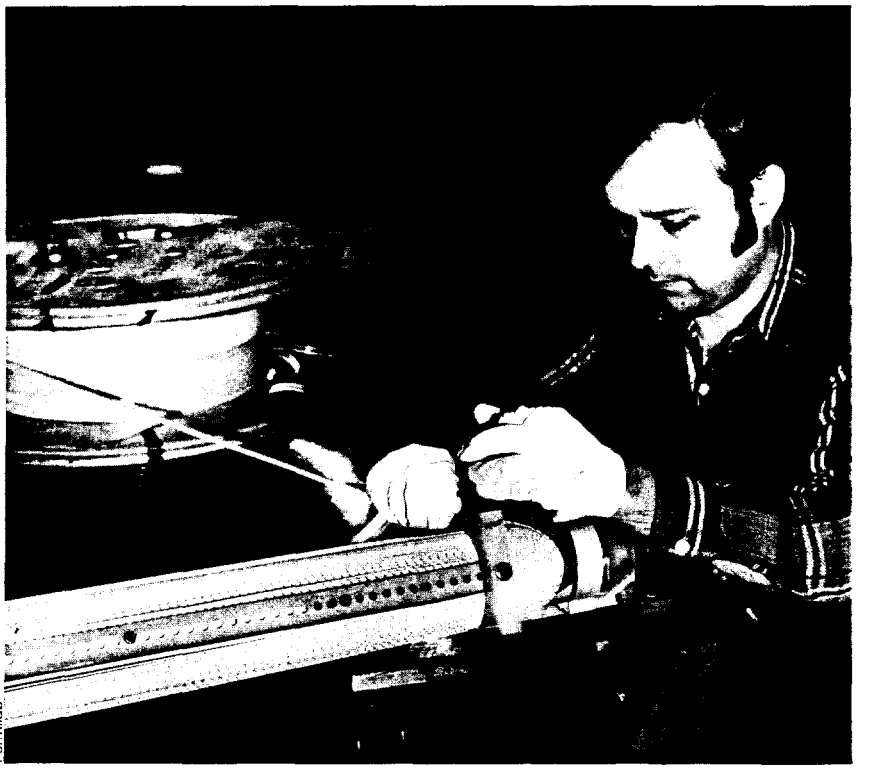

Fermilab

The Phelps-Dodge Company furnished copper for the cans, which were made by the Janney Manufacturing Company.

Fermilab bought all these kit materials for delivery to the wire manufacturers, whose task was to push and pull each 10-inch billet of copper-tubed niobium-titanium into a strand of superconducting wire 27 thousandths of an inch in diameter. Each strand would thus contain 2100 filaments of copper-coated niobium-titanium superconductor. Theoretically, each billet would produce 220,000 feet of superconducting wire. In practice, Fermilab paid a premium for any usable lengths over 210,000 feet that met specifications.

After the wire had been tested for dimension and superconducting properties, it went to the New England Electric Wire Company, where it was formed into flat 23-strand Rutherford cable. Fermilab magnet builders worked with the cable manufacturer to develop tooling and methods to "keystone" the cable, slightly changing its shape to fit the curve required by magnet design. To the finished cable they added a wrap of the insulating material Kapton. Tollestrup had discovered that wrapping with Kapton not only eliminated short circuits in the cable but insulated the superconductor against thermal transference that led to quenching. Both Fermilab inventions—keystoning and the Kapton wrap—played significant parts in the success of the Doubler magnets.

New England Electric Wire delivered the cable to Fermilab's Magnet Fabrication Facility for winding into coils for magnets. Each magnet used 110,400 feet of wire, twisted into 4,800 feet of cable. The 796 dipole magnets and 224 quadrupoles in the Doubler used enough wire to circle the earth 2.3 times, says contracts manager Lawrence Vonasch. In addition, prototype and experimental magnets used millions more feet of wire.

"We had learned very early," says Larbalestier, "that the properties of the conductor determined the properties of the magnet." The process of making 10-inch billets into 0.027-inch wire takes many steps, including an initial extrusion into two-inch diameter rods, various heat treatments, and "cold-working," drawing the wire into ever-finer diameters. No single step is more crucial in determining the critical current than the heat treatment the wire receives. How hot should the wire be heated? For how long? At what wire diameter should the heat treatment occur? Each wire company had its own proprietary recipe.

Fermilab dealt with four manufacturers of superconducting wire—Magnet Corporation of America, Supercon, Airco and Intermagnetics General Corporation (IGC). The first orders gave only a few billets to a manufacturer to make into wire. Fermilab would test it, rejecting wire below a certain level of performance. The vendors' early efforts yielded wildly erratic results. As a company's performance improved and the needs of the magnet program increased, Fermilab furnished more billets. By the project's end in 1982, IGC—the remaining wire vendor—was processing 150-billet orders into highly uniform wire.

Close communication between Fermilab and the manufacturers influenced the success of the

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Fermilab

Above: Billets at Intermagnetics General Corporation (IGC), manufacturer of most of the wire for the Energy Doubler. Each 10 inch billet yielded about 200,000 feet of 0.027 inch superconducting wire, on spools in background. Opposite: IGC employee winds superconducting wire onto a spool.

Laboratory-industry collaborations, says physicist Lundy, who put together and ran its mass-production assembly line for superconducting magnets. Wisconsin's Remsbottom, a skilled hands-on veteran in the superconducting field who, says Lundy, "knew as much about how to make superconducting wire as anyone in the world," spent most of his time on the road, traveling from Wah Chang to IGC to New England Electric Wire and back again. "If you were a Fermilab vendor, you knew that every two weeks or so, Bob would show up." Often Lundy, who was himself a practical and inventive engineer as well as a high-energy physicist, accompanied him on these trips. "They let me in because I was with Bob," he says. These personal visits provided a direct channel for the back-and-forth flow of information that helped improve the quality of the wire.

ASSUMING THE RISKS—AND CUTTING THE PROFIT

Fermilab's decisions not only to purchase the raw materials for the superconducting wire but to require the wire manufacturers to use the Fermilab Kit were key factors in determining the nature of the working relationships that evolved. These decisions had important and controversial consequences, worth examining for their effect on the success—and the limitations—of Fermilab's major procurement of superconducting wire in creating and encouraging the superconducting wire industry in the United States.

The greatest cost component in producing superconducting wire is the cost of the alloy. It was expensive—about $100,000 a ton—when Fermilab began buying it in 1974. For large corporations with deep enough pockets to assume the level of financial risk required to buy large quantities of alloy, the Doubler represented a relatively limited market that did not justify the necessary investment in research and retooling. They just weren't interested. Smaller, specialized companies that did find the Doubler market worth pursuing lacked the financial resources to buy large quantities of alloy. From Fermilab's point of view, the Laboratory's purchase of alloy helped the fledgling industry by assuming one of the major financial risks for these small manufacturers, that operated, recalls Orr, "on the ragged edge of nothing."

"Sure they took away some of the risk," says Carl Rosner, president of IGC, the manufacturer that ultimately supplied most of the wire. "They also took away most of the profit. By refusing to allow us to buy the alloy ourselves, to our own specifications, and mark it up, they took away our major opportunity to make any money on the contract."

"It's true we didn't have the cash on hand to buy niobium," he adds "but with an order from Fermilab we

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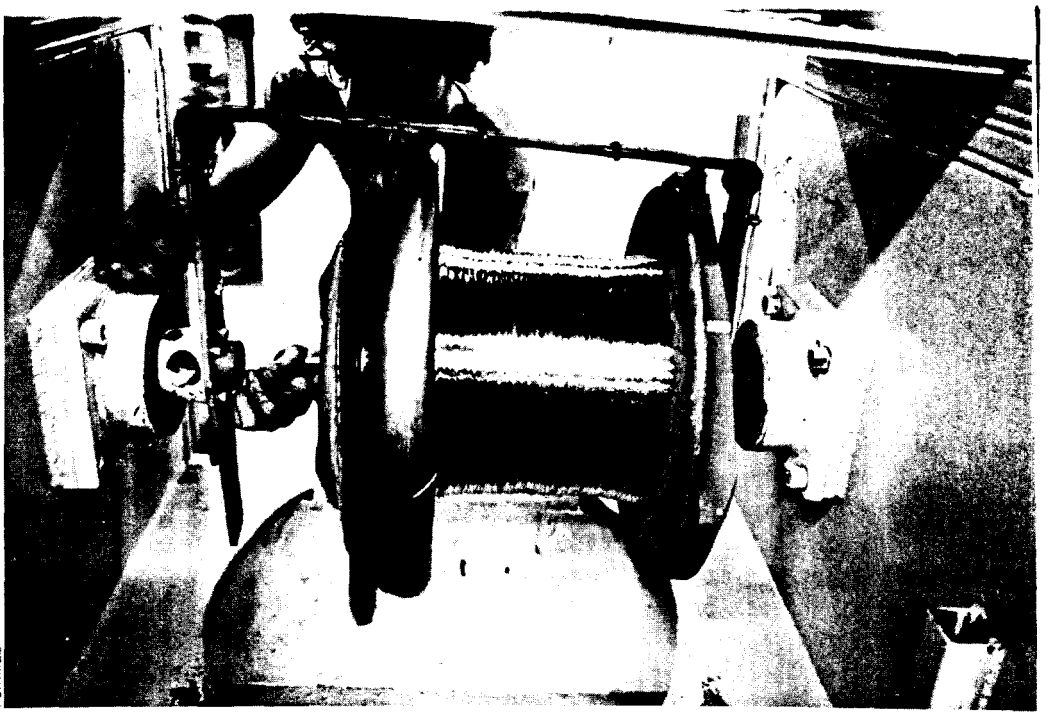
Fermilab

could have gone to the bank for a loan. That's how it's supposed to work."

By furnishing kits to the wire manufacturers, Fermilab eliminated many technical variables in an enterprise in which systematic control of the parameters of superconducting magnets was absolutely crucial to success. But the kits also took away most of the opportunities for vendors to use their own proprietary materials and methods—and thus even more of the opportunities to profit.

