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NEW APPLICATIONS FOR LINEAR ELECTRON ACCELERATORS*

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Electron linacs in the 100 MeV to 25 GeV energy range have by now been in operation for periods ranging from one year to over 20 years. In 1951 the Mark III accelerator at Stanford became the first electron linac to exceed an energy of 100 MeV. Since then significant increases in maximum electron energy have been made by the Mark III (reaching an energy of 1 GeV in 1960) and SLAC (exceeding 20 GeV in 1967). In the energy range between 100 and 600 MeV, emphasis has more recently been on the development of linacs with high intensity and duty cycle; for example, the NBS, Saclay and MIT accelerators.

Because linacs approaching present limits of duty cycle and energy have been in operation for a number of years, most of the "easy" physics experiments have by now been carried out with these accelerators. Major increases in linac energy and duty cycle would make possible a new generation of such experiments. However, current worldwide trends in accelerator funding have reduced the chances for achieving major improvements in linac performance by straightforward increases in either length or rf power. Instead, more indirect and less costly schemes, such as recirculation or SLED[22], will most probably be the means for achieving major performance gains. Superconducting linacs, of course, offer the possibility of greatly improving linac duty cycle and energy resolution. Even in the case of a superconducting linac, recirculation may be the best path toward attaining energies of interest for medium- and high-energy physics.

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In the absence of major projects for increasing linac capabilities, the application of new techniques and instrumentation to existing accelerators can help satisfy the stricter requirements of second-generation physics experiments within present energy and current limitations. As a further application of electron linacs within their present range of capabilities, a number of proposals have been made for using a highly relativistic electron beam to perform experiments of basic interest which are not directly related to nuclear or particle physics. In this paper, some programs and proposals in each of the three preceding categories — major increases in energy by recirculation or other means, sophisticated improvement projects on existing machines, and new applications for electron linac beams — will be discussed. It should not be inferred that the listing to follow is complete.

Improvement Projects on Existing Linacs

In this section some projects are discussed which will extend the capability of existing accelerators by means of new instrumentation or technques, but which do not depend upon major improvements in basic machine parameters. As the first example consider PEGGY, the polarized electron source for SLAC. Using a polarized Li^6 atomic beam and a pulsed ultraviolet light source, a highly polarized electron beam with 2×10^8 electrons in a 1.5 μsec pulse has been produced in preliminary tests.[1] The experimental arrangement is shown schematically in Fig. 1. A polarized atomic beam from an oven and six-pole magnet polarizer enters the ionizer from the left. Light from an intense, pulsed ultraviolet source intersects the beam. By photoionization, the electrons are stripped from the beam in the ionizing region. The electrons retain to a high degree the polarization of the atoms in the incident beam. An appropriate electron-optical system then extracts the polarized electrons and injects them into the accelerator. The polarized source for SLAC was

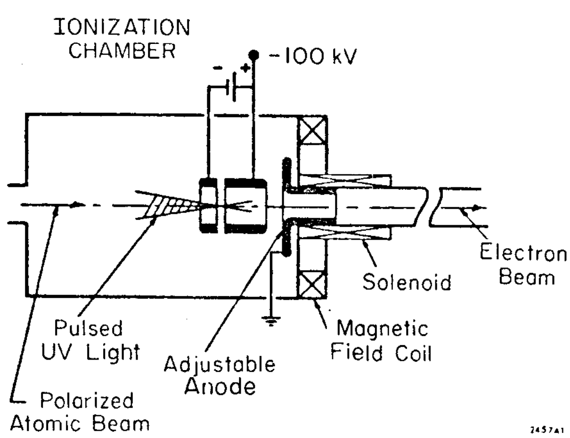

FIG. 1--Schematic diagram showing how a polarized electron beam is produced by PEGGY (after V.W. Hughes, et al.[1]).

constructed, and is currently undergoing final tests, at Yale University. It will be installed at SLAC in 1974.

