NEW SOURCES OF RADIATION

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2010-07-01

LBL-9961

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Proceedings of the International School
of Radiation Damage and Protection, Erice, Italy,
September 16-26, 1979

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MASTER

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September 1979

Biology & Medicine Division

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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LBL-9[illegible]

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INTRODUCTION

Man, in all cultures, has worshipped radiation. The most stirring words ever written are the words used in Genesis to describe the Creator focusing His Will that there be light. Now, approximately twenty billion years later, that initial flash of light has cooled to approximately $4^{\circ}K$, but still retains all of its mystery.

In the last one hundred years or so, our knowledge of radiation has increased considerably beyond the visible part of the electromagnetic spectrum discussed in Genesis. Means of producing new and different kinds of radiation have sprung forth from the ingenuity of scientists and engineers, and have been applied in elegant ways to the study of nature and to some of the most pressing problems of society. This process has been so intense and productive that very little remains that is "new" in the sense that it has not been proposed or studied—if not embodied already in an operating device. To that extent, therefore, there are very few "new" sources of radiation; as is well known, there is little, if anything, new under the sun. If this seems regrettable, you should take heart from another human endeavour, the institution of marriage, whose enduring charm it is, precisely, to visit endless renewal upon the known.

In that spirit, we shall consider as new not only the novelty of a device *per se*, but the novelty of its interaction with the world at large. "New sources," then, is to be understood as new sources brought to bear on old problems as well as old sources brought to bear on new problems.

It is impossible to cover the enormous range of endeavours that deal in the production and use of radiation within a single lecture, or even a single course. Indeed, to encompass radiation and its entwinement in the fabric of our civilization would require several careers!

Most of us here will be interested in one particular aspect of radiation: its interaction with matter. It is that knowledge which we wish to expand in order to heal, to diagnose, and to predict, prevent, and assess damage. It should be remembered, however, that the importance of any given source for any given application cannot be foretold. Until lasers became almost household appliances, visible light was not a major hazard; until recently, radiologists operating an x-ray machine in their office did not have to worry about modulation transfer functions for CT scanners, and most physicists innocently thought that pi mesons were nothing but the carriers of nuclear force.

The present discussion is an attempt to select examples of radiation sources whose application may make new or unconventional demands on radiation protection and dosimetry. A substantial body of knowledge about high energy facilities exists and, partly for this reason, the great high energy accelerators will be mentioned only briefly. The textbook by Patterson and Thomas (1973) is recommended for those interested in further details. In addition, many excellent and complete descriptions of the new high energy physics facilities have been published and are easily available to the interested student (Cole and Donaldson, 1977; Hendrickson, 1979).

SOURCES AND SOURCE CHARACTERISTICS

General Features

The sources of radiation to which we shall refer are mostly based on accelerators. The radiation produced still consists, to a large extent, of the familiar charged particles: electrons and protons, as well as neutrons. However, there are several noteworthy developments that will become apparent in the course of this discussion, and attention is called to them here:

1. Accelerators have changed, and can no longer be conceived as a single machine speeding protons or electrons from a simple ion source to a hole in the wall, with perhaps a couple of quadrupoles and a bending magnet thrown in for good measure. New particle accelerators are complex systems of accelerators, beam transport and beam storage elements, each of which performs a specialized function in a carefully optimized region of phase

space. The name of the facility often is only a reflection of its most important application. Thus, a "storage ring" or a "synchrotron radiation facility" may both be based on the same accelerator system, even though emphasis is given to the main purpose of application.

The engineering insouciance associated with this drastic change in the scale of operations is not restricted to the more exotic high energy physics machines. For example, the University of Western Ontario, in Canada, has built a variable energy racetrack microtron for therapy that includes a full-fledged electron linac instead of an accelerating cavity. In a later design, called a "shuttle microtron," electrons are accelerated back and forth along a linac, and steered back into the accelerator by an appropriately shaped magnetic field (Froelich et al., 1973; 1977). (The design of these machines was motivated by the search for small, inexpensive, variable energy machines for radiation therapy in the 30-MeV region.) Similarly, new designs for megavolt electron microscopes have discarded the old-fashioned electron gun, and use symmetrical cascade generators, i.e., an electron accelerator (Reinhold and Gleyvod, 1973).

2. The above developments have come about, to a large extent, as a consequence of the advances in the theoretical understanding of the physics of particle beams. This has made possible acceleration cycles where antiprotons, made on a tungsten target with 80 GeV/c protons at Fermilab, will be collected for injection into the booster synchrotron and decelerated to 200 MeV, for transfer into a storage ring and electron cooling (i.e., reduction in the spread of transverse velocities) before being accelerated to 400 GeV. At the high beam currents necessary for storage rings, when the particles can no longer be treated as approximately independent, the theory of these machines overlaps considerably with the physics of plasmas. Even at lower intensities, one could reasonably ask whether, for example, the shuttle microtron is not really a magnetic mirror machine. Indeed, a recent textbook on charged particle beams provides such a unified treatment of ion sources, accelerator beams, and plasmas (Lawson, 1977).

3. A further development that has played an important role in the design, operation, and use of the new sources of radiation has been the availability of high-speed computers. These have contributed to advances in the theoretical understanding of particle beams and plasmas by making sophisticated calculations possible. Computers provide fast and extremely complex control functions and data acquisition and analysis are unthinkable without them. The same is becoming true of radiation therapy

and diagnosis. The availability of microprocessors is expected to have a similarly revolutionary effect on the field.

4. Superconductivity is quickly becoming an established technology. Projects under way to achieve the highest beam energies, the Energy Doubler at Fermilab and the ISABELLE colliding beam facility at Brookhaven, are based on superconducting magnets. The quantities involved (e.g., 516 dipoles and 372 quadrupoles in the case of ISABELLE) are already on an industrial scale. At the lowest beam energies, a superconducting storage ring has been built for very cold (10^{-6} eV) neutrons, using the "ultracold" neutron beam of the High Flux Reactor at the Institut Laue-Langevin in Grenoble (Kugler et al., 1979). This machine achieves beam bending by coupling the 3.5 T guiding magnetic field to the magnetic moment rather than the (inexistent) charge of the neutron. For this reason, one order higher multipole magnetic fields are required than for electrically charged particles, and quadrupole magnets must be used for bending while sextupole magnets are used for focusing. Thus, super-conductivity may be expected to become as much a part of new radiation sources and their applications as, e.g., RF engineering.

5. Secondary radiations (e.g., neutrons, synchrotron radiation) were often considered a nuisance in the past because they interfered with experiments and required extensive shielding. They have now become the source of some of the most interesting applications. It is perhaps a reflection of the Zeitgeist that the recycling of "waste" radiation has become one of our more productive efforts. Intense pulsed neutron sources are at various stages of planning or operation in Canada, Great Britain, Japan, the U.S., and the U.S.S.R., mainly based on accelerators. Use of these sources has become one of the most general experimental methods in condensed matter research, yielding information that, in many cases, is inaccessible by any other technique. Applications spanning biology, chemistry, physics, and materials research are constantly increasing. The use of neutrons from a high energy proton linear accelerator incident on a molten-lead target to produce fissile fuel from a surrounding blanket of U-238 or Th-232 has also been proposed in the accelerator breeder concept (Steinberg et al., 1977). This idea has the notable advantage that, if depleted fuel elements are irradiated, reprocessing steps (and the concurrent risks of diversion) are minimized. The most spectacular use of "waste" radiation is, of course, that of synchrotron radiation, to be discussed in somewhat more extent below. Here, it should be pointed out that the design of the latest storage rings, such as PEP, actually requires synchrotron radiation as a mechanism for damping undesirable oscillations.

6. In the case of charged particles, the charge state has become an increasingly important parameter that requires attention but is also a means for great design flexibility. Negative ion sources, especially H^-, are more and more common at high energy accelerators and provide the energy resolution necessary to study nuclear energy levels. These sources have long been an intrinsic part of tandem accelerators, which now play such a prominent role in the new generation of heavy ion machines. An understanding of charge exchange is also vital for the improvement of neutral beam injectors in magnetic fusion devices. These are, in a sense, neutral beam accelerators. If this seems odd, the neutron storage ring discussed above is a similar example, pointing out that current advances require great care in applying conventional thinking to new sources of radiation.