"Fermilab helped us enormously," says Rosner. "They forced us to accelerate our learning curve in superconducting technology. But our experience making wire for the Doubler should have positioned us as a world leader in superconducting technology." Instead, he believes, Fermilab's refusal to allow vendors to profit left U.S. superconductor manufacturers like IGC ill equipped to compete in the world market that took off in the 1980s with the advent of magnetic resonance imaging.

Maybe so, says Bruce Chrisman, Fermilab's Associate Director. "But if we had let those guys mark up the niobium, it would have sent the cost of the Doubler up so high that DOE would have told us to forget it. The Doubler would never have been built, and there wouldn't be any market to talk about today."

WHY IT WORKED

Another thorny issue in this rocky marriage between science and commerce concerned who would have custody of the information that the partnership engendered. What tradition is more hallowed in science than the free dissemination of the results of scientific investigation? What commodity is more precious to a technology-based company than hard-won technical secrets? To Fermilab scientists, it seemed only natural and ethical to share what they learned about superconducting wire with the world. To the wire makers, it seemed like giving away the farm. From their point of view, the scientific community simply handed foreign firms a state-of-the art recipe for making superconducting wire, effectively eliminating the leg up that U.S. companies had gained from their fast and arduous scramble up the learning curve.

If "The Case of the Superconducting Wire" raises difficult questions, it also shows that science and industry can find common ground where both can thrive. Although it didn't work perfectly, the collaboration between Fermilab and the superconducting technology industry did indeed work.

Asked why, Wisconsin's David Larbalestier says, "I think it came down to honesty—good old-fashioned intellectual honesty. In all the organizations, there were people who could focus on the things that were real. It's all too easy in this business to get egos into play. But the question is, 'Will the game be played in an honest fashion?' "It's not a trivial thing—simply to understand," he adds, "In the long run in this country, we need a long-term commitment to understanding."

Successful companies in the collaboration had the motivation to innovate and experiment and invest resources to supply the materials to build the world's highest-energy particle accelerator, and in doing so they built a new industry. High-energy physics did not invent MRI, but it did push superconducting technology out of the nest so that when MRI came along, the industry was ready to fly. For the future, we can't predict the exact flight plan, but we can be sure that superconducting technology has just begun to soar. In the words of the late Robert Marsh, of Teledyne Wah Chang, still the world's largest supplier of superconducting alloys, "Every program in superconductivity that there is today owes itself in some measure to the fact that Fermilab built the Tevatron and it worked."

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Technology Transfer at SSRL

by ARTHUR BIENENSTOCK

From its inception, the Stanford Synchrotron Radiation Laboratory has worked closely with industry.

AT A TIME WHEN SYNCHROTRON radiation facilities costing about $500 million each are under construction around the world, it is easy to forget how tentative was the National Science Foundation's early commitment to the field. Synchrotron radiation research began on the SPEAR storage ring in July 1973, using a pilot-project beam line funded by Stanford University and its NSF-funded Center for Materials Research. Subsequently, the NSF decided to fund the Stanford Synchrotron Radiation Project (SSRP) on SPEAR for two years, providing staff to partially construct, and support users on, the five experimental stations of Beam Line 1. This event marked the first time that synchrotron radiation from a multi-GeV storage ring, capable of producing x rays, became available to a large number of users.

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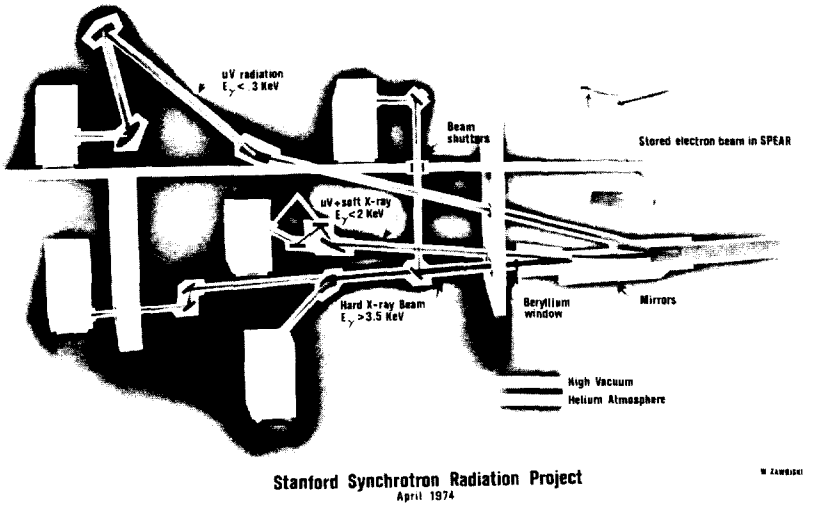

Beam Line 1, the first synchrotron radiation facility at SPEAR, supplied intense x-ray beams to five experimental stations.

In selecting SSRP for funding, the NSF passed up an opportunity to develop a fully dedicated synchrotron radiation facility based on the Cambridge Electron Accelerator because it was uncertain that the scientific payoff would be sufficient to justify funding the operation of the accelerator in addition to the synchrotron radiation facility itself. By choosing to support the SSRP instead, it could limit its obligations, as SLAC was already operating SPEAR for high energy physics. That is, SSRP was to be operated in a "parasitic" mode. The appellation "Project" itself mirrored the transitory nature of the commitment. Only in October 1977 was the Project transformed into a full-fledged Laboratory with a formal change of University status and NSF funding of a major expansion project.

Viewed in the context of technology transfer, the initial NSF decision was brilliant. The SSRP staff was simply too small to capitalize on the then-apparent potentialities of x-ray and vacuum ultraviolet beams that are 100,000 times more intense than standard laboratory sources. As a result, the collaborations and cooperative undertakings initiated with scientists from other academic, federal and industrial laboratories were quite unusual for condensed matter research in universities and national laboratories up to that time. These began with the planning, construction and installation of SSRP's first experimental stations on Beam Line 1 and have continued as the SSRL constructed new facilities. Such interactions have been duplicated, with variations in the detailed nature of the arrangements, at almost all other synchrotron radiation facilities.

Had the original staff been larger and more self-contained, the Laboratory might have attempted to do things "on its own," as is the custom in most condensed matter research. It is extremely likely that there would have been fewer innovations and that much less "technology transfer" would have taken place.

In this article, therefore, I describe briefly the development of Beam Line 1 and some of the cooperative programs and other interactions between U.S. industry and SSRL.

BEAM LINE 1 had five experimental stations in its first configuration, two of which are particularly relevant to technology transfer. The extremely important $E_\gamma < 2$ KeV station was designed and assembled by Robert Bachrach and Frederick Brown of the Xerox Palo Alto Research Center (PARC). Its Grasshopper monochromator (a device for selecting individual wavelengths from the broad spectral range produced by the storage ring) was a major innovation. In the process of its development, they worked closely with its fabricator, Baker Engineering. Because this monochromator opened up a new spectral region for synchrotron radiation research, this company has been able to sell units to other facilities.

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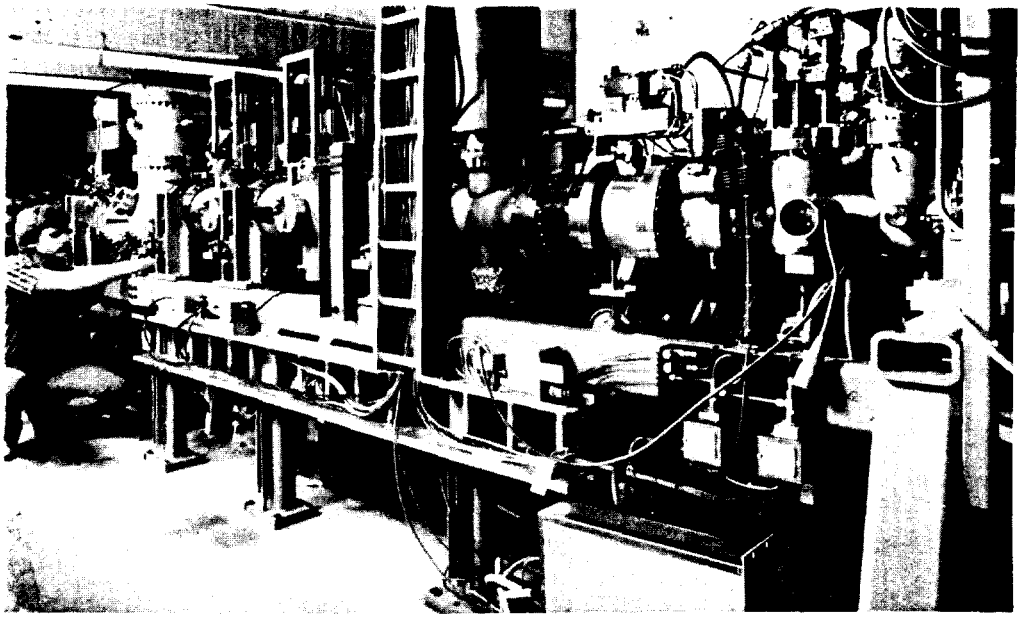

A beam transport system that brings synchrotron light from the SPEAR storage ring to the SSRL experimental hall. This system supplies soft-x rays to an experimental station used by the University of California and other laboratories.

The station was particularly valuable for studies by Stanford and Xerox PARC scientists of metal-semiconductor interfaces. As solid-state electronic systems evolved from individual transistors to integrated circuits, the classical picture of the rectifying junction as a bulk metal in contact with a bulk semiconductor became increasingly simplistic and insufficient. This station helped scientists elucidate the role of vapor-deposited metal atoms in creating the surface electron states needed for the junction's effectiveness.