A second improvement in instrumentation that has been of importance in extending the usefulness of SLAC is the beam knock-out system (BKO).[14] A block diagram of the SLAC BKO system is given in Fig. 2. This system can isolate a

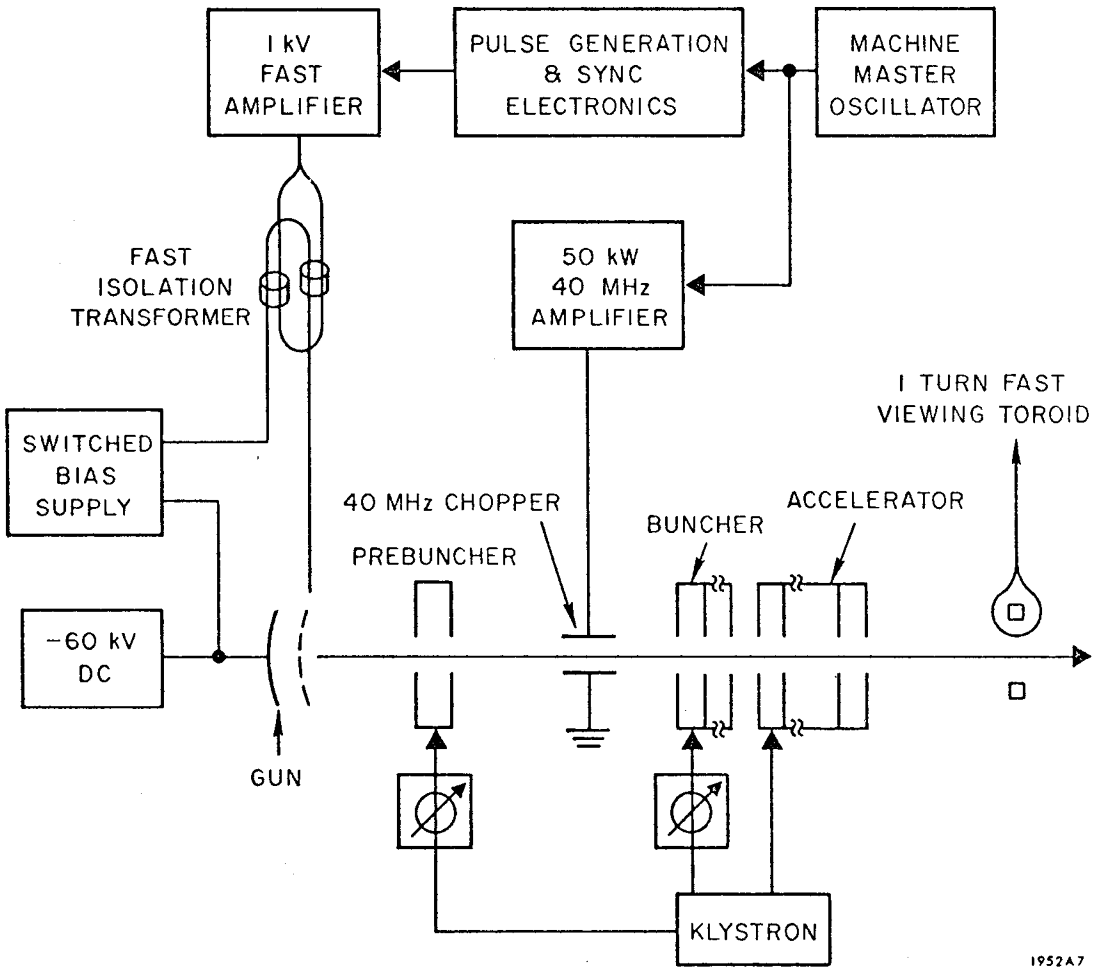

FIG. 2--Block diagram of the SLAC beam knock-out system (after R. F. Koontz, et al.[14]).

single microwave bunch, or produce a train of single bunches separated by tens of nanoseconds. Since each bunch is on the order of 10 picoseconds in length, such a bunch or bunch train is of use in experiments requiring precise time measurements as, for example, in time-of-flight measurements.

In addition to their primary mission to produce beams for physics research, electron linacs have increasingly been called upon to act as efficient injectors for electron-positron storage rings. The SLAC accelerator, for example, must serve as an injector for SPEAR and later possibly for the proposed PEP (Proton-Electron-Positron) ring.[2] The principle future use of the linac at Orsay will be to serve as an injector for the ACO and DCI rings.