Source Parameters

A new source of radiation, to be new, must have a quality of excess to meet the name; it must do something, at least, better than any other device. Whether this requirement, that a machine give evidence of miracles before it is technologically canonized, is a psychological quirk or not, it is based on the reasonable need for certain desirable design characteristics.

These design parameters arise because there are time and space scales associated with the systems with which the radiation interacts. In addition, there is also a "truth scale," which determines the significance of the interaction, and is usually referred to as "statistics." More appropriately, the information content to be derived from the interaction is also called the "signal-to-noise ratio."

The spatial extent of the interacting system determines the necessary energy of the radiation. At the quantum-mechanical level, the wavelength of the radiation must be comparable to the dimensions of the structure being studied, whether a quark or a crystal, and this specifies the energy or momentum. Macroscopically, the range of heavy charged particles in matter is determined by their energy.

Fluorescence decay or charge collection times in detectors influence the desired time scale of the beam, as does the doserate dependence of biological systems and the immobilization time of a patient.

Most of the effects due to radiation have a small probability of occurrence. In order to measure the effect reliably, it is necessary to have a large flux of radiation or a large number of detectors, or both. The large signal-to-noise ratio of life is sustained by nature, using solar energy and a great number of detectors—also known as "plants." Clinical trials are a similar means of achieving high information content.

Radiation generally comes in beams that are not parallel. The brightness is a measure of the source flux density per unit solid angle. It is inversely proportional to the square of the emittance (Lawson, 1977), an all-important quantity describing the extent ("beam spot") and divergence of a beam, as well as its momentum spread and relative timing. The emittance contains all the information about the beam and, accordingly, the beam entropy can be defined as the logarithm of the emittance in units of the area of a phase-space cell. In the case of colliding beams, the intensity-related quantity is called luminosity, and is proportional to the product of particle densities in each beam and the interaction volume. One of the most important consequences of the advances in accelerator theory has been the design of accelerator optics capable of focusing a maximum intensity of particles into the volumes compatible with required source dimensions.

APPLICATIONS AND EXAMPLES

A limited sampling of applications of both old and new radiation sources is given in Table 1, under headings that may seem exaggerated only upon a first examination. In the remainder of this lecture, we shall comment briefly upon a few selected examples.

In the life-and-death category, the greatest impact on medicine can be expected from meson factories and heavy-ion accelerators, which may well end up being complementary rather than competing modalities. The possible therapeutic advantage of these two types of radiation derives from their dose distribution in matter and the high rate of energy deposition (LET) in a selectable depth of material.

It should be emphasized that the direct benefits from the application of these types of radiation to therapy are not the only medical application and may not even be the most important one. Technology does not progress in isolation, and the development of meson factories has already resulted in the incorporation of the side-coupled electron linac into most clinical units used in the United States (Rosen, 1971). Radioactive secondaries from nuclear interactions of heavy ions have been refocused into radioactive beams at the BEVALAC (Alonso et al., 1979), and implanted noninvasively in test animals. The usefulness of beams of radioactive iodine, gallium or technetium,

Table 1. **Some Applications of Old and New Radiation Sources**

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1. Life and Death
   - Radiation therapy
   - Radiation biology and biochemistry
   - Radiology
   - Radiopharmaceuticals
   - Radioisotope implantation
   - X-ray diffraction (synchrotron radiation)
   - Neutron diffraction
   - Electron microscopy
2. War and Peace
   - Weapons neutron research
3. Energy
   - Inertial fusion
   - Neutral beam injection
   - Magnetic confinement fusion
   - Well-logging
   - Ion implantation (solar cells)
   - Spallation breeder
4. History and Origin of the Universe
   - Simulation of big bang with heavy ions
   - Radioisotope dating
   - Cosmic rays
   - Nucleosynthesis
5. The Fundamental Laws of Nature
   - Nuclear physics
   - High energy physics
   - Radiation chemistry
   - Nuclear chemistry
6. Technology and Civilization
   - Ion implantation
   - Paint curing
   - Microlithography
   - Analysis of materials
     - Neutron activation
     - Induced x-ray emission
     - Backscattering
   - Wear and corrosion studies
   - Criminology analysis
   - Crystallography

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that can be made to stop inside any desired organ without the need to inject voluminous pharmaceuticals and circumvent the blood-brain barrier, can be easily visualized. Finally, the sophisticated diagnostic and therapy techniques required to take full advantage of these facilities are likely to have a revolutionary impact on medicine as a whole.

Some of the salient features of the meson factories are summarized in Table 2. These machines have been built primarily for physics research, and hence the emphasis on duty factor, variable energy and energy resolution, which will allow very precise studies of effects associated with nuclear energy levels.

The use of H^- beams is the reason for the recently achieved energy resolution of TRIUMF, as well as for some of the problems that this facility had to solve. The binding energy of the electron in H^- is only 0.75 eV, so that any collision, even the slightest, will remove this electron and the residual hydrogen atom will be lost from the beam during acceleration. In the rest frame of the H^-, however, the magnetic guiding field B appears as an electric field of strength $0.3\ \beta\gamma B$. Therefore, the maximum field that allows for an H^- lifetime comparable to the acceleration cycle is ~5 kG, leading to a much larger machine.

The advantage of this sensitivity of H^- to collisions is that, in a knife-edge, the neutral H atom traversing a very small thickness of material will emerge, while at greater thicknesses it is stripped to H^+ and bent away. Thus, beams with very small radial emittance (correspondingly well-defined in energy with respect to the acceleration cycle) can be produced. Such microbeams may also be of great interest for possible applications to biology and materials science.

Figure 1 is a schematic of the Los Alamos beam areas. Note the large fraction of beams that are dedicated to applications. It is interesting to note that the Weapons Neutron Research Area is not intended to serve aggressive purposes. In fact, the director of the facility has argued very eloquently that the availability of such facilities to the major powers is an important factor in achieving a comprehensive test ban treaty. Figure 2 is a picture of the Swiss Institute of Nuclear Research machine. The ring cyclotron is another instance of the imaginativeness of modern accelerator designers, where the conventional distinction between a cyclotron and a synchrotron has become slightly blurred. Figure 3 is a schematic diagram of the TRIUMF beam lines. Here, the thermal neutron facility, which provides thermal neutron fluxes of 10^{-12} $cm^{-2}s^{-1}$ is not only competitive with a nuclear reactor, but actually compensates for the lack of one in Western Canada.

Table 2. Meson Factories

Laboratory	Accelerator Type	Maximum Proton Energy (MeV)	Design Current (μA)	Maximum Achieved Current (μA)	Duty Factor	Comments
Clinton P. Anderson Meson Physics Facility, Los Alamos USA	Proton linac (800 m long)	800	1000	500	6%	Full energy in 1972. Can accelerate H^+ and H^- simult. Cockroft-Walton injectors, drift-tube linac to 100 MeV, side coupled linac to 800 MeV. $\Delta p/p \approx 0.25\%$.
Swiss Institute for Nuclear Research, SIN, Villigen, Switzerland	Ring cyclotron	590	100	112	100%	Full energy, Jan. 1974. 72 MeV sector focused cyclotron injector; separated 8-sector cyclotron with 4 RF cavities to 590 MeV. $\Delta E/E = 0.07\%$.
TRIUMF, Vancouver, Canada	Sector-focused H^- cyclotron	500	100 (500 MeV) 300 (450 MeV)	100 (at 1% duty factor)	100%	Full energy Dec. 1974. Large radius (310 m), 4000-ton magnet to keep H^- together. $\Delta E/E \approx 0.01\%$ (173±12) keV at 200 MeV. Variable energy 180-520 MeV.
Institute for Nuclear Research Moscow, USSR	Proton linac	600	500	—	1%	Under construction. Low duty factor for high instantaneous intensity (e.g., neutrino experiments)

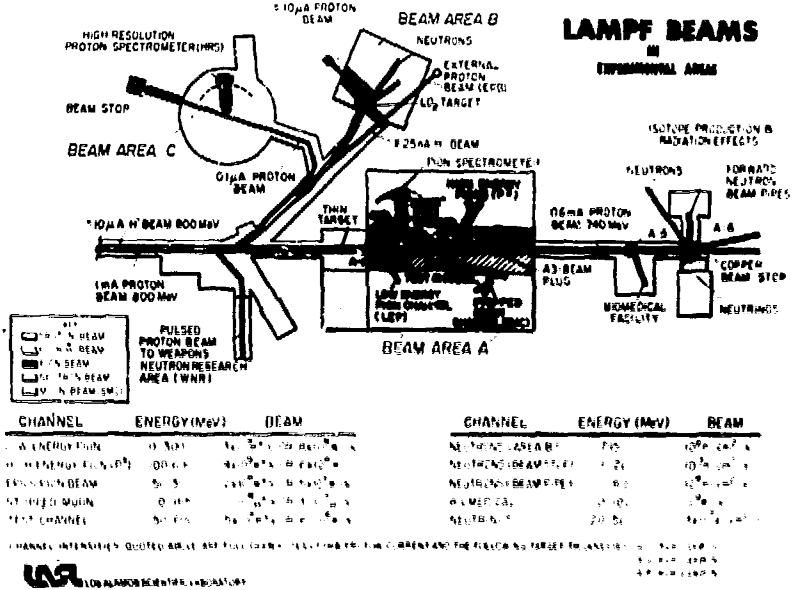

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Fig. 1. Schematic diagram of beam areas at the Los Alamos Scientific Laboratory Clinton P. Anderson Meson Physics Facility. Courtesy of J. DiCello Los Alamos Scientific Laboratory.