The beam line is an interesting example of "two-way technology transfer." The Xerox PARC monochromator innovation was commercialized by Baker Engineering. It allowed a great deal of academic research, including the pioneering metal-interface studies of Stanford University Professor William Spicer's group. These studies, in turn, accelerated and enhanced the parallel work of the PARC group led by Bachrach. The two groups stayed in close contact and later cooperated in the development of SSRL's Beam Line 5 on which they pioneered the concept of having multiple undulators (an undulator is an array of magnets inserted into the storage ring to increase the effective intensity of the photon beam) on a single beam line. That line also includes a new monochromator optimized for undulator radiation. Xerox PARC's considerable investment in Beam Line 5 followed from the value of the research its staff performed on the first Grasshopper station.

Some years ago, I attempted to assess the impact of industrial use of SSRL for an article* on SSRL-Industry relations. Among the comments received at the time was one from George Pake of Xerox. He wrote that the work at SSRL contributed "strongly to their leadership in crystal growth of GaAs-based heterostructures." Another part of the letter, which addressed their work on semiconductor-metal interfaces, states that it "... will provide the scientific base for very advanced Xerox technology."

A second station, which pioneered the concept of the rapidly tunable x-ray monochromator, was designed for the acquisition of Extended X-ray Absorption Fine Structure (EXAFS) data. Dale Sayers and Edward Stern of the University of Washington and Farrel Lytle of the Boeing Company had previously shown that it should be possible to obtain detailed information about the environments of individual atomic species in complex materials through analysis of the fine structure in the x-ray absorption coefficient as a function of photon energy. EXAFS promised to advance our understanding of protein functioning, catalytic behavior and the properties of amorphous materials. Prior to SSRL, however, its

**A. Bienenstock, "Stanford University Synchrotron Laboratory: Universities, Government and Industries Strongly Linked," in Emerging National R&D and Management Trends, Where are they Leading," edited by S. A. Johnson, Jr., University Press of America, (1986), p. 145.*

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use was extremely limited because standard laboratory x-ray sources did not have enough intensity to yield the statistical accuracy required for the structural analysis.

Recognizing the potential importance of synchrotron radiation, with its high intensity and continuous spectrum, a team that included scientists from AT&T Bell Labs, Boeing, SSRL, Stanford University and the University of Washington developed the central station of Beam Line 1 for EXAFS. In the years that followed, EXAFS analysis was generalized to yield the environments of dilute species and atoms on the surfaces of materials. The technique was, and continues to be, used extensively by scientists from industrial laboratories—particularly for the study of catalysts and amorphous materials. It is also in heavy use by structural biologists, geologists and other academic scientists, as well as by scientists from Department of Energy laboratories who are trying to solve some of the nation's most complex environmental clean-up problems.

SSRL's role in EXAFS research illustrates the unusual nature, plus the extreme effectiveness, of its technology transfer efforts. The laboratory recognized that the technique could be extremely valuable to industry, as well as to basic science, at a time when others were quite skeptical. It collaborated with academic and industrial scientists to develop generally usable and innovative instrumentation as well as mathematical techniques for data analysis. SSRP scientists gave lectures at industrial laboratories to familiarize others with these techniques. Users were taught how to acquire and analyze data. Graduate students trained in EXAFS techniques and went on to industry. As a consequence, they are used in a large portion of industrial research at synchrotron radiation laboratories throughout the world. The technology that has been transferred is the very means to perform studies defined by industry itself. At the same time, academic and federal laboratory research has been advanced considerably by the participation of industrial scientists.

For the review of SSRL-industry relations discussed above, Peter Eisenberger, then of Exxon Research and Engineering, stated, "Our research at SSRL on the structure of oil, particularly the metal impurities in it, has contributed to improved processing of oil. Our research at SSRL concerning the structure of catalysts, including measurements under operating conditions, has led to improved understanding of the functioning of those catalysts and therefore contributed to the formulation of new chemical processes."

Joseph Wong, then of General Electric, talked of the use of EXAFS studies of metallic glasses to optimize the composition and processing of next-generation, low-loss electrical distribution transformers. EXAFS studies of coal assisted in minimizing fouling and corrosion due to coal-firing.

The three other stations on Beam Line 1 were the product of SSRP collaborations with federal and academic laboratories, but have been used extensively by industry. One was implemented by scientists from the California Institute of Technology to study changes in atomic spacings in muscles as they contract and expand. Later, a Stanford student modified it for the study of atomic rearrangements in glasses as they are cooled from the melt. It has been used most extensively by scientists at IBM's Almaden Laboratory to study the structure of polymers.

Another station was developed by SSRP and scientists from the University of California, San Francisco to study the sizes of proteins in solution. Later, a collaboration of EXXON and Stanford scientists used this station to study aspects of the refining of heavy crude oils, as mentioned in the statement of Eisenberger quoted above. Still later, the station was decommissioned as more effective stations for small-angle x-ray scattering studies were established.

IN THE TWO DECADES since its establishment, the laboratory has changed markedly. Operated, maintained and improved by SSRL, SPEAR has become fully dedicated to synchrotron radiation. It functions for users about six months a year (limited by funding) and has 26 experimental stations available for users.

With this combination of increased operational time and number of experimental stations, SSRL can perform considerably more effectively its primary "technology transfer" role—the provision of synchrotron radiation and sophisticated instrumentation so that industry can perform the experiments it deems important. Nearly a hundred U.S. corporations have used SSRL in that way. Industrial scientists and engineers continue to perform experiments actively at SSRL, competing for beam time, in spite of the expense

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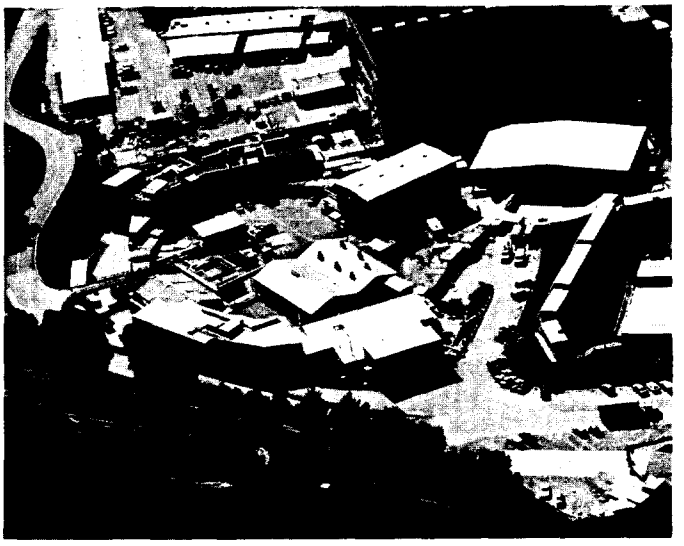

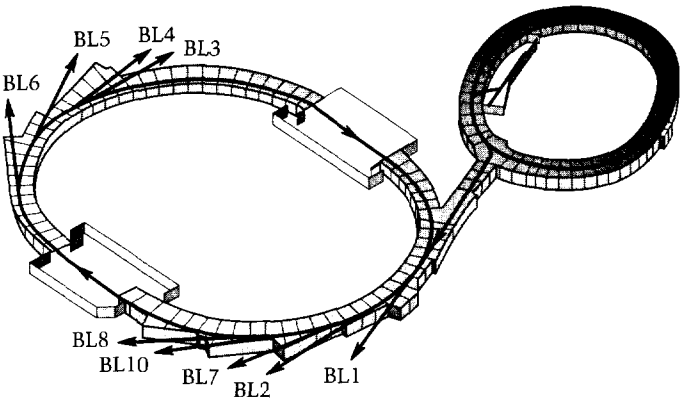

Above left: Aerial view of the Stanford Synchrotron Radiation Laboratory. The SPEAR storage ring is at the center of the photo, and the new injector synchrotron is at upper right. Above right: Schematic diagram of SSRL, showing some of its synchrotron radiation beam lines.

of mounting experiments away from their home laboratories.

SSRL has changed in other ways during the past 15 years. The laboratory constructed a dedicated synchrotron injector for SPEAR, the Department of Energy has assumed responsibility for its funding, it has become a division of SLAC, it has pioneered insertion devices and routinely used them to produce synchrotron radiation, and the staff has grown to well over 100. New synchrotron radiation facilities have been, and continue to be, built throughout the nation and world. With these changes has come an augmentation of SSRL's traditional technology transfer roles.

As his responsibilities for the design of the injector wound down, Helmut Wiedemann served as a consultant to the Maxwell-Brobeck Corporation. In this role, he helped that company to complete the nation's first commercial synchrotron radiation source, installed at Louisiana State University in 1992. This storage ring has been commissioned and has already exceeded its design energy and is approaching its design current.

Similarly, George Brown (now at University of California, Santa Cruz) and SSRL's engineering head, Richard Boyce, who together led the world's first implementation of x-ray undulators, have assisted AT&T Bell Laboratories as consultants in its design of a beam line for the Advanced Photon Source presently under construction at Argonne National Laboratory.

SSRL scientist Roman Tatchyn has worked as a consultant with Adelphi Corporation, designing high-reflectivity, multilayer x-ray monochromators for use in synchrotron radiation-based angiography. The monochromators were manufactured, in turn, by the multilayer group of Ovonic Synthetic Materials, Inc., for which I have also consulted. This work is aimed at achieving a capability to obtain good images of the heart arteries without the relatively dangerous arterial catheterization procedure now used.

Both Adelphi and Ovonic Synthetic Materials are relatively small companies, but they are large compared to SSRL's smallest commercial user, the one-man company, Hirsch Associates. Gregory Hirsch is developing an x-ray microscope for commercial production. His use of an experimental station that Piero Pianetta established for testing x-ray optics and lithography systems has been invaluable in developing this product.