To be captured in a single rf "bucket" on injection into a storage ring, the injection pulse-width must usually be limited to about one-half of an rf period. For the present SPEAR ring, with an rf frequency of 50 MHz, the injection pulse-width is therefore on the order of 10 nsec. Next year, the energy of SPEAR will be increased by adding a more powerful rf system which operates at a frequency of 350 MHz. For injection into the Improved SPEAR, the injection pulse-width must consequently be reduced to the order of 1.5 nsec. The time required to fill a storage ring to a given current level is inversely proportional to the peak current during the injection pulse, to the injection pulse-width, and to the ring circumference. In the case of the large diameter rings operating at high rf frequencies that are envisioned for the future, it will be important to obtain the highest possible peak pulse current from the injector linac. It is especially difficult to obtain an adequate peak positron current. At SLAC, a peak (unanalyzed) positron current of 30 mA has been obtained,[3] which represents a conversion efficiency of about 10%. For a current of this order, the filling rate for the positron beam in SPEAR is in excess of 50 mA per minute.

Rf Systems for Storage Rings

Large storage rings are playing a role of increasing importance in the attainment of high center-of-mass energies for particle physics experiments. The energy loss per turn for a charged particle circulating in a storage ring varies as the fourth power of the stored energy. Therefore, the size and cost of the rf system required to make up the radiation loss increases rapidly with the energy of the ring. For example, in the SPEAR ring operating at 2.5 GeV, the radiation loss per turn is 270 keV. For the proposed PEP storage ring, the energy radiated by an electron is calculated to be about 25 MeV per turn. For two circulating beams of 100 mA each, the rf power transferred to both beams is about 50 kW for SPEAR and 5 MW for PEP. More detailed rf system parameters for SPEAR, Improved SPEAR and PEP are given in Table I. A diagram showing the major dimensions of the proposed PEP ring is given in Fig. 3. The 60-meter-long rf system for the electron-positron ring would be split and located in two different straight sections.

TABLE I

Rf System Parameters for Several Storage Rings

		SPEAR	Improved SPEAR	PEP e^+-e^-
Stored Energy	(GeV)	2.5	4.3	15
Circulating Current, Each Beam	(mA)	180	50	100
Energy Loss per Turn	(MeV)	0.27	2.3	27
Power Radiated, Both Beams	(kW)	100	230	5400
Frequency	(MHz)	50	358	350
Peak Rf Voltage	(MV)	0.5	6.3	55
Total Cavity Length	(m)	3	8.4	60
Total Shunt Impedance (Aluminum)	(MΩ)	4	150	1000
Power Dissipated in Cavities	(kW)	60	270	3000
Total Rf Power	(kW)	160	500	8400
Power per Klystron	(kW)	---	125	300
Number of Klystrons		---	4	28

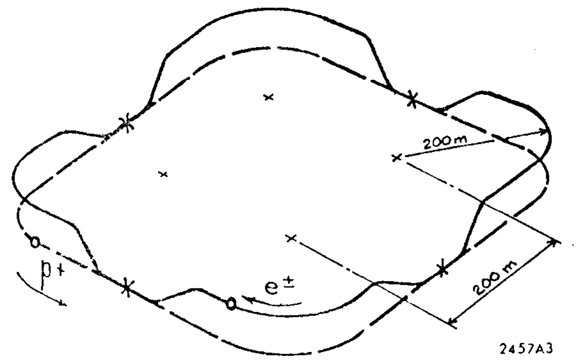

FIG. 3--Schematic diagram of the PEP ring (after R. Bangerter, et al.[20]).