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Fig. 2. A view of the ring cyclotron at the Swiss Institute of Nuclear Research. Courtesy of Dr. Hans Blattmann, SIN.

Heavy ions, i.e., beams of atomic nuclei from helium to uranium, are potentially the most versatile new sources of radiation. They are currently undergoing clinical trials at the BEVALAC in Berkeley (U.S.) together with an extensive program in radiation biology and chemistry. The use of radioactive beams has already been mentioned, and radiography with heavy ions is also being actively studied. In the energy category (Table 1), heavy-ion beams are a promising contender for inertial fusion, and various studies are also being pursued in that direction. Ion implanation by low energy beams of boron is now a known technology, and holds some promise in developing solar cells with efficiencies that may make direct solar energy conversion economically competitive. Figure 4 is a view of the Mark I device developed by the Western Electric Company in the U.S. (Rodue et al., 1974). This 300 kV ion implantation device produced maximum currents of 60 μA $^{11}B^+$, 90 μA $^{31}P^+$, and 110 μA of N_2 , and has since been replaced by more advanced models giving throughputs of 200 two-inch wafers/hour for doses up to $2 \times 10^{14}/cm^2$.

Deductions about the origin and the confinement time of cosmic rays in the galaxy depend upon a knowledge of heavy ion

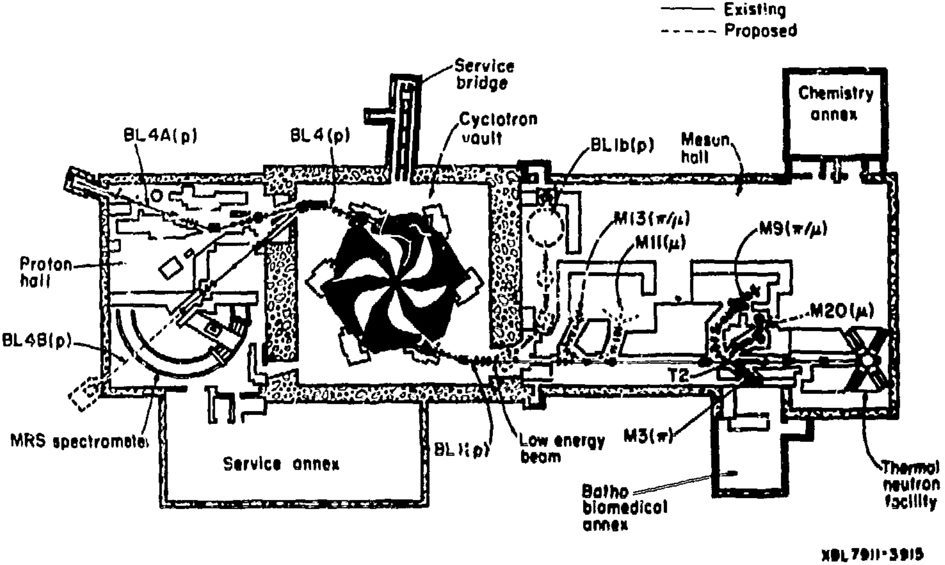

Fig. 3. Schematic diagram of beam areas at the TRIUMF facility. Courtesy of TRIUMF Laboratories.

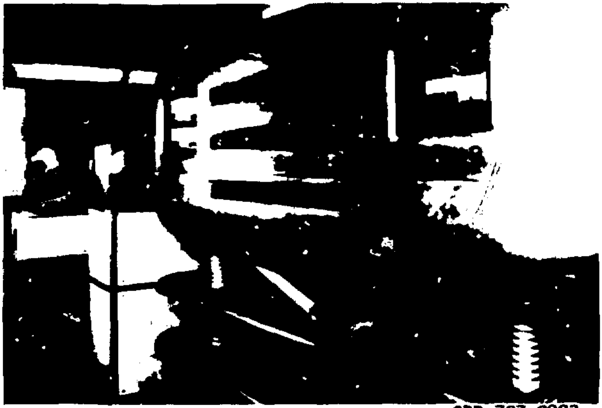

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Fig. 4. Mark I ion implantation device developed by the Western Electric Company. Courtesy of Western Electric.

cross sections and their role in depleting the observed cosmic ray fluxes in the interstellar material. On a shorter time scale, the use of heavy-ion accelerators, such as the 88-inch Cyclotron at Berkeley, as a mass spectrometer for radioisotope dating has opened up an entirely new field of research (Muller, 1977). Finally, heavy-ion beams are being used in studies of nuclear matter, where entirely new phenomena, such as pion condensation and the formation of quark matter, have been predicted for velocities of the incident heavy nucleus sufficiently high to compress the target nucleus to several times its normal density.

As a consequence of this, there are more than sixty proposed and existing heavy-ion facilities in the world at present. Most of these projects are for heavy-ion machines with energies below approximately 100 MeV/A (Ball, 1977), and an excellent recent review of the field may be consulted for further details (Grunder and Selph, 1977). The energy per nucleon to be achieved at the planned facilities is plotted as a function of atomic mass in Fig. 5 for the low-energy facilities. Of

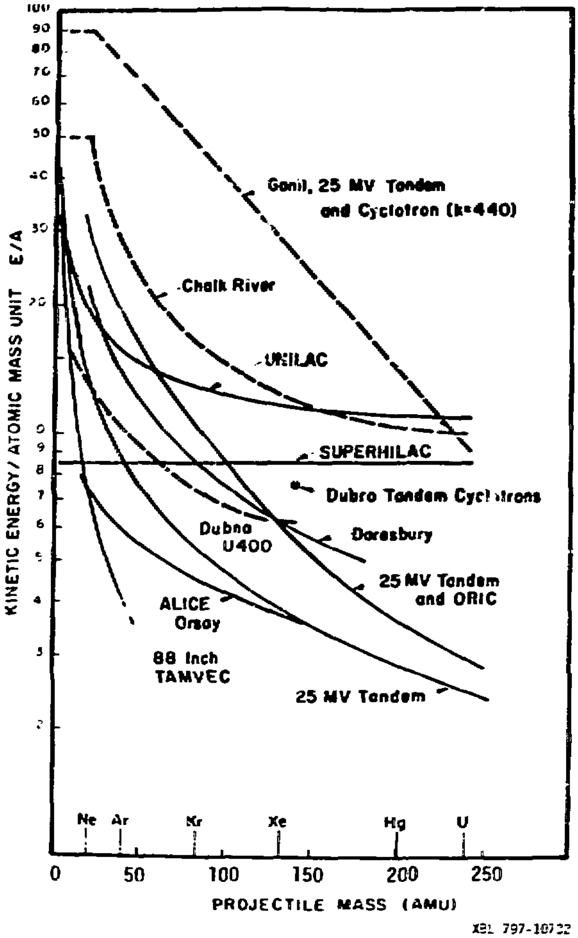

Fig. 5. Energy per atomic mass unit as a function of projectile mass for low-energy heavy ion facilities. Courtesy of J. Ball, Oak Ridge National Laboratory.

these, the recently completed Phase I at Oak Ridge is a good typical example. It consists of a "super-tandem," a 25 MV Pelletron (Herb, 1971) constructed by the National Electrostatics Corporation, and the Oak Ridge Isochronous Cyclotron (ORIC), a combination known as the Holifield Heavy Ion Research Facility (HHIRF). This machine uses a charging chain of metal cylinders, rather than a belt, as shown in Fig. 6. A schematic of the HHIRF machine is shown in Fig. 7. It constitutes a major departure from the traditional tandem configuration in that the

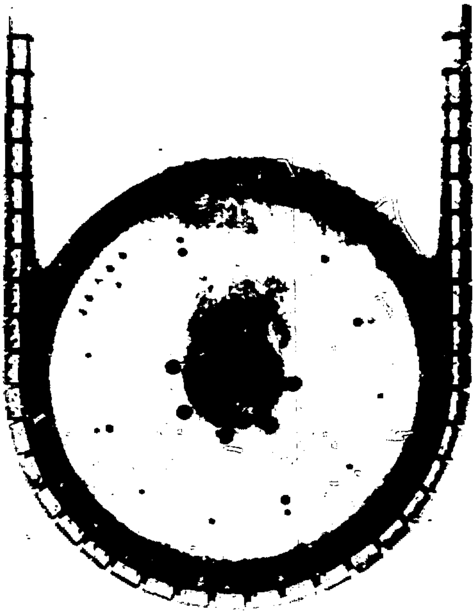

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Fig. 6. Charging chain of metal cylinders used in the Pelletron electrostatic accelerator. Courtesy of G. Norton, NEC.