Part of SSRL's ability to make these contributions results from having the staff to build and improve its accelerators as well as to design and use the extremely demanding insertion-device beam lines. The requisite

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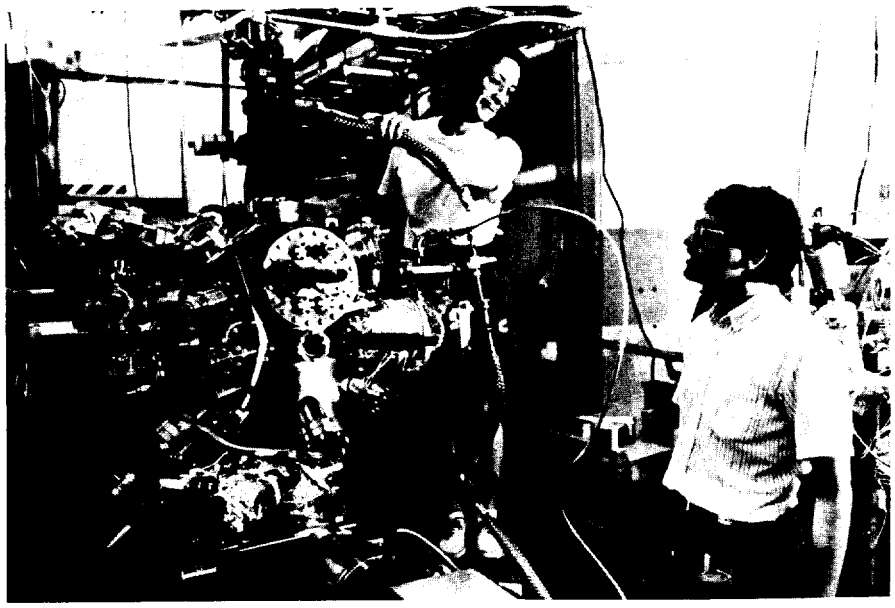
skills are in short supply nationally, which is hindering the nation's progress towards full implementation of the synchrotron radiation sources now under construction. While the ultimate solution to this shortage may come through the training of students, consultantships offer the means by which industrial organizations can proceed with their own synchrotron radiation programs. They also allow companies to obtain expertise without having to make a full-time staffing commitment. This type of arrangement between universities and industry was quite common in the 1950s and 1960s, when U.S. industry was extremely strong technologically.



Jackeline Pawela of Stanford University and Mahesh Samant of IBM Research Division at work on the surface science chamber built by IBM for SSRL. A collaboration between IBM and Stanford's Chemical Engineering Department is using this equipment to study the catalytic properties of metal surfaces, one application of which is in methanol synthesis.

SSRL CONTINUES to develop in collaboration with industry scientists, new scientific and technological capabilities. Its staff members are currently involved, with 20 different companies. For example, protein crystallography has become an increasing portion of SSRL's scientific program under the leadership of Keith Hodgson and SSRL scientist Paul Phizackerley. The high intensities make possible the acquisition (using rotation camera instrumentation) of high-resolution data before radiation damage destroys the difficult-to-grow protein crystals. Much smaller crystals can also be studied. The so-called Laue technique, which utilizes a polychromatic x-ray beam, allows data acquisition in milliseconds, enabling the study of time-dependent phenomena.

While much of the protein crystallography at SSRL is performed by academic groups, pharmaceutical companies have become increasingly involved because of the growing reliance on information about molecular structures in drug design. Among the more interesting projects involves a drug being designed by the Syntex Corporation to inhibit replication of the HIV virus. In order to understand how the inhibitor works at a molecular level, Syntex scientists are collaborating with Henry Bellamy of SSRL to determine the crystal structure of the inhibitor attached to HIV-protease—a protein that allows the virus to reproduce itself. The information gained from this study will guide scientists from Syntex and other pharmaceutical companies in developing even more effective inhibitors, one of which could ultimately lead to a new drug able to stop the HIV infection.

SSRL insertion devices called wigglers provide about 100 times more intense radiation than ordinary synchrotron radiation, or 10 million times the intensity of an x-ray tube. This increase has supported the development of the grazing incidence x-ray scattering (GIXS) technique at SSRL for the study of atomic arrangements at or near the surfaces of materials. By carefully controlling the angle at which the x-ray beams hits the surface, its penetration depth can be varied from about 2 nanometers to many micrometers.

Over the past few years, Paul Fuoss of AT&T Bell Labs, David Kisker and G. Brian Stephenson of IBM Yorktown Heights Laboratories, and SSRL's Sean Brennan have exploited this capability to improve an important industrial semiconductor synthesis

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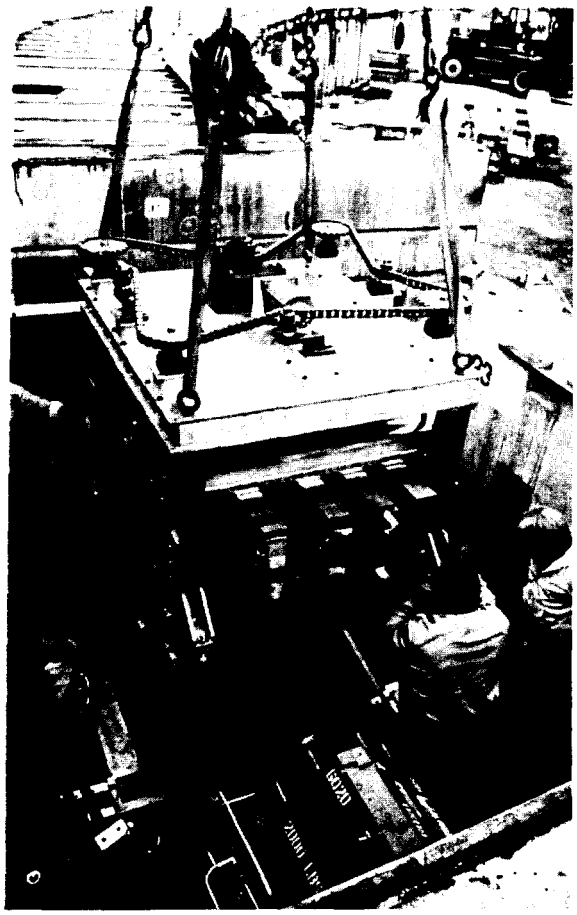

Installation of insertion devices called undulators for SSRL's Beam Line 5.

process. With organometallic vapor phase epitaxy, films of compound semiconductors like GaAs are made by reacting two organometallic molecules, which carry the As and the Ga, at the surface on which the films are to be deposited. Since the gases carrying these compounds scatter x rays very weakly, they do not obscure the growing surface, which is of interest in these studies. This GIXS technique has proven to be extremely powerful for *in-situ* studies of the growth process while it is underway, and other x-ray techniques can be used simultaneously to monitor aspects of the gases themselves. This collaboration has been extremely successful, leading to scores of publications and invited papers explaining the relationship between process parameters and the nature of the final product.

The same grazing-incidence approach has also been used for a somewhat different type of problem. Extremely small concentrations of certain impurities, such as transition metals occurring at or just below the surface of an integrated circuit chip, can ruin its performance. As device densities increase with growing miniaturization, the impurity concentrations must drop considerably if appreciable yields are to be obtained. A recent SSRL workshop concluded that for dynamic random access memory process technologies expected to be in manufacturing by the end of 1994, these contamination levels will have to be 1 billion atoms per square centimeter or less. In 1998 the limit will be 100 million atoms per square centimeter, 20 times less than the present detection limit. In order to assure effective wafer processing development, it is highly desirable to have a considerably more sensitive analysis technique, preferably with good depth resolution, so that the manufacturing procedures contributing the impurities can be readily identified.

Recently, Stephen Laderman of Hewlett-Packard Laboratories proposed that grazing-incidence synchrotron radiation be used to achieve considerably greater sensitivity, plus greater depth resolution, than the best instruments presently available to chip manufacturers. In this approach, the x rays excite impurity atom fluorescent radiation, which is then analyzed with a solid-state detection system that monitors intensity versus photon energy. For very high sensitivity, the incident x-ray energy can be varied from one that excites a specific atom's fluorescence to one that does not. To obtain depth information, the signal is measured as a function of the angle of incidence of the synchrotron radiation beam.

The approach has been developed and tested by two separate but cooperating teams. One is led by Laderman and Brennan and the other by Michael Madden of Intel, David Wherry of Fisons and Pianetta of SSRL. A recent SSRL workshop concluded that this method would be used widely by U.S. semiconductor companies if adequate facilities were available at SSRL.

Many of the techniques developed at SSRL and other synchrotron radiation facilities can be similarly adapted for the purpose of industrial analysis. To become valuable, however, laboratory managers will have to find ways to make these facilities available with less recourse to the lengthy scientific review procedures presently employed. This should become easier when SSRL obtains enough money to operate throughout most of the year and after more beam lines are commissioned at SSRL and the other laboratories.

The projects described above represent only a fraction of the technology transfer efforts presently underway at SSRL. Some of the names I have mentioned identify SSRL's other immensely important technology transfer mechanism—the training of graduate students. These people did their Ph.D. research here as Stanford University students in either the Applied Physics or the Materials Science and Engineering department. Each went on to industry and gained further experience. Brennan and Pianetta, returned to SSRL to help develop its capabilities further, assist its users and participate in collaborations such as those I have discussed. The others have remained in industry and identified ways of using synchrotron radiation to meet the needs of their companies. This classical method of transferring technology to industry is enhanced considerably when relatively unique facilities, such as synchrotron radiation laboratories, are located at universities.

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by GEORGE CARYOTAKIS

MICROWAVE TUBES *for* SCIENCE & INDUSTRY

High power microwave sources developed for particle accelerators have potential applications in emerging technologies.

INVENTED OVER 50 YEARS AGO, the klystron and the magnetron made microwaves a usable form of energy, launched radar and helped win World War II. After the war they became a mainstay of particle accelerators, providing the power needed to boost subatomic particles to ever higher energies. Microwave tubes have also made possible satellite communications, UHF television, and have a number of other commercial applications.

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During the 1950s and 1960s microwave tubes became a popular new field of study in electrical engineering and applied physics. Stanford University, MIT, University of California and several other major schools were funded by the Department of Defense to do research in the field. Their graduates helped establish a sizable microwave tube industry in the United States.