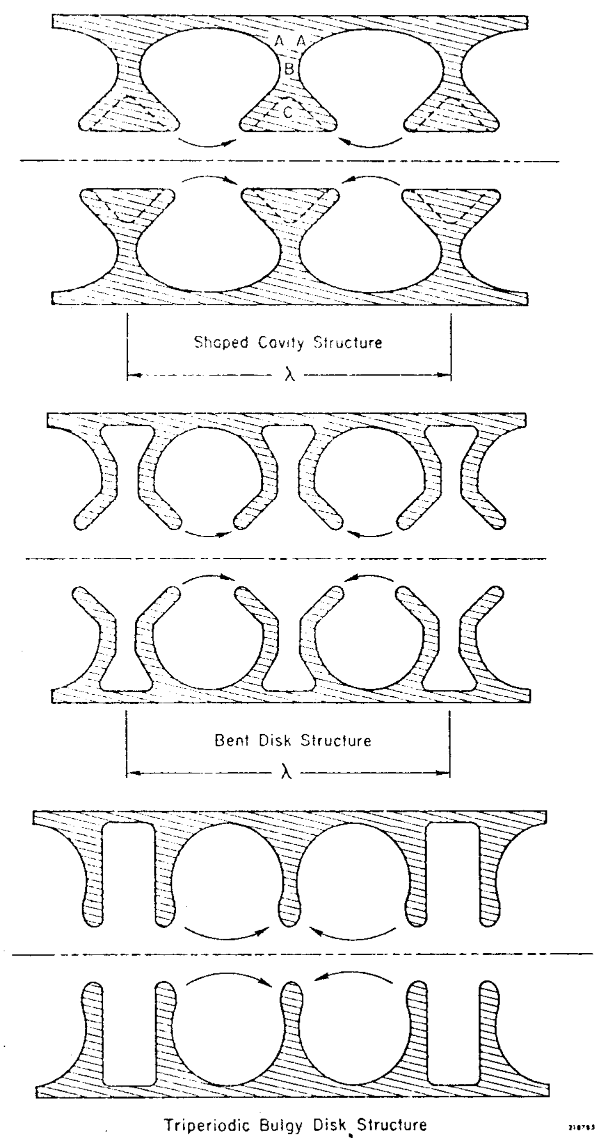

FIG. 4--Some possible structures for high energy storage ring rf systems.

For SPEAR and for other storage rings constructed to date, the peak rf voltage requirement is not large and can be handled by one or two reentrant cavities of conventional design. For Improved SPEAR, however, the peak voltage requirement has become sufficiently large (over 6 Megavolts) so that the use of an rf structure with a high shunt impedance per unit length is desirable. Taking into account a number of factors such as physical size, availability and cost of power sources, shunt impedance vs. frequency and over-voltage requirements as a function of frequency, a linac-type structure operating in the 200-400 MHz frequency range represents a reasonable choice[4,5] for an accelerating cavity. For a ring of the PEP size, the rf system becomes similar to a 50-MeV, 60-meter-long, continuously-operating linac with a beam power of 5 MW.

The detailed requirements for a structure suitable for storage ring rf systems have been discussed elsewhere.[5] Several structures of potential interest are shown in Fig. 4. The top structure shows a series of π-mode cavities, which can be shaped for optimum shunt impedance. By cutting slots at A-A, side-mounted cavities can be added to achieve resonant coupling and $\pi/2$-mode operation, at the expense of a considerable increase in mechanical complexity. By cutting a slot in the cavity wall at B, magnetic field coupling makes it possible to power a number of cavities operating in the π-mode from a single rf feed-point. In Fig. 4 two structures which use on-axis electric field coupling, the bent disk and triperiodic structures, are also shown. Normalizing all structures to a 1-cm beam aperture radius at 2856 MHz, the side-coupled or inductively-coupled structures shown at the top both have a shunt impedance per unit length of about 60 MΩ/m (for copper), allowing for a 20% loss due to the coupling slots. The shunt impedance of the bent disk structure is about the same, while the triperiodic bulgy disk structure has a shunt impedance of about 50 MΩ/m.

A five-cell, inductively-coupled, π-mode structure at 358 MHz has been chosen[4] for the Improved SPEAR rf system. A cut-away drawing of this structure is shown in Fig. 5.