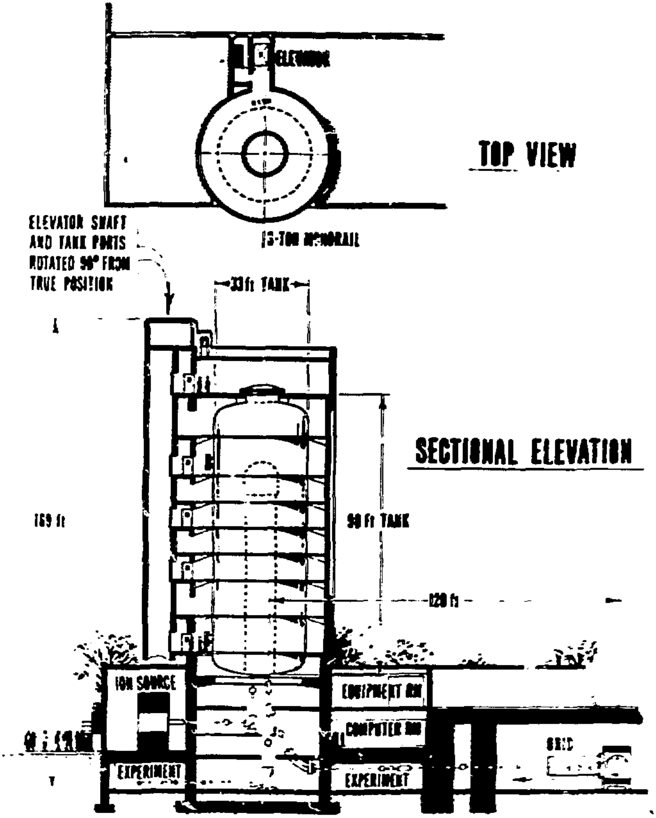

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Fig. 7. Schematic diagram of the Holifield Heavy Ion Research Facility in Oak Ridge, TN. Courtesy of J. Ball, Oak Ridge National Laboratory.

accelerator has a "folded" structure, with both low and high energy acceleration tubes in the same column. Negative ions are accelerated upward into the HV terminal, stripped to positive ions, and accelerated downward to the final potential. The pressure vessel is 30 m high and 10 m diameter, making such an arrangement possible. At 7 atm, it requires 100,000 kg of SF6. Beam energies will be 25 MeV/A for light ions and 6 MeV/A for A up to 160. A new booster cyclotron to raise this energy to 500 q^2A^2 is planned in Phase II of the design.

The use of heavy-ion accelerators in the region just around 100 MeV/A is being seriously considered for driving inertial confinement fusion (Godlove, 1979). This approach to fusion aims at compressing a deuterium-tritium pellet by a factor of 10^4 by implosion with a short (~10 nsec) pulse of radiation, in order to obtain the high plasma densities required for ignition. The use of lasers and light charged particles, also pursued vigorously at this time, may result in preheating (and consequent expansion) of the pellet due to Bremsstrahlung. Heavy ions are attractive because they do not present this problem, and also because the high energy of the particles and their large stopping power reduce the peak current requirements from megamperes to kiloamperes. Table 3 shows some of the characteristics that such a driver might have. Current thinking envisions a three-stage program, consisting of an Accelerator Demonstration Facility (ADF) to perform the necessary research and development, followed by a Heavy Ion Demonstration Experiment (HIDE) and a final stage for initial studies of reactor design, an Engineering Test Facility (ETF).

The prospect of heavy-ion fusion, as well as many other applications depending on intense, high energy pulsed beams, are closely related to progress in pulsed power technology. One of the more significant concepts in this regard is that of the linear induction accelerator (Faltens et al., 1977; Leiss, 1979). A possible configuration is shown schematically in Fig. 8. In this configuration, an electromagnetic pulse produced by a switched high-voltage generator is used to accelerate the beam through the cavity. In other configurations, known as "core-type," a rapidly changing magnetic flux is used to accelerate the charged beam. When a large number of such independently phased modules are threaded by a charged particle beam, they can be thought of as a linear betatron. Such linacs have been built and operated (at lower power levels than required for fusion) for many years, with great reliability. The modular construction makes the induction linac attractive because it places relatively modest demands on each module, which results in greater reliability and lower cost. Approximately 10^4 such modules are envisioned in a 5-km long accelerator for a power plant igniter system.

Table 3. **Heavy-Ion Driver Characteristics**

("Uranium" Ions, Charge = +1 to +4)	
Beam Energy	1 MJ
Beam Power	100 TW
Kinetic Energy	5 to 25 GeV
Range	0.1 to 1 gm cm^{-2}
Specific Energy	20 to 100 MJ/gm
Target Radius	1 to 5 mm
No. of Beams or Clusters	2 to 4
Beams/Cluster	1 to 5
Current/Beam	2 to 7 kA

Physics

- Energy deposition profile understood (classical)
- Beam propagation focussing tractable

Technology
- Mature
- Techniques for high current exist but need demonstration

All fusion reactors, of whatever type, should produce significant numbers of neutrons. What may not be immediately apparent is that most of the magnetic confinement experiments will use high power neutral beam injectors to heat the plasma (Kunkel, 1979), and that these "neutral" beam injectors are themselves sources of substantial fluxes of neutrons (Berkner et al., 1979).

A schematic of a typical neutral beam injection system is shown in Fig. 9. The most critical item in these systems is the ion source, which has to supply tens of amperes of ions more or less continuously, so that well-collimated beams can be formed in simple electrostatic accelerating structures. These are a

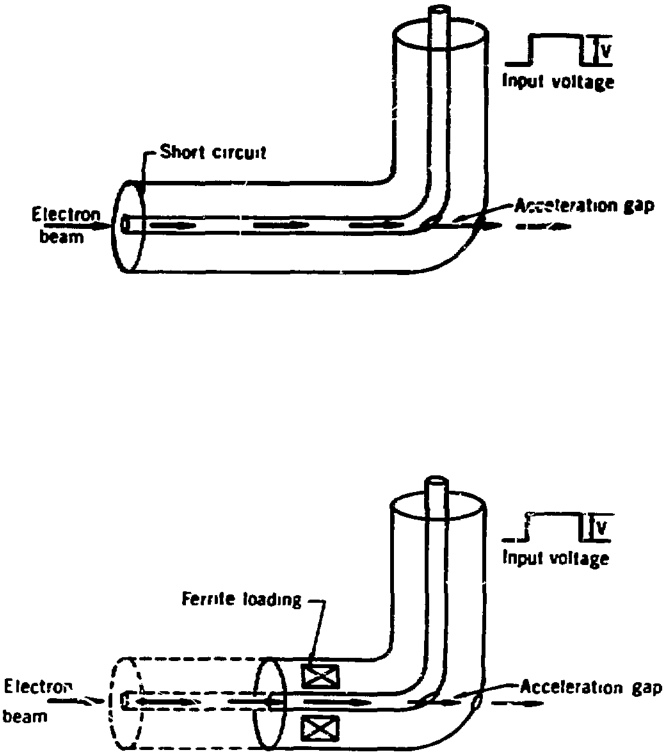

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Fig. 8. Evolution of induction accelerating cavity. Courtesy of D. Keefe, LBL.