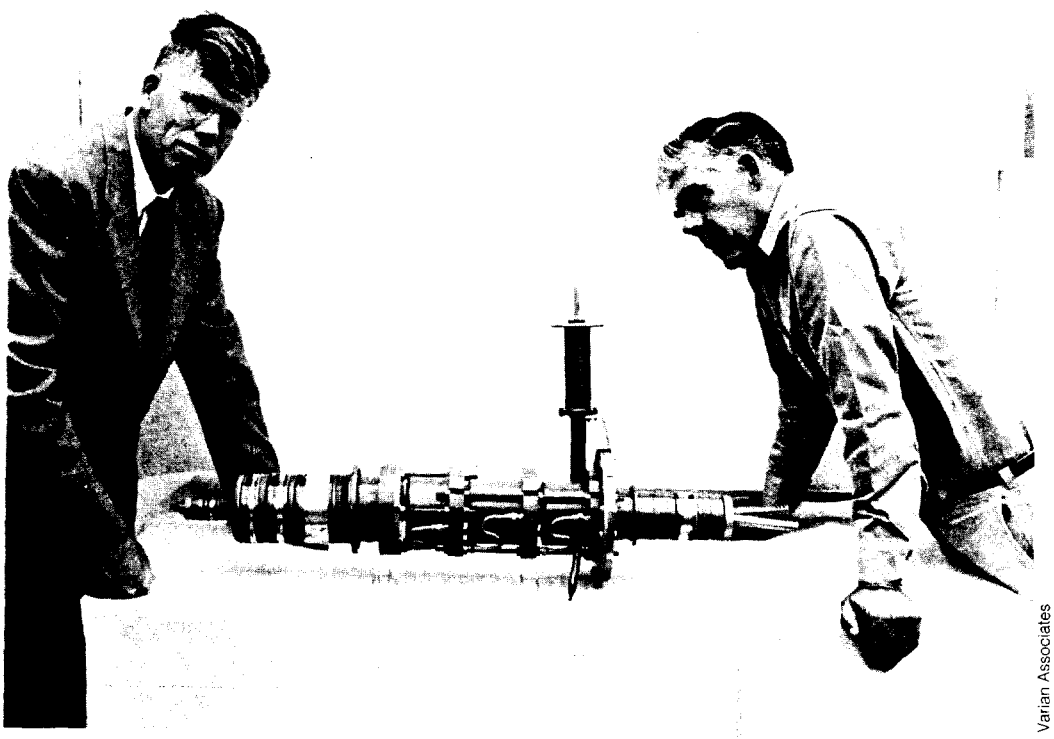
After the klystron amplifier came the traveling-wave tube, also a velocity modulation device, but one where the electron beam interacts with a propagating rather than a resonant circuit, hence an amplifier capable of octave bandwidths. It became the microwave tube of choice for electronic countermeasures (against radar) as well as a general-purpose medium-power microwave source. Its future appeared so bright that several new companies were founded to manufacture the device.

IN THE 1970S, magnetic fusion research generated a need for large amounts of microwave power at millimeter wavelengths in order to heat plasmas. The internal workings of conventional tubes cannot withstand the power densities involved, and so a new device, the gyrotron, originally invented in the Soviet Union, was developed in this country. It produces hundreds of kilowatts of power at wavelengths of the order of a millimeter. The gyrotron is a "fast wave" device that depends on relatively large cavities interacting with the rotational energy of a spinning electron beam. Successful tokamaks throughout the world depend on gyrotrons for plasma heating.

These microwave tubes were the principal products of an industry that, in the mid-1980s, approached sales of $1 billion in the U.S. alone. But that was the high water mark. By that time, low-power traveling-wave tubes, reflex klystrons and small magnetrons were being replaced in many military and commercial applications by devices based on gallium arsenide.

Even more serious to the industry was the ending of the Cold War. Defense spending fell as spares levels were cut back drastically in all services. Traveling-wave tubes were particularly hard hit, but all microwave tube sales were affected. Today, microwave tube industry sales are down by more than a factor of two from a decade ago.

Russell, left, and Sigurd Varian with an early commercial model of the klystron they invented at Stanford University.



Varian Associates

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There are significant future opportunities in high-power microwave tube production. To exploit them, industry executives must take a longer-term view of their business.

Meanwhile, the "scientific" sector of the microwave tube market continued to grow. In addition to new tokamaks for fusion, a number of powerful accelerators came on line in the United States, Europe and Japan. Although gyrotron development and manufacturing continued in the U.S. (with increasing competition from Europe) the U.S. tube industry participated less and less in the market for accelerator klystrons. At the Stanford Linear Accelerator Center, a decision was made in the 1970s to develop the first 500 kW continuous wave (CW) storage-ring klystrons and to establish a manufacturing facility for the pulsed klystrons in the 245 sockets of the SLAC Linear Collider. Other accelerator projects found prices and deliveries by U.S. companies unacceptable and opted to buy European klystrons instead. Philips, in Germany, and Thomson in France developed 1 MW CW klystrons for the DESY and CERN accelerators, patterned after the PEP klystrons at SLAC. Most recently, the Superconducting Super Collider Laboratory contracted with Thomson for two types of injector klystrons.

American microwave tube companies have been forced to make deep cuts in their technical personnel in an effort to remain profitable as defense cutbacks continue. In this process of layoffs and early retirements, the industry has lost a great number of its experienced, specialized engineers and, with them, a good deal of of tube-making know-how. In order to improve profitability, R&D has been cut, with the result that strategic planning horizons have become very short. Capital investment has slowed down considerably, since much of it was supported by the Defense Department. Risk taking is at a minimum, as evidenced by the fact that European tube makers have been able to win, in this country, a significant percentage of all contracts placed for newer, more powerful klystrons, not only for scientific applications, but for defense as well.

This is unfortunate. This country's military posture requires an industrial base in microwave systems for which tubes are essential components. But even beyond defense, microwave tubes will be basic to a number of projects of national importance—scientific and industrial—that will require large amounts of microwave power. The market for these systems is likely to grow, not shrink. It will be an international market, unprotected by military secrecy or the Buy American Act. It will occur in Big Science, pollution control, industrial heating and fusion. In all these applications of microwave power, there is no information riding on the tube output and no detector at the receiving end. Microwaves are used simply to transfer energy.

BIG SCIENCE is providing today a substantial demand for high-power microwave tubes. CERN, SLAC, Fermi National Accelerator Laboratory, DESY (Germany) and KEK (Japan) are major users of high-power klystrons in both electron and proton accelerators. The next big machine, called the Next Linear Collider, will be an electron-positron collider. It is being designed to operate initially at 500 GeV, but in its ultimate version could reach 1.5 TeV. For the 500 GeV level, it would be approximately 15 km long and require a total of about 2000 klystrons or other microwave sources, each producing 100 megawatts. Such tubes are currently under development at SLAC, KEK and the Budker Institute of Nuclear Sciences in Novosibirsk. In the event that klystrons are used, the initial complement of tubes will cost approximately $200 million, depending on quantity pricing, and the annual business in spares represents well over $20 million. At the 1 TeV level the above numbers would have to be multiplied by four.

Needless to say, no microwave system in existence even approaches this power level, and no single microwave tube company in the world is equipped to meet the production

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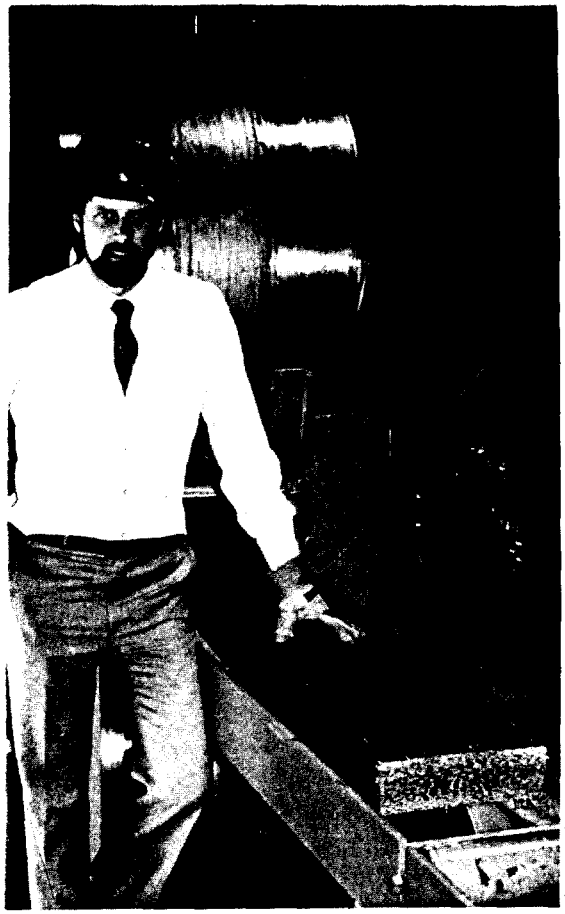

MacMillan Bloedel Ltd.

Mark Churchland, one of the inventors of the process, with a beam of Parallam, a composite structural lumber produced with the help of microwave power from klystrons, being formed at a MacMillan Bloedel pilot plant in Canada.

rates involved. As to the likelihood that such a machine will ever be built, a great number of intelligent people think so, judging from the related research that is proceeding in several major laboratories around the world. It will be built somewhere in the world, by an international consortium—including Americans, Japanese, Germans and perhaps Russians and French.

The next potential market for microwave tubes falls under the attractive title "pollution control." It is actually another huge accelerator, being proposed by Los Alamos National Laboratory in New Mexico and Brookhaven National Laboratory in New York, in connection with a concept called Accelerator Transmutation of Waste (ATW). It addresses the problem of dealing with high-level, long-lived nuclear wastes from both weapons production and commercial reactors. An intense proton beam from the accelerator is directed at a target, generating an intense flux of neutrons. Waste material is fed continuously to this reactor, which transmutes the waste and also produces power.