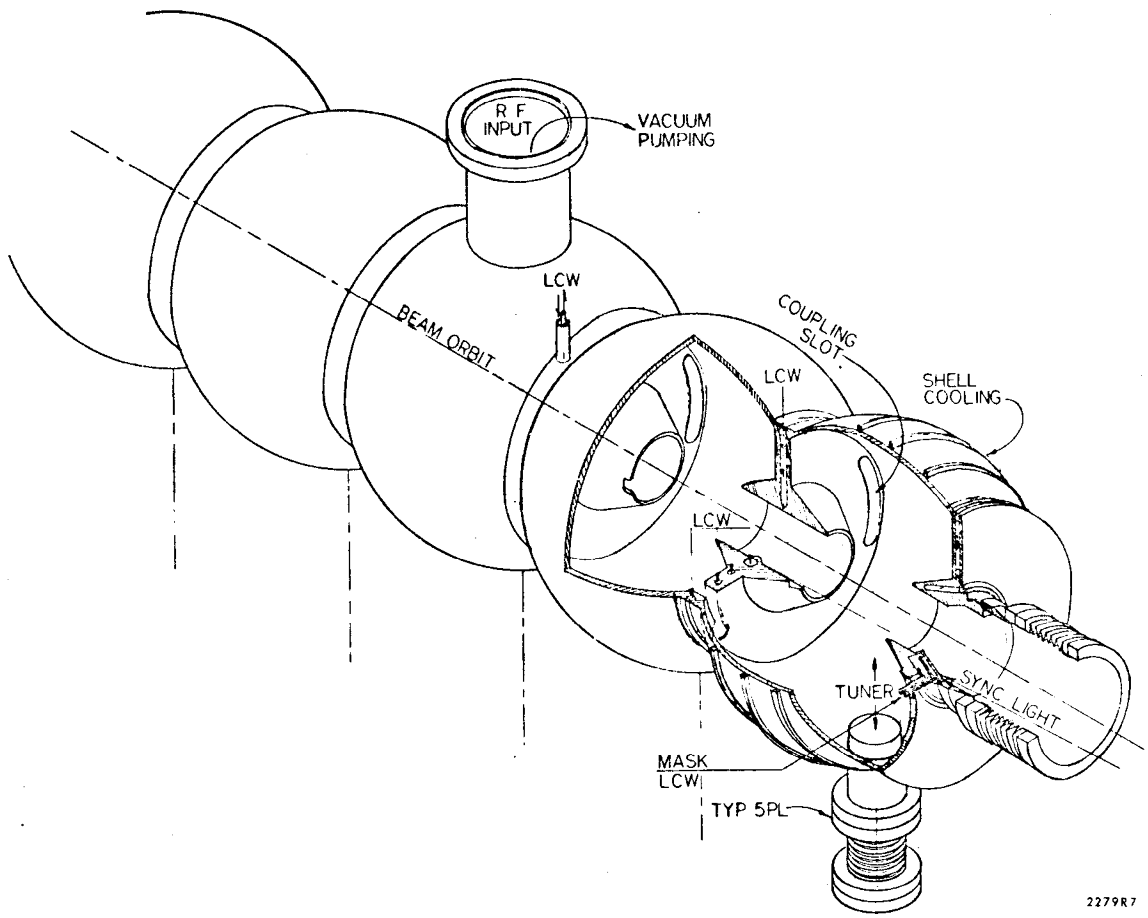

FIG. 5--Rf cavity for the 4.5 GeV Improved SPEAR (after M.A. Allen and R.A. McConnell[4]).

Recirculation

Recirculation of an electron beam one or more times back through a linac structure has been proposed as a method of increasing the energy of existing linear electron accelerators. The RLA (Recirculating Linear Accelerator) project[6] has been proposed as a method for approximately doubling the energy of the SLAC accelerator by storing the beam in an external loop and then reinjecting it into the machine for a second pass to reach a final energy of about 42 GeV. A layout of RLA is shown in Fig. 6. The beam is stored in the loop, at energies