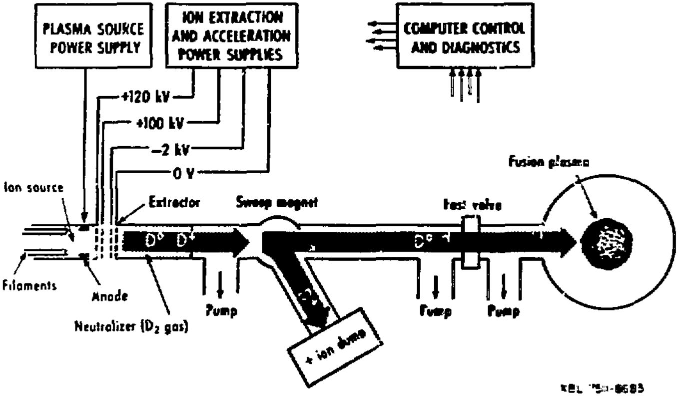

Fig. 9. Schematic diagram of a typical neutral beam injection system for plasma heating. Courtesy of R. Pyle, LBL.

set of grids with aligned apertures in the case of the Berkeley systems. Positive ions are currently used and neutralized in a gas. The efficiency for producing neutral ions is rather small, and efforts to produce negative ion sources with the required intensities are under way.

The large amounts of neutralizer gas must be pumped out to avoid reionizing the neutral beam emerging from the sweep magnet. Accordingly, the Berkeley facility, shown in the photograph of Fig. 10, has a large (170,000ℓ) vacuum system. The spherical chamber seen in the photograph is part of this system, serving to expand and lower the pressure of residual gas. This facility has produced 1 MW of power at 120 keV energy (Berkner et al., 1977). Four such beam lines are envisioned for the Tokamak Fusion Test Reactor (TFTR) currently under construction at Princeton.

Most of these injectors will operate with deuterium, and thus will generate neutrons from the d-d interaction between the beam and the neutralizer. Deuterons in the beams (both charged and neutralized) will become imbedded in materials that they strike, and will thus become high-density targets for following beam particles, resulting in more neutrons. A measurement of the absolute yield of neutrons at various shaping currents and a

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Fig. 10. Neutral beam injection test stand at the Lawrence Berkeley Laboratory. Courtesy of R. Pyle, LBL.

comparison with calculations are shown in Fig. 11, taken from Berkner et al. (1979).

The only facility currently producing relativistic heavy ions for research and biomedical applications is the Berkeley Bevalac, which can accelerate heavy-ion beams with charge-tomass ratios of 0.5 up to 2.6 GeV/u. A schematic view of the facility is shown in Fig. 12. Its injector system consists of two Cockroft-Walton accelerators, one air-insulated at 750 kV and the other pressurized at 2.5 MV, either of which can inject into the SuperHILAC, an Alvarez-type linac of 8.5 MeV/u. The beams from this machine are then transported via a 250-m long transfer

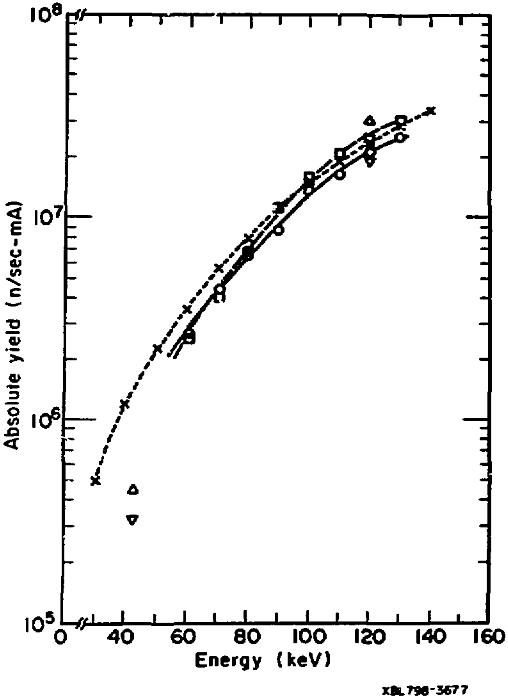

Fig. 11. Neutron yield as a function of deuteron energy in a neutral beam injection line. Courtesy of J. McCaslen, LBL.

line to the Bevatron, a weak focusing synchrotron. The Bevatron vacuum of 2 x 10^{-7} Torr allows only acceleration of fully stripped beams. An improvement program, involving the installation of a high-vacuum liner shown schematically in Fig. 13, is planned, and will allow acceleration of uranium and partially stripped ions.

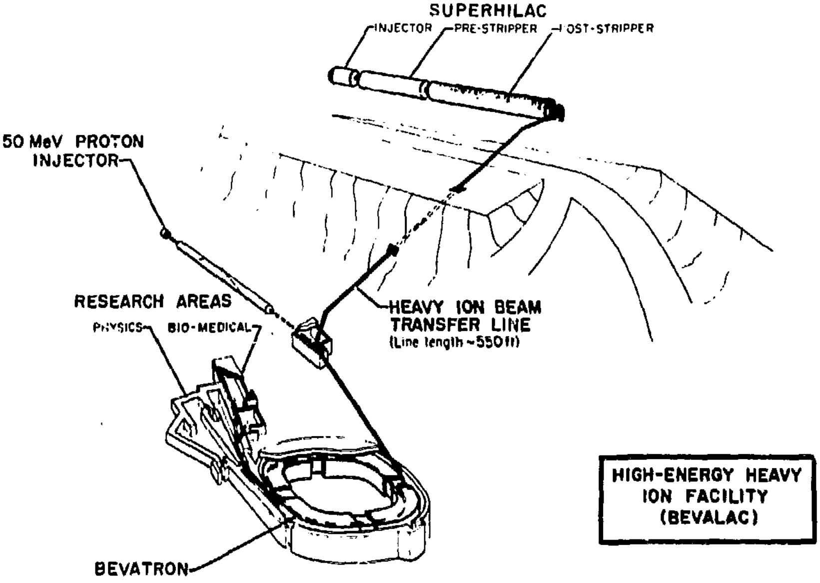

Fig. 12. The BEVALAC: A high-energy heavy-ion facility at LBL.

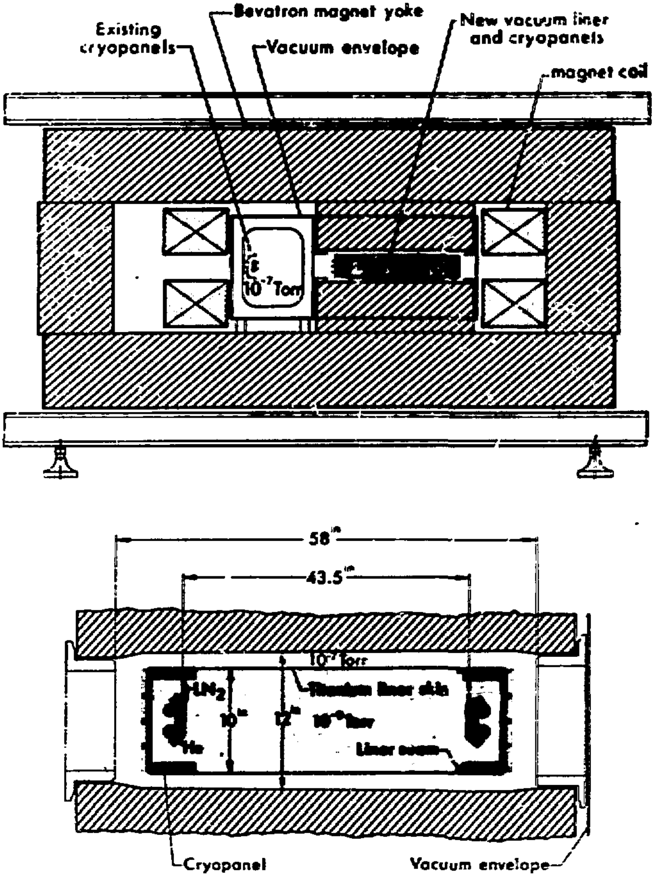

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Fig. 13. Proposed vacuum chamber liner for uranium acceleration at the LBL BEVALAC. Courtesy of H. Grunder, LBL.