The machine is a linear accelerator operating in continuous-wave mode at 1.6 GeV with a beam power of 400 MW. The bulk of the microwave power is needed at a frequency of 700 MHz. At an efficiency of 70 percent, the microwave power needed is about 600 MW. Because overall efficiency is very important to ATW, consideration is being given to microwave sources such as the klystrode and the magnicon; both are relatively new devices theoretically capable of efficiencies higher than conventional klystrons but require additional development. Currently, no 700 MHz, megawatt-level microwave sources exist, but at approximately half that frequency there is an impressive array of 1 MW klystrons available from various countries, but none from the U.S. If the machine were built tomorrow, it would not have American tubes in it.

The business that would result from a single ATW machine, operating 6500 hours a year with six hundred 1 MW tubes powering it, is impressive. Thomson has been offering 1 MW CW klystrons at $250,000 each, which is considerably below the price quoted by other companies. At that price, a single machine's initial complement of tubes would be worth $150 million and the annual spares about $25 million.

How real are the prospects for ATW machines ever being built? Disposal of radioactive wastes through long-term storage in repositories faces a number of political and technical obstacles. States and communities do not want the stuff transported across their land or buried within it. The proposed machine could potentially reduce the timescale currently associated with such storage by a factor of approximately 1000, that is, from periods of the order of ten thousand years to thirty years or less. The project has obvious appeal (especially to future generations) but no significant funding as yet.

MOVING TO INDUSTRIAL USES of high power microwave tubes, a process has been developed in which resin-coated veneer strands, a by-product of the plywood-making process, are shaped by a press and

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heated by microwaves, forming a 12 inch by 16 inch continuous beam of composite structural lumber. The company behind it is MacMillan Bloedel, a Canadian firm that, back in the late 1960s, began experimenting with microwaves for drying wood. That turned out to be a loser, but they persevered and came up with the present product, which goes by the trade name of Parallam. MacMillan Bloedel says that they have invested over $140 million in the product so far. The process can produce beams of arbitrary length, with a consistency and durability that is impossible in natural lumber. The company recently formed a joint venture to manufacture Parallam and has built a plant in Colbert, Georgia. It is powered by four 100 KW CW klystrons and has an annual capacity of 2 million cubic feet of saleable product.

The world is running out of big trees from which to produce high grade lumber, while the demand for two-by-fours continues unabated. Obviously, the process has the potential of producing structural lumber, long after natural lumber becomes unavailable or prohibitively expensive. The use of microwave energy to cure the resin-coated strands is fundamental to the process, but larger plants will have to be planned, with bigger and more efficient power sources. The Parallam joint venture expects that these installations will be built all over the world, close to the sources of wood and the markets served. They are clearly on to something, although they had to wait 20 years for a payoff—a Canadian example for this country to emulate.

Big Science is providing a substantial demand for high-power microwave tubes.

FINALLY, THERE IS NUCLEAR fusion, humanity's ultimate hope for clean energy. Interactions between microwaves and plasmas remain an integral part of tokamak systems for both plasma heating and profile control. Electron-cyclotron plasma heating requires millimeter wavelengths and has been the principal incentive for the development of gyrotrons in Russia, the United States, and now Europe and Japan. Klystrons are used to provide microwave power at "lower-hybrid" frequencies of about 3–5 GHz.

The previously uncoordinated international fusion research has recently acquired new focus in the form of the "International Thermonuclear Experimental Reactor" or ITER, a collaboration among the U.S., Japan, Russia and Europe, with headquarters in San Diego. The experimental reactor will be the largest tokamak ever built. Its "confinement quality," the product of plasma density and the average time for energy to escape, will exceed the break-even level by a factor of 10—and thus reach ignition. It will generate 1000 megawatts of fusion power, which is a thousand times higher than any existing reactor.

The proceedings from a recent ITER workshop outline the various forms of power input required. A substantial number of very expensive long-pulse or continuous-wave tubes will be needed for this experimental reactor, with the promise of much greater numbers when fusion power becomes a reality sometime in the next century.

I give the foregoing examples to show that there are, in fact, significant future opportunities in high-power microwave tube production. To exploit them, however, industry executives must take a longer term view of their business, a stance that is becoming rather uncommon in our corporate world. So the question arises, will there be a manufacturing facility in this country ten years from now to make these devices competitively, and serve defense needs? Does anybody care? Should anybody care?

At least the scientific community cares, because microwave power sources are the sine qua non of future accelerators as well as tokamaks. There is also an indication that the U.S. government may care, as evidenced by a recent Department of Energy initiative to encourage technology transfer from the national laboratories to industry. This initiative is quite broad and covers a variety of disciplines. It does not represent a governmental industrial policy in the manner of the Japanese or the French, but it does provide the

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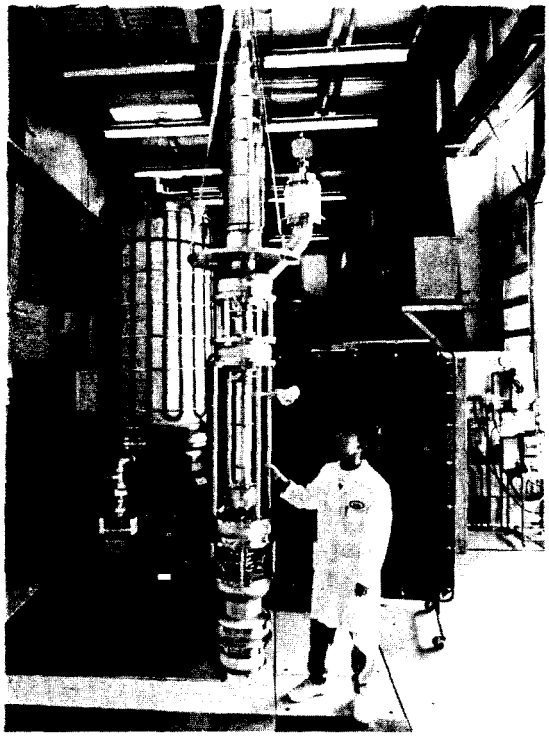

Experimental 500 kilowatt continuous-wave klystron designed for the SLAC B Factory. A 1.2 megawatt tube is under development.

building blocks for one, should industry and government agree that it is necessary.

As yet, there is no such explicit agreement, although there now exists considerable concern at the Pentagon that the U.S. microwave tube industry is in serious decline. At SLAC an experiment is under way to test joint projects between national laboratories and industry as ways to restore this country's industrial superiority in high-power microwave tubes. This class of tubes represents only a small part of the microwave tube industry, which in turn is a tiny (but critical) sector in U.S. manufacturing. If this joint project is successful, however, it could provide a model for rescue operations in other sectors, similarly threatened by foreign competition.

The project consists of pooling the resources of SLAC and a microwave tube manufacturer (Varian Associates) to develop a device of mutual interest. This is very powerful klystron (1.2 megawatts continuous power) essential to the B Factory, a storage ring electron-positron collider proposed for construction at SLAC. It is the same kind of microwave source needed for the ATW proton accelerator mentioned earlier and a product currently available only from French, German, British and Japanese tube manufacturers. The klystron being developed by the SLAC-Varian team incorporates some novel features and should outperform all existing devices. The collaboration will be governed by a Cooperative Research And Development Agreement (CRADA) under which the government and industrial partners make comparable contributions to the project and the industrial partner acquires certain rights to the product design and know-how.

Varian is contributing some important klystron design information. SLAC's contribution will be to supply the manufacturing facility and tube construction know-how. As indicated earlier, SLAC has been manufacturing high-power klystrons for its particle colliders for many years. It has been doing so quite successfully, as far as both quantity and quality of tubes are concerned, with more than 600 tubes produced in the last five years, at an excellent yield. The SLAC expertise is complementary to what remains in the U.S. tube industry and can fill the gaps created by the financial constraints mentioned earlier. Currently, the SLAC klystron laboratory is developing a 100 MW pulsed klystron at 11.4 GHz and has undertaken, on behalf of DESY in Germany, the development of a 150 MW, 3 GHz klystron. Both of these tubes are well ahead of the current state-of-the-art.

If this CRADA is successfully executed, the microwave tubes that will result will be marketed by a U.S. company and will be superior to any foreign tubes. SLAC will have state-of-the-art microwave sources to power the B Factory and will be able to buy them in this country. The cost of the enterprise will have been shared by government and industry. The endeavor could serve as a textbook case of government-industry collaboration.

0022120

Where Are They Now?

by DAVID HITLIN & MICHAEL RIORDAN

SINCE THIS ISSUE OF THE BEAM LINE is concerned with technology transfer, we highlight here another important export from high-energy physics to other areas of endeavor: people. In common with other academic disciplines, this field retains only a fraction of those who received their Ph.D.degree. Some leave immediately afterward, either because of a desire to pursue more attractive or more interesting endeavors, or because of a lack of employment opportunities in the field. Others go on to postdoctoral or junior faculty positions, deciding on a career change only after a number of years.

Sometimes those leaving high energy physics move to another academic discipline. Departments of computer science, applied mathematics and molecular biology, for example, are often populated by people whose training was in particle physics. More often, the move is to the "real world." Their work may involve continued research and development, either in a national laboratory or industrial laboratory, or it may entail a more dramatic shift—to medicine, engineering or even investment banking and management consulting. In some instances, their entrepreneurial skills supplement their technical training, and they launch new high-technology businesses.

We decided to look up some old friends and acquaintances who have moved on to do, as the saying goes, "useful things" in the world at large. We asked them whether their early training in high energy physics had proven valuable to them in their new endeavors. Without exception, we found that these people, who have made their mark in a variety of different fields, found that they had benefited from their years in high energy physics—whether they had worked on theory or experiments.

Here, then, are a few capsule sketches of some of our friends who also add to the export side of the technology transfer ledger.