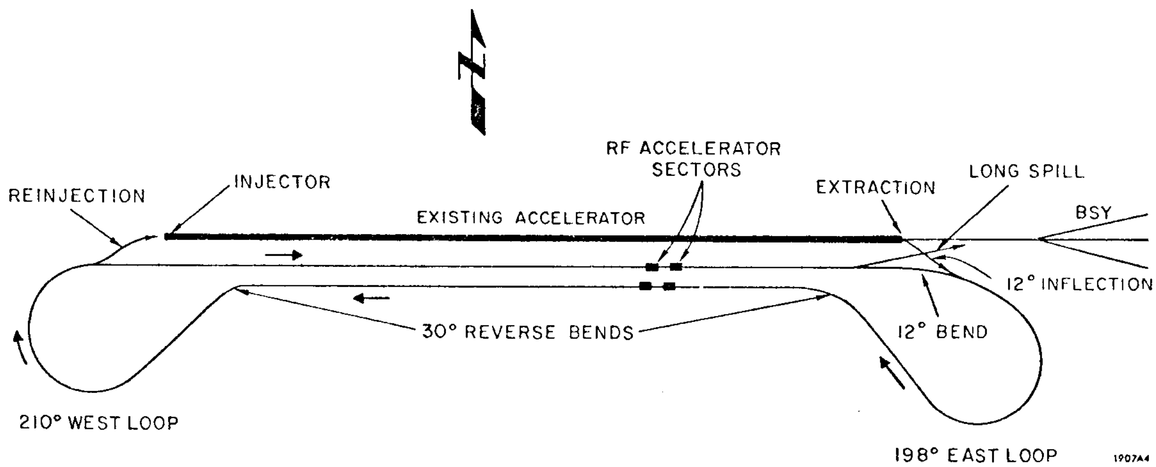

FIG. 6--Proposed layout of RLA.

up to 20 GeV, for 2.8 msec (120 turns). The storage time is equal to the normal period between successive accelerator pulses of 1/360 sec. A synchrotron radiation loss of up to 200 MeV per turn is compensated by the energy gain from two sectors of standard SLAC accelerator structure. These sectors will be powered by a special klystron now under development which has a peak output power of 500 kW at a duty cycle of about 10%. Parameters for the RLA rf system are listed in Table II.

TABLE II

RLA Rf System Parameters

Operating Frequency	2,856	MHz
Length	200	m
Maximum Unloaded Energy Gain	200	MeV
Maximum Recirculation Energy	20	GeV
Radiation Loss at 17.5 GeV	140	MeV
Peak Beam Current at 17.5 GeV	38	mA
Rf Repetition Rate	43,000	pps
Rf Pulse Length	2.6	μsec
Number of Klystrons	16	
Peak Rf Output Power per Klystron	500	kW
Average Rf Output Power per Klystron	55	kW
Rf Duty Cycle	11	%
Modulator Duty Cycle	14.5	%
Klystron Efficiency	43-52	%

Recirculation has also been proposed[7] as a means for increasing the energy of the superconducting accelerator at Stanford's High-Energy Physics Laboratory (HEPL). A layout of a prototype four-orbit system is shown in Fig. 7.

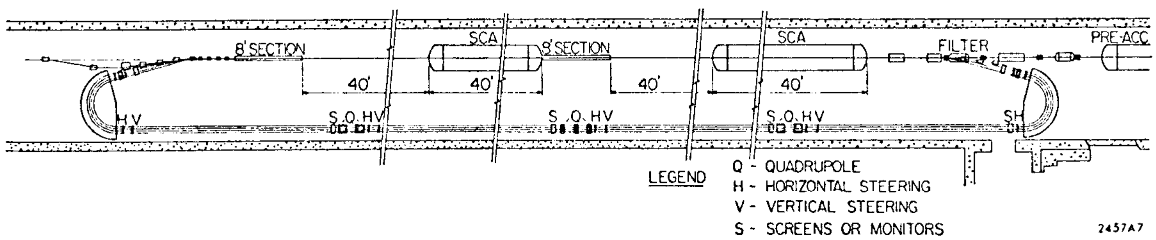

FIG. 7--Schematic layout of the prototype recirculation system at HEPL (after R. E. Rand[7]).

The design is based on the expectation of 9 MeV from the preaccelerator and an energy increment of 67 MeV per orbit for 80 ft of superconducting structure, giving a first-orbit energy of 76 MeV and a final energy of over 300 MeV. A longer range proposal at HEPL is to build 160 ft of structure, which would give a final energy exceeding 600 MeV. The high energy resolution and low beam emittance inherent in the superconducting linac are maintained by the design of the transport system. The system uses a novel multi-channel bending magnet in which the field in each channel is independent and may be separately varied. As pointed out by Rand,[7] this type of magnet could be applied to recirculation at higher energies. For final energies greater than 400 MeV, use of a multi-channel bending magnet of this type could lead to a considerable reduction in weight and cost as compared to the simple magnet design considered previously for racetrack microtrons.