Several projects to build facilities for the production of multi-GeV heavy ion beams are currently in the proposal and design study stage. At the Gesellschaft fuer Schwerionenforschung (GSI) in Darmstadt (Federal Republic of Germany), the project to accelerate uranium to energies up to 10 GeV/u, is envisioned as a three-part program summarized in Table 4. In the first stage, their present accelerator, the UNILAC (Fig. 14), will be upgraded by inserting new acceleration cavities in the Alvarez linac section.

The second stage involves the construction of a strong-focusing, separated function synchrotron, the SIS-100, shown schematically in Fig. 15. It will accelerate ions with q/A between 0.042 (corresponding to U^{10+}) and 0.5. The final energy will be variable between 20 MeV/u and 14 GeV/u. The machine will have a mean radius of 125 m and a circumference of 785 m. Use of superconducting magnets is not planned in order to ramp the magnetic fields at rates up to 2 T/s. There will be 12 RF accelerating cavities operating on a frequency range of 0.83 to 7.6 MHz with acceleration at harmonic numbers of 20 or 40. The vacuum in the machine will be approximately 10^{-11} Torr.

The final stage of this proposal would involve design and construction of a high intensity preinjector for the UNILAC to take advantage of the high currents produced by sources for single and double-charged ions.

Table 4. SIS Project

Energy	Intensity (sec^{-1}) Neon	Intensity (sec^{-1}) Uranium	Injection energy (MeV/u)	Target Date
2 to 20 MeV/u	10^{13}	2×10^{11}	-	1981-1982
20 to 140 MeV/u	10^{11}	10^{10}	1.4	
0.1 to 14.1 0.1 to 7.3 GeV/u	5×10^{9}		5.9	1984
0.5 to 14.1 0.5 to 8.8 GeV/u	3×10^{10}	5×10^{8}	20	1986

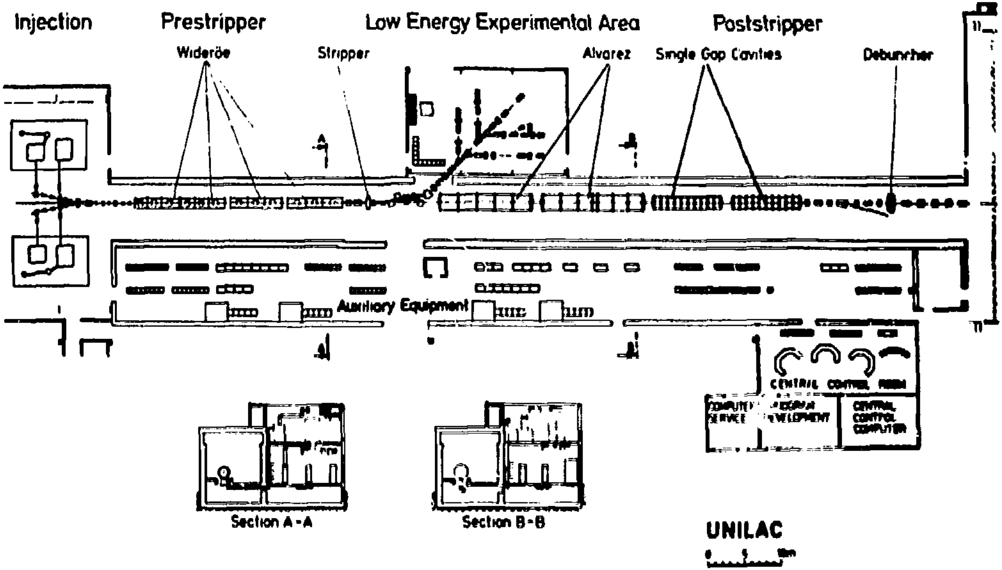

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Fig. 14. Schematic diagram of UNILAC experimental beam areas. Courtesy of UNILAC.

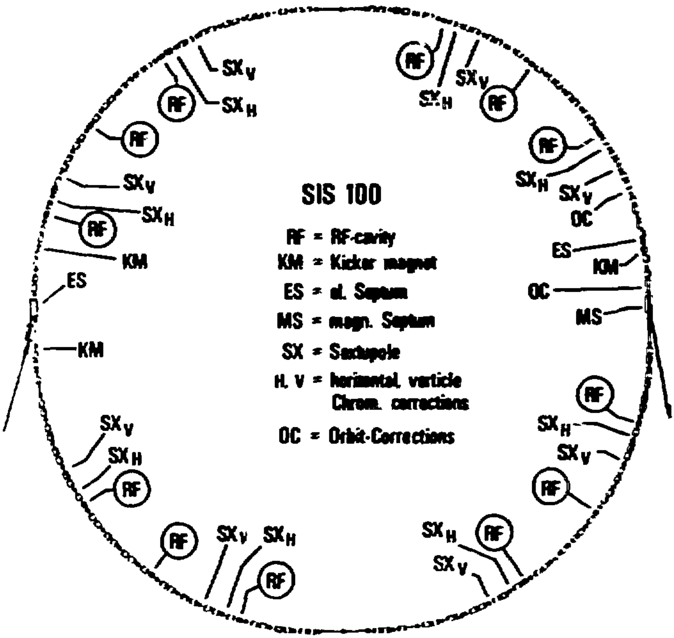

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Fig. 15. Schematic diagram of SIS-100 synchrotron planned at Gesellschaft fuer Schwerionenforschung in Darmstadt, West Germany. Courtesy of that laboratory.

Operation of the SIS project is planned for 1986, at an estimated cost of 190 million German marks.

The VENUS (Variable Energy Nuclear Synchrotron) project presently under study at the Lawrence Berkeley Laboratory in the United States, is intended to satisfy the requirements outlined in Table 5. An approach that is expected to fulfill these is to combine an accelerator and storage ring in a single facility without sacrificing the performance of either component. The scheme proposed is shown in Fig. 16, and consists of two identical superconducting rings, located inside a single tunnel,

Table 5. **VENUS Capabilities and Design Criteria**

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1. Intense ion beams of all masses, from protons through uranium.
2. Low energies to 40 MeV/A, overlapping the range of the 88-inch Cyclotron.
3. Intermediate energies at intensities significantly greater than those at the BEVALAC.
4. Highest beam energies well above the BEVALAC range, i.e., to 20 GeV/A for the heaviest ions.
5. Center of mass energies $E_{CM}/A = 40$ GeV/2A or more with colliding beams of equal mass nuclei (i.e., the total CM energy available is 20 GeV times the number of nucleons).
6. Construction and operation should be as economical as possible, with minimum power consumption and staffing requirements.
7. Flexible for adaptation to future research and operating criteria.

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with the SuperHILAC as injector. One ring would serve as SuperHILAC booster to accelerate the 8.5 MeV/A injected ions to about 1 GeV/A. At this energy they can be stripped without significant losses and transferred to the second ring for acceleration to a maximum of 20 GeV/A for the heaviest ions, up to 25 GeV/A for light ions, and 50 GeV for protons.

The S-shaped reinjection line is used for storage ring-colliding beam operation: half the particles at the desired energy would be split from one ring and reinjected in the opposite direction (reversing the magnetic field) into the other ring. Two different heavy ion beams can also be stacked in one ring and separated subsequently for colliding beam experiments. Both rings are to consist of the same configuration of superconducting magnets, and are referred to as Ring 1 and Ring 2.

In the colliding beam mode, approximately 100 pulses would be accumulated. Three interaction regions are presently planned. In these, as in all storage rings, it will be necessary to have small transverse beam dimensions to maximize the luminosity. For the heaviest beams, 200 particle-milliamperes seem to be a reasonable expectation for the attainable currents. The luminosity for the heaviest ions at 10 GeV/u has been estimated at 10^{29} cm^{-2} s^{-1}. This is somewhat less than that of high-energy physics storage rings, but the cross sections for heavy ion reactions are expected to be higher, so that comparable event rates will be obtained. At 10^{-11} Torr

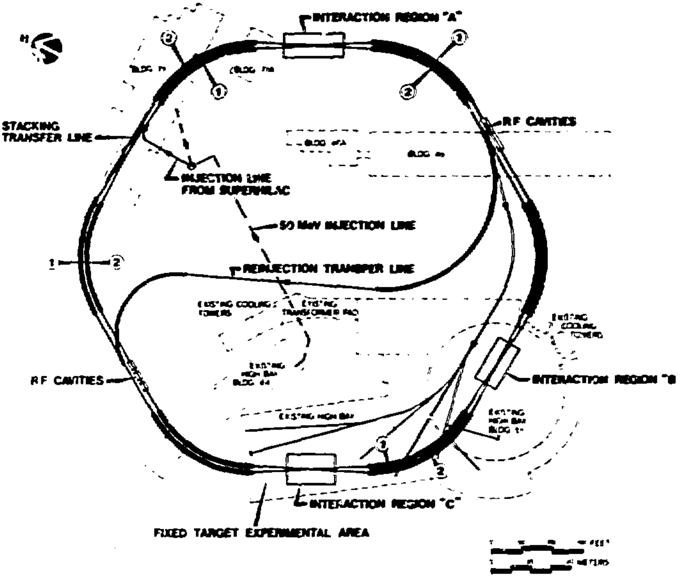

Fig. 16. VENUS: A relativistic ion synchrotron and storage ring, LBL.

vacuum, good beam quality and intensity should be maintained for a few hours.