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Peter Biggs

BORN AND EDUCATED in London, England, Peter Biggs came to the United States in 1970 and worked on a Nobel-prizewinning experiment at the Brookhaven National Laboratory. But he soon made a transition from high-energy physics to medical physics and has never looked back.

Biggs earned his bachelor's degree in physics at Imperial College, and a Ph.D. in nuclear physics at the University of London—doing his thesis research on pion photoproduction at the Frascati National Laboratory in Italy. After four years working as a postdoctoral research associate at the Daresbury Nuclear Physics Laboratory in England, he joined the MIT particle physics research group headed by Samuel Ting. He played a key role in building the particle detectors and other equipment used in the MIT-Brookhaven experiment that discovered the famous *J* particle in 1974, for which Ting was awarded a share of the 1976 Nobel Prize in physics.

Shortly thereafter, Biggs left the field of high-energy physics to pursue an interest in radiation therapy for the treatment of cancer. Starting as an Assistant Professor of Radiation Therapy at the Harvard Medical School in 1975, he began to apply some of the techniques he had learned as a graduate student and postdoc to delivering an optimum dosage of x rays for the elimination of tumors in cancer patients at Boston's Massachusetts General Hospital. This work included detailed studies of the photon and electron beams that were then finding increased use in radiation therapy (See "Little Linacs Fight Cancer" on page 10 of this issue). As part of this work, he developed Monte Carlo computer programs to simulate the radiation dosage and detection techniques to monitor it.

Now Associate Professor of Radiation Therapy at Harvard and Radiation Biophysicist at Massachusetts General, Biggs also serves as a special consultant on radiotherapy physics to other hospitals in the Boston area. He has worked with a local small business on the development of a computer-controlled collimator for medical accelerators and a system to provide fast electronic images of a patient's treatment area. His current interests include the clinical use of these collimators and the development of a "dynamic therapy" technique to maximize the dose delivered to a tumor while minimizing that applied to nearby normal tissue.

Highly regarded in his field of radiation therapy, Biggs was awarded the Farrington Daniels Award by the American Association of Physicists in Medicine. He has clearly found his niche applying the techniques of particle physics to the cure of cancer.

0022122

Terry Braunstein

ONE OF THE FIRST STANFORD GRADUATE students to earn his Ph.D. based on research done at Stanford Linear Accelerator Center (SLAC), Terry Braunstein is now a managing partner of the Strategic Decisions Group in nearby Menlo Park, California. Although it may seem like a distant field of endeavor, he says his particle physics background serves him frequently in his work as a management consultant to major corporations around the world.

Braunstein arrived at SLAC in 1966, just as the first particle beams were turning on. The faculty were "hungry for grad students," he recalls, and he had his pick of experiments. He chose to work on a muon-proton scattering experiment with Martin Perl's group, but its results proved to be fairly inconclusive—confirming that muons behaved much like electrons in these encounters.

In early 1972, while working as a SLAC postdoc, Braunstein began auditing Stanford courses on the subject of decision analysis. He wanted to see if he could pick up any techniques that might be useful to him in the Monte Carlo computer simulations he was then making of a detector used in his experiment. In fact, he didn't learn much of use to high-energy physics because the two sets of techniques were fairly similar, but went by different names. "Those guys were applying these techniques to a completely different world of fascinating problems," he recalls, "Why are cities decaying? Why is the world choking in its own pollution? Why do people make irrational decisions?"

So interested did Braunstein become in this new field, that when the invitation came that fall to join a new decision analysis group at Stanford Research International (SRI), he quickly accepted. This group had been started by some of the same people involved in the Stanford course, and included several other high energy physicists too. Together they developed their own particular, analytical approach to management consulting—using computer simulations based on what he likes to call "decision trees," combined with creativity and change management techniques.

In the late 1970s members of this group, including Braunstein, began to drift away from SRI into various management consulting firms. But five of them came back together in 1981 and founded the Strategic Decisions Group in offices just across Sand Hill Road from SLAC. The firm has grown to include 21 partners and 140 employees today. It is a multimillion-dollar operation with satellite offices in Boston and London—and includes numerous Fortune 500 companies among its clients. Braunstein himself specializes in management of R&D resources and strategic development for technology-driven companies, an area where he says his understanding of science is indispensable.

0022123

Thomas Humphrey

WHILE COMPLETING HIS DISSERTATION in experimental particle physics at the California Institute of Technology during the mid-1970s, Thomas Humphrey became involved in the Exploratorium, a unique science museum located in San Francisco. Thus he began a completely new career that required him to apply his diverse talents to science education and the development of museum exhibits.

After earning a bachelors degree in physics from Notre Dame in 1966, Humphrey went on to Caltech to pursue graduate studies in the field. He ended up in particle physics, eventually joining an experimental team headed by Barry Barish and Frank Sciulli—with whom he did his Ph.D. research at Fermilab on the production of hadrons in high-energy neutrino scattering from atomic nuclei.

Following completion of this research in 1975, Humphrey left the field and took a position as Assistant Director at the Exploratorium. There he worked on the development of interactive science exhibits with its famous founder and Director, Frank Oppenheimer—himself a particle physicist of sorts who had a novel idea for a different kind of science museum. "The Exploratorium had a down-and-dirty feeling that I liked," Humphrey recalls of those early days. "We got to build all our own equipment for the exhibits, something I'd learned to do in high-energy physics." He also liked working in small groups and having the opportunity to educate the general public about science.

From 1978 to 1984, Humphrey took time off to work as a sculptor in Cleveland, Ohio, exhibiting his sculptures in a series of shows and in the prestigious May Show at the Cleveland Museum of Art. He returned to the Exploratorium in 1984 as co-founder of its Teacher Institute, which now forms the core program of its activities as a Science Resource Center for the state of California. He directed these Institutes for three years. They have provided exhibit-based educational experiences for nearly a thousand high school science and math teachers.

In 1987 Humphrey returned to working on museum exhibits as Director of Exhibit Development. In the process of designing and building many different exhibits for the Exploratorium, he made ample use of his diverse talents in science, art and education. Many of these exhibits focus on the subjects of mathematics, sound and perception. Since 1991 he has been serving as Director of the Exploratorium's new Center for Public Education, continuing his deep involvement with the museum's ongoing exhibit and educational programs.

0022124

Jim Martin

JIM MARTIN is Director of the Palo Alto Laboratory of Rockwell International's Science Center. Trained as an experimental high energy physicist at MIT, where he earned his Ph.D in 1971, and at Stanford Linear Accelerator Center (SLAC), Jim has been at Rockwell for nearly 15 years, working in a variety of areas, such as robotics and ultrasonic imaging for nondestructive materials testing. For the last five years Jim was Director of Rockwell's Asia-Pacific Technology Liaison Office in Tokyo, which he founded. Its Palo Alto laboratory is primarily involved in R&D in information science, particularly decision analysis, planning, modeling and diagnostics.

Jim has found his elementary particle physics background valuable in several ways, crediting it with making a difference in his work "time and again." While a knowledge of deep inelastic structure functions is of dubious commercial value, a thorough understanding of scattering theory served him well in his work on ultrasonic imaging, as did his understanding of sophisticated signal processing and modeling techniques such as Monte Carlo simulation. Just as valuable was his orientation toward problem solving and "seeing the big picture," developed through his work on a variety of complex high energy physics experiments. No less useful was his experience in working as part of a large scientific team comprised of physicists, graduate students, engineers and technicians, all organized effectively in support of a long-term goal. The long time scale of high energy physics, even a decade or two ago, made it crucial to look ahead, often several years. This outlook has proven valuable to Martin in many of his endeavors.

Rockwell's Palo Alto Science Center is currently developing decision modeling techniques in a variety of distinct areas, such as remote reporting and diagnostic systems for railway locomotives, automated reasoning as applied to avionics and the planning and modeling of transportation systems. New tools are being developed to speed up complex planning exercises, allowing faster reaction to rapidly changing situations, such as those involving natural disasters and military contingencies. These efforts all require a comprehensive grasp of the detailed functioning of a complex enterprise together with strong computational skills—characteristics routinely acquired by high energy physicists.

0022125

Harry Saal

HARRY SAAL is President, CEO and Chairman of Network General Corporation in Menlo Park, California, which he founded in 1986. Saal received his Ph.D. in elementary particle physics from Columbia in 1969, and then spent the next three years as a Research Associate at SLAC. As his interests turned to computer science, he became Deputy Director of SLAC's Computation Group and then Visiting Associate Professor at the State University of New York, Buffalo.

In 1973 Saal joined the IBM Scientific Center in Haifa and later the General Products Division in San Jose, working first on enhancements to the computer language APL and later on time-sharing systems. An early believer in local area networks, he began Nestar Systems in 1978. In 1986 he went on to start fast-growing Network General, a leader in the field of network diagnostic hardware and software. He was named the Bay Area Software Entrepreneur of the Year in 1990.

Asked about the relevance of his background in basic research, Harry responded with several connections. Because high energy physics is on the cutting edge of research, he stressed, the culture of the field requires rigorous discourse as well as the ability to find new problems and make novel attacks on them. This requires one to see the larger context of a specific problem and to take risks, both of which can be valuable in other endeavors. The focus on difficult problems also requires "pushing the envelope" in technology—both in the application of existing tools and techniques and in the development of new technology. The scale of experiments also requires working in large groups. Indeed, high energy physics experiments may be regarded as the prototype for many large scientific and technical endeavors.

Saal, whose Network General is a pioneer in computer network diagnostics, pointed out another parallel that is rather directly connected with his current interests. He finds an analogy between network analysis and experimental physics. In analyzing the

performance of a complex system such as a network, one begins with a theoretical model of the network, through its protocols, topology and specific hardware. There are as yet no reliable simulations of network performance. However, by observing the time sequence of events occurring on the network, one can develop an experimental construct, which must fit its observable quantities. Its retransmission rates, packet lengths, etc. can be analyzed against the model to draw conclusions about the state of the network. The state of the art at present requires a trained user to interpret the data. In the future, artificial intelligence techniques may make comparisons with the network model a more automatic process. In this area network diagnostic analysis is may well be ahead of experimental physics.