The ring tunnel elevation will be below the present Bevatron and its experimental hall. For fixed target operation, the beam would be extracted from Ring 2 and transported 10 m up to the level of the present Bevatron experimental halls. A vertical section through the projected ring is shown in Fig. 17. Beams would be injected vertically down from the SuperHILAC, which will be 57 m above the VENUS rings.

An aerial view of the Lawrence Berkeley Laboratory, with the proposed VENUS layout superimposed, is shown in Fig. 18, showing

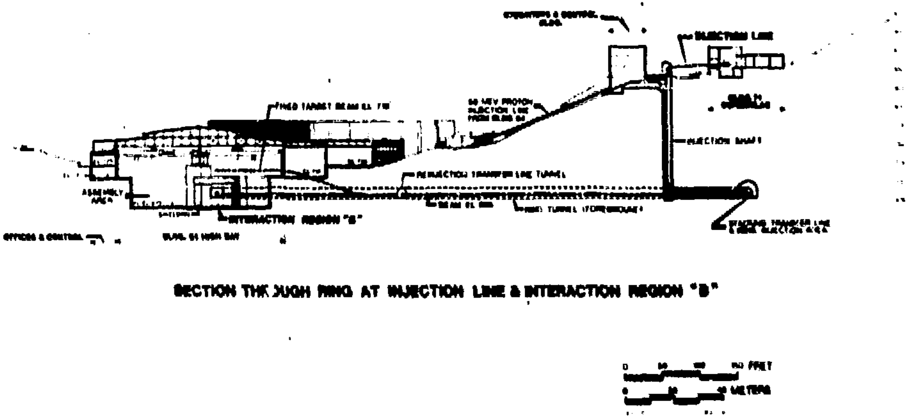

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Fig. 17. VENUS: A relativistic ion synchrotron and storage ring, LBL. Section through the ring at the injection line and interaction region B.

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Fig. 18. Photograph of LBL with proposed VENUS layout superimposed.

the desired maximum utilization of existing facilities. Half the tunnel is estimated to be cut-and-fill, and the other half will be bored tunnel, similar to construction of the PEP tunnel. There are no known earthquake faults going through the LBL site, but the design is planned for the maximum earthquake stresses that can be expected.

The facility will require four separate RF systems to: (1) accelerate to 1 GeV in Ring 1; (2) bunch beams after stacking in Ring 2 (one RF system will be needed per ion species simulatneously accelerated); (3) capture the beam after reinjection in Ring 1 (for colliding beam operation); and (4) acceleration to final energies in Ring 1 and 2. For this purpose, two types will be designed: a 70-kV system with a large, 1:7.5 frequency swing, and a high voltage, 250-kV system requiring only a 10% frequency swing.

Superconducting magnets will be of the type tested at Berkeley in an experimental superconducting accelerator section, with a maximum field of 5 T and a rate of rise of 1 T/s. Superconducting quadrupoles will also be used, since their smaller fields place fewer demands on the technology.

The project contemplates authorization for construction in 1983 and completion in 1987, at a cost of 100 to 150 million dollars (1979).

In France the recently completed Saturne II accelerator at Saclay is beginning a program to produce proton and eventually heavy-ion beams. Proton intensities will be 2.5 x 10^{12} per pulse. The heaviest nuclei that can be accelerated with the existing vacuum will be neon ions at intensities estimated to be 10^8 per pulse. The injector system is at present a 750 kV pressurized Cockroft-Walton accelerator, followed by a 20 MeV linac. A Cryogenic Electron Beam Ion Source (CRYEBIS) has been built at Orsay and will soon be installed. It is designed to provide 200 keV/u beams of fully stripped heavy ions. Saturne II itself is a 3 GeV, strong-focusing synchrotron. A view of the ring tunnel is shown in Fig. 19.

Several other high energy heavy-ion projects are under way in Japan (NUMATRON) (Hirao, 1979), and the U.S.S.R. (the recently operational U-400 Cyclotron, with energy of 725 q^2/A^2 in Dubna (CERN, 1979b), and the planned adaptation of the Dubna synchrophasotron to produce beams up to uranium with energies of 3.4 GeV/A (Baldin et al., 1979).

The high energy physics facilities now in operation, construction or planning stages are shown in Table 6 for completeness (Richter, 1979). A summary of their sophisticated design features and the fundamental insights expected from their use, that would do them justice, cannot be given in the space available here.

Synchrotron radiation is possibly the fastest-growing new field centered around electron accelerators and electron-positron colliding beam facilities. This radiation arises from

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Fig. 19. View of SATURNE II ring tunnel in Saclay, France. *Courtesy of the Institut Gustave-Roussy.*

particle, this distribution is folded into a small forward cone by the transformation to the laboratory frame of reference, as shown in the lower part of Fig. 20. In principle, all charged particles emit synchrotron radiation in magnetic fields. The radiated power varies approximately with the inverse fourth power of the mass, and, until recently, the only synchrotron radiation seen came from electron beams. However, even though the proton mass and energy are such that synchrotron radiation from protons would not be expected in observable amounts, even at SPS and Fermilab machines, the magnetic field discontinuities inevitably present near magnet edges have resulted in observable proton synchrotron radiation at CERN, at energies above 350 GeV and for beam intensities as low as 10^{11} per pulse (CERN, 1979a).

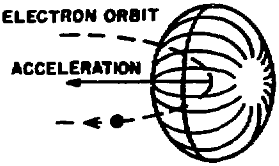
The power emitted by synchrotron radiation is substantial, on the order of 6 MW in PEP, and must be made up by continuous acceleration of the electron and positron beams stored inside the radial acceleration imparted to a charged particle by the magnetic field. In the rest frame of the circulating particle, this radiation has the well-known dipole radiation distribution

Table 6. High Energy Facilities*

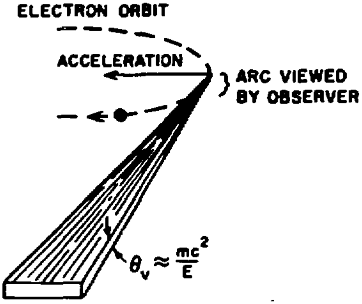
Type	Name (Laboratory)	Energy (GeV)	Status
e^+e^- colliding beams	PETRA (DESY) PEP (SLAC/LBL)	18x18	Operational 1979
e^- beam	SLAC	35	Operational
p beam	FNAL SPS (CERN)	450	Operational Operational
pp colliding beams	ISR (CERN)	31x31	Operational
p beams	DOUBLER (FNAL)	1000	1982
p colliding beams	AA (CERN)	300x300	1982
pp colliding beams	ISABELLE (BNL)	350x350	1986
e^+e^- colliding beams	LEP (Europe)	80x80	After 1988
p beam	UNK (USSR)	3000	After 1988
pp colliding beams	TEVATRON (FNAL)	1000x1000	1985

*Adapted from Richter, 1979.

shown in the upper part of Fig. 20. For a relativistic the rings. This power is radiated in a continuous spectrum characterized by a critical energy $\epsilon_c = 2.2\ E^3/R$, where E is the total energy and R is the radius of curvature (Winick, 1975). Figure 21 shows a typical spectrum obtained using the SPEAR storage ring at Stanford. Specific wavelengths from this continuum are selected using precision tunable monochromators. This is the only known means of obtaining intense sources of electromagnetic radiation over the entire spectrum ranging from 0.1Å to the visible.



CASE I : $\frac{v}{c} \ll 1$



CASE II : $\frac{v}{c} \approx 1$

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Fig. 20. Radiation emission pattern by electrons in circular motion. Courtesy of H. Winick, Stanford Synchrotron Radiation Laboratory.

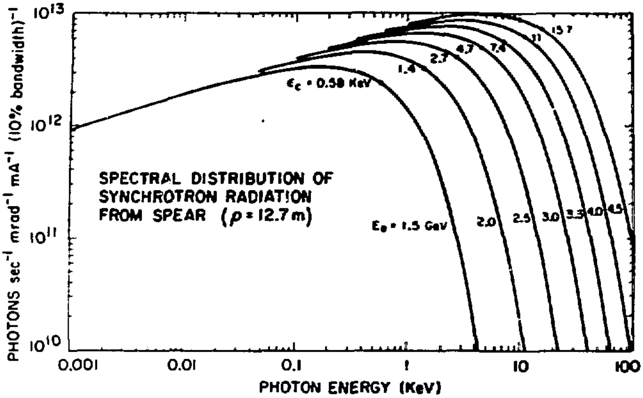


Fig. 21. Typical spectrum obtained using the SPEAR storage ring at Stanford. Courtesy of H. Winick, Stanford Synchrotron Radiation Laboratory.

As seen in Fig. 20, the entire radiation pattern of the beam is collimated into an angle $\sim 1/\gamma$ perpendicular to the plane of the beam orbit. The photon source size, given by the beam cross section, is typically less than $1\ mm^2$. The brightness of synchrotron radiation sources is thus expected to be between 10^4 and 10^7 times greater than any conventional x-ray or line-discharge source. In addition, synchrotron radiation is pulsed, with a time structure dependent on the electron bunch length, typically nsec, and polarized. These characteristics have resulted in an explosion of research in physics, chemistry, and biology, of which the study of muscle cells *in vivo* and spectroscopy of proteins may be most interesting in the context of this course. A recent review of synchrotron radiation applications has been given by Bienenstock (1979).

Synchrotron radiation sources in operation and under construction are listed in Table 7 (van Steenbergen, 1979). All new dedicated sources are built as electron storage rings to take advantage of the greater source stability and 100 duty factor. An artist's view of the Stanford Synchrotron Radiation beam line arrangement is shown in Fig. 22. It shows how five

Table 7. Synchrotron Radiation Facilities⁺

IN OPERATION

		GeV	λ_c
USSR:	VEPP4 (NOVOSIBIRSK)	7.0	0.27 $(1.1)_w$
	VEPP3 (NOVOSIBIRSK)	2.0	2.9 $(1.0)_w$
	VEPP2M (NOVOSIBIRSK)	0.7	23
	*ARUS (EREVAN)	4.5	1.5
	*SIRIUS (TOMSK)	1.4	5.4
	*PAKHRA (MOSCOW)	1.3	10
	*FIAN, C60 (MOSCOW)	0.7	28
	N-100 (KARKHOV)	0.1	3100
GERMANY:	PETRA (HAMBURG)	18.0	0.18
	DESY (HAMBURG)	7.5	0.4
	DORIS (HAMBURG)	5.0	0.5
	*BONN I (BONN)	2.5	2.7
	*BONN II (BONN)	0.5	77
USA:	SPEAR (STANFORD)	4.0	1.1 $(1.6)_w$
	**SURF II (WASHINGTON, D.C.)	0.25	344
	**TANTALUS I (WISCONSIN)	0.24	258
FRANCE:	DCI (ORSAY)	1.8	3.4
	**ACO (ORSAY)	0.54	39
JAPAN:	*INS. ES (TOKYO)	1.3	10.1
	***SOR (TOKYO)	0.4	95
ITALY:	ADONE (FRASCATI)	1.5	8.3 $(4.6)_w$
SWEDEN:	*LUSY (LUND)	1.2	11.8

IN CONSTRUCTION

	GeV	λ_c
***JAPAN (TSUKUBA), PH. FACT.	2.5	3.0 $(0.6)_w$
***UK (DARESBURY), SRS	2.0	3.9 $(0.9)_w$
***GERMANY (BERLIN) BESSY	0.8	20
PEP (STANFORD) 1979	18.0	0.16
CESR (CORNELL) 1979	8.0	0.35
***ALADDIN (WISCONSIN) (1980)	1.0	11.6
***NSLS (BROOKHAVEN) (1981)	2.5	3.0 $(0.6)_w$
***NSLS (NAT'L LAB) (1981)	0.7	31

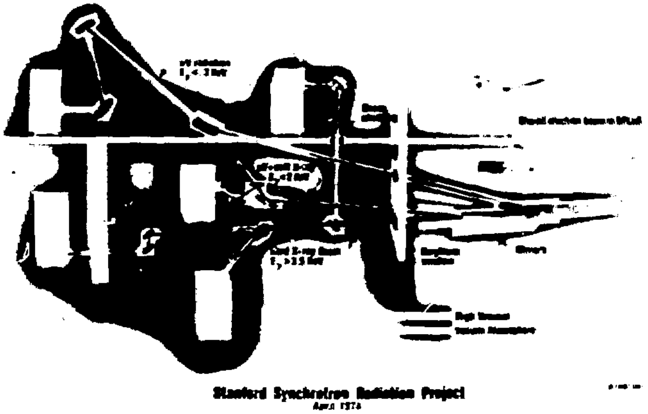
⁺ Adapted from van Steenbergen, 1979.

* Synchrotron

** Dedicated to synchrotron radiation research

*** Designed for synchrotron radiation research

w Wavelength shifter



CBB 797-9821

Fig. 22. Artist's view of the Stanford Synchrotron Radiation beam line arrangement. Courtesy of H. Winick.

simultaneous users can share a single beam line. The UV and soft x-ray beams are split off by grazing incidence reflection on polished metal surfaces and continue to grating monochromators. The high vacuum environment of the source is of great importance to users of soft x-rays and the region below 500Å (vacuum ultraviolet).

The critical energy of synchrotron radiation, as well as the power radiated, are inversely proportional to the radius of curvature of the beam. This feature is used to produce higher energy synchrotron radiation by means of "wiggler" magnets, which consist of several short sections of magnetic fields of alternating polarity, the integrated effect of which does not result in a net orbit deflection. Recently, a wiggler was operated for the first time in the SPEAR storage ring. It consists of a seven-pole device, 1.25 m long, which can be powered up to fields of 1.8 T, and resulted in an increase of a factor of 6 in radiation intensity. Sequential arrays of wigglers, known as "undulators," have also been proposed, with some expected advantages due to excitation of coherent oscillations.

In the rest frame of the circulating electron, the periodic magnetic field of a wiggler or similar structure appears as a plane electromagnetic wave travelling toward the electron. Compton scattering between the virtual photons of this electromagnetic wave and the electrons in the beam bunch results in real backscattered photons going forward in the laboratory frame. From another point of view, the equivalent electron energy has been transferred to the energy contained in the wiggler. Mirrors that do not interfere with the electron beam can be added at each end of the wiggler to create a resonant cavity. When sufficient photons are produced in phase, their amplitudes add and the intensity increases above the laser threshold. Such a laser is called a "free electron laser," since it is due to stimulated radiation between an upper level consisting of a free electron and a virtual photon and a lower level consisting of a scattered electron of less energy and a scattered photon. Theoretical treatments have been given by Madey (1971) and Pellegrini (1979). Laser action has been observed at Stanford and the U.S. Naval Research Laboratory. These lasers can be tuned by changing the electron beam energy. The possibility of obtaining a continuously tunable, high power and high efficiency laser, unrestricted by properties of a material medium has stimulated active development at many United States laboratories, as well as at the University of Trento and Frascati in Italy (Lubkin, 1979).

We thus come full circle to where the accelerators acquired in the course of studying the nucleus are used to generate visible light. Imitation has been called the sincerest form of flattery. If so, the unconscious reenactment of creation to which we seem bound may be well received. It is only to be hoped that our endeavors will also merit the verdict accorded to the original creation: "And He saw that it was good."

ACKNOWLEDGEMENTS

The author greatly appreciates the graphical material generously provided by J. Ball, J. DiCello, H. Grunder, H. Gutbrod, D. Keefe, J. McCaslin, G. Norton, R. Pyle, W. Samaroo, R. Stock, and C. Weber. The competent secretarial help of Grace Walpole is also gratefully acknowledged, as well as the assistance of R. Stevens and the Lawrence Berkeley Laboratory Photography Department. Some of this work was supported by the Office of Health and Environmental Research of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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