0022126

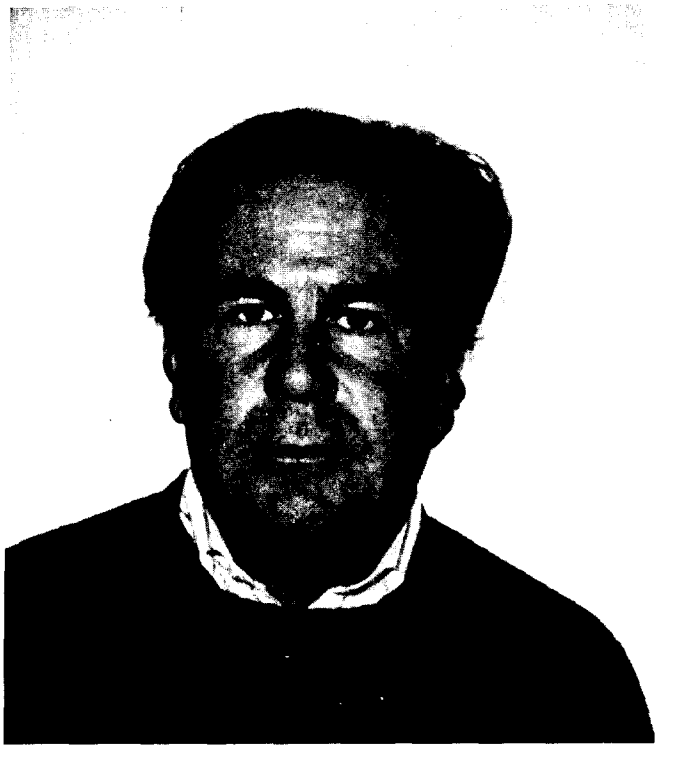
Roberto Suaya

BORN IN ARGENTINA, Roberto Suaya received his Ph.D. in theoretical elementary particle physics from the University of Buenos Aires in 1973 for theoretical research done at Stanford Linear Accelerator Center on quantum electrodynamics. After academic appointments in the physics departments at the University of Illinois, McGill and San Jose State, he entered the world of integrated circuit design, where he is today a leading exponent of the application of automated layout techniques for VLSI (Very Large Scale Integration) circuit design and manufacture. He has pursued these activities at the Fairchild Research Center, at Schlumberger Palo Alto Research and at Stanford Research International. He is currently a consultant to Weidlinger Associates in Los Altos.

"If I had it to do over again, I'd have started my career in precisely the same way," Roberto volunteered as we discussed the pertinence of his training in theoretical physics. Why? "It's a cultural matter. The education in physics is unique in showing you how to select and then attack new problems, characterize them, and bring to bear the appropriate models and mathematical tools. It's a wonderful intellectual exercise!" He has even found that some of the optimization questions he deals with in VLSI are best handled as simulated annealing problems, a technique well known to theoretical physicists.

Roberto also recalled with pleasure the several years in the early 1980s during which he was a Visiting Associate with Caltech's Computer Science and Silicon Structure Project. This pioneering effort, which developed the "Silicon Compiler," a library of digital logic functions designed as actual chip structures, has formed the basis of a great deal of modern integrated circuit practice. Roberto spearheaded silicon compilation research within the industry.

The thrust of the most forward-looking research in VLSI design is the further automation of the chip design process, extending the technology to automatic layout synthesis. These problems are of sufficient complexity that it is often useful to guide the optimization with



Monte Carlo methods, another staple of the physicist's arsenal. These automated design techniques have not reached complete maturity, but they have already proven their ability to reduce the cost of VLSI design and the time required to bring a new project to market.

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CONTRIBUTORS

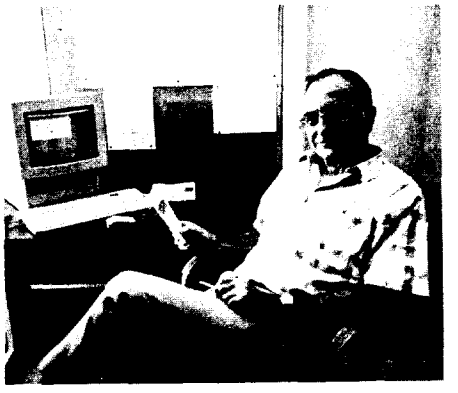
FREDERICK REINES, distinguished professor of physics at the University of California, Irvine, in 1956 co-discovered the neutrino, an elementary particle that interacts so weakly with matter that it could pass unaffected through light-years of lead. A member of the National Academy of Sciences and recipient of the National Medal of Science, Reines was among the first "neutrino astronomers," who observed a burst of the ghostly particles from supernova 1987-A.

JOHN FORD is Vice President of Varian Health Care Systems. He received a Ph.D. degree in physics from the Georgia Institute of Technology in 1972. For the last 21 years he has been involved in the development and marketing of numerous advanced medical products having much experience with medical accelerators. He is currently responsible for coordinating research activities that relate to advanced medical products, and for developing Varian's international markets in health care.

When she enrolled in "Physics 101a: Newtonian Mechanics" as an undergraduate at Columbia University in 1969, JUDY JACKSON little knew that the course was the start of a life-long involvement with physics. Her career as a science writer and editor brought her to Fermilab in 1991; she edits high-energy physics publications for the Laboratory's Directorate.

0022128

ARTHUR BIENENSTOCK is a Professor in Stanford University's Applied Physics and Materials Science & Engineering departments. He has been director of the Stanford Synchrotron Radiation Laboratory since 1978. In recent years, his research has concentrated on the structure of amorphous materials. In the past, he also worked in solid-state physics theory and experiment. He serves on the Science Advisory Committee of the European Synchrotron Radiation Facility and is a Councilor-at-Large of the American Physical Society.



GEORGE CARYOTAKIS is completing his third year as head of the Klystron/Microwave Department at Stanford Linear Accelerator Center. He came to SLAC after a 30-year career at Varian Associates, where he began as a Research Engineer and retired as a Senior Vice President. At SLAC he is involved with the development of very high power klystrons for the Next Linear Collider and for the B Factory. Caryotakis has been active in government advisory committees on microwave tubes and holds several patents on klystron and traveling-wave tube design.

DAVID HITLIN, a Professor of Physics at Caltech, is currently in his third year as Chairman of the SLAC Users' Organization. Active in experiments at SLAC since 1969, his research has emphasized the detailed study of the weak decays of strange and charmed quarks. He has for the past several years been heavily involved in plans to upgrade the PEP storage ring to a high-luminosity asymmeteric energy B Factory for the study of *CP* violation.

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DATES TO REMEMBER

Apr 26–30	Second International Workshop on Physics and Experiments with Linear e^+e^- Colliders, Waikoloa, HI (F. Harris, University of Hawaii, Department of Physics, 2505 Correa Road, Honolulu, HI 96822 or LCSW@UHHEPG or FAH@UHHHEPG).
May 3–5	1st European Workshop on Beam Instrumentation and Diagnostics for Particle Accelerators (Ch. Parthe, CERN, SL Division, CH-1211 Geneva 23, Switzerland, or DIPAC@CERNVM).
May 3–7	4th ICFA Seminar on Future Perspectives in High Energy Physics, Hamburg, Germany (DESY, Notkestrasse 85, 2 Hamburg 52, Germany).
May 6–8	5th Annual International Industrial Symposium on the Super Collider (IISSC), San Francisco, CA (Pamela E. Patterson, IISSC, Box 171551, San Diego, CA 92197).
May 17–20	1993 Particle Accelerator Conference, Washington, DC (C. W. Leemann, CEBAF, 12000 Jefferson Avenue, Newport News, VA 23606 or LEEMAN@CEBAFVAX).
May 31–Jun 4	Physics Computing '93, Albuquerque, NM (American Physical Society, 335 E. 45th Street, New York, NY 10017).
Jun 2–5	Workshop on Physics at Current Accelerators and the Supercollider, Argonne, IL (Argonne National Laboratory, High Energy Physics Division, Bldg. 362, 9700 S. Cass Avenue, Argonne, IL 60439 or MCB@ANLHEP).
Jun 11	Fermilab Users Annual Meeting, Batavia, IL (Joy Miletic, Fermilab Users Office, MS 103, Box 500, Batavia, IL 60510 or USERSOFFICE@FNAL).
Jun 21–Jul 2	Beauty Physics at Proton Accelerators, Snowmass, CO (Vera Luth, SSCL, 2550 Beckleymeade Aveue, MS 2080, Dallas, TX 75237 or BPHYSICS@SSCVX1).
Jun 28–Jul 25	Aspen Physics Program: Workshop on Electroweak Physics at the TeV Scale (Jim Sauls, Aspen Secretary, Department of Physics, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208 or JAS@MAROON.PHYS.NWU.EDU).
Jul 26–Aug 6	21st Annual SLAC Summer Institute on Particle Physics: Spin Structure in High Energy Processes, Menlo Park, CA (Conference Coordinator, MS 62, SLAC, Box 4349, Stanford, CA or SSI@SLACVM).
Aug 10–15	16th International Symposium on Lepton and Photon Interactions, Ithaca, NY (by invitation) (Lepton-Photon '93, Newman Laboratory, Cornell University, Ithaca, NY 14853 or LEPPHO@CRNLNS).
Aug 23–26	Synchrotron Radiation Instrumentation, Gaithersburg, MD (Charles Clark, NIST, A253 Physics Building, Gaithersburg, MD 20899).
Sep 19–23	Third International Workshop on Theory and Phenomenology in Astroparticle and Underground Physics (TAUP 93), Assergi, Italy (by invitation) [Laboratori Nazionali del Gran Sasso, I-67010 Assergi, Italy, phone (862) 437231 or FAX (862) 410795].

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