The Racetrack Microtron

The racetrack microtron[8] is a compact electron accelerator capable of producing a high-intensity, high-duty-cycle beam in the 100-600 MeV energy range. In the design as shown in Fig. 8, the racetrack microtron for energies above 100 MeV involves electron linac technology in two essential ways. First, the injector is a short linac with an energy of 10 to 30 MeV. Second, the accelerating cavity between the magnets is a linac structure with a length of 5 to 20 meters.

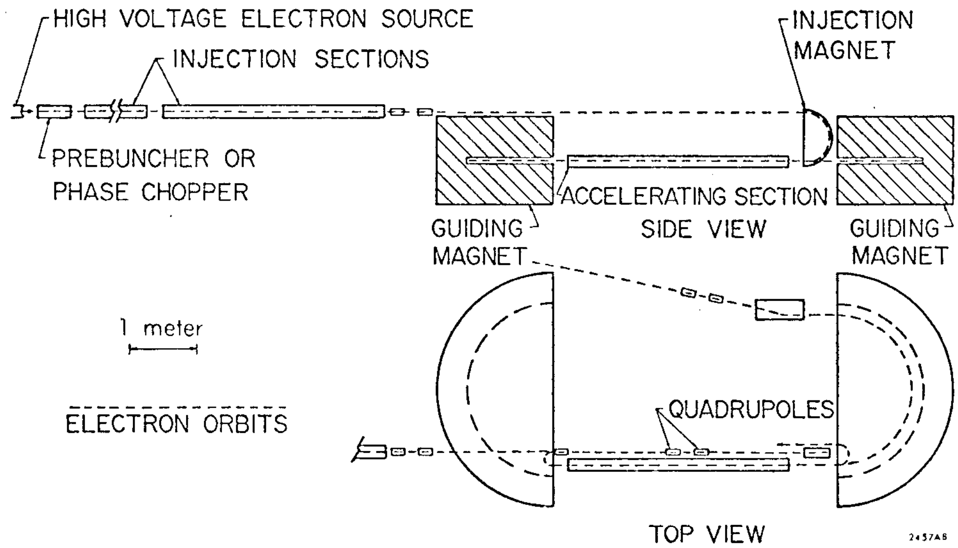

FIG. 8--Schematic diagram of a racetrack microtron.

Because of phase stability, the absolute energy spread remains roughly constant during the 20 to 30 turns that the beam remains in the machine. The relative energy spread, which is inversely proportional (roughly) to the number of turns, is therefore reduced by more than an order of magnitude over the energy spread in the injected beam, and will typically fall[8] in the range 10^{-3} to 10^{-4}. Because of the good inherent energy resolution, the high efficiency for conversion of rf power into electron beam power, and its compact nature, the racetrack microtron is an ideal machine for medium energy physics. A conventional (non-superconducting) racetrack microtron for medium-energy physics experiments has, in fact, been proposed for construction by a group of several universities in Italy.[9] A superconducting racetrack microtron is under construction at the University of Illinois.[10]

Accelerators for Radiation Therapy

Electron linacs have a long history of use for X-ray and electron radiation therapy. Karzmark and Pering[11] have recently reviewed the history, principles and contemporary developments in this field. In addition to electron linacs, lower-energy microtrons (10 MeV in Sweden,[12] and up to 30 MeV in the USSR) are also now under development for radiation therapy. More recently, there has been an interest in negative pion radiotherapy because of the feasibility of a relatively precise restriction of the intense portion of the radiation dose to the selected treatment region, and the more favorable oxygen enhancement ratio of negative pions relative to X-rays. An electron energy on the order of 400 MeV and a beam power greater than 100 kW are required to produce a flux of negative pions adequate for therapy. A 300 kW, 400 MeV racetrack microtron, using a conventional linac accelerating structure, has been proposed[13] which can meet hospital requirements on cost, space and operational reliability. Figure 9 shows what such a facility might look like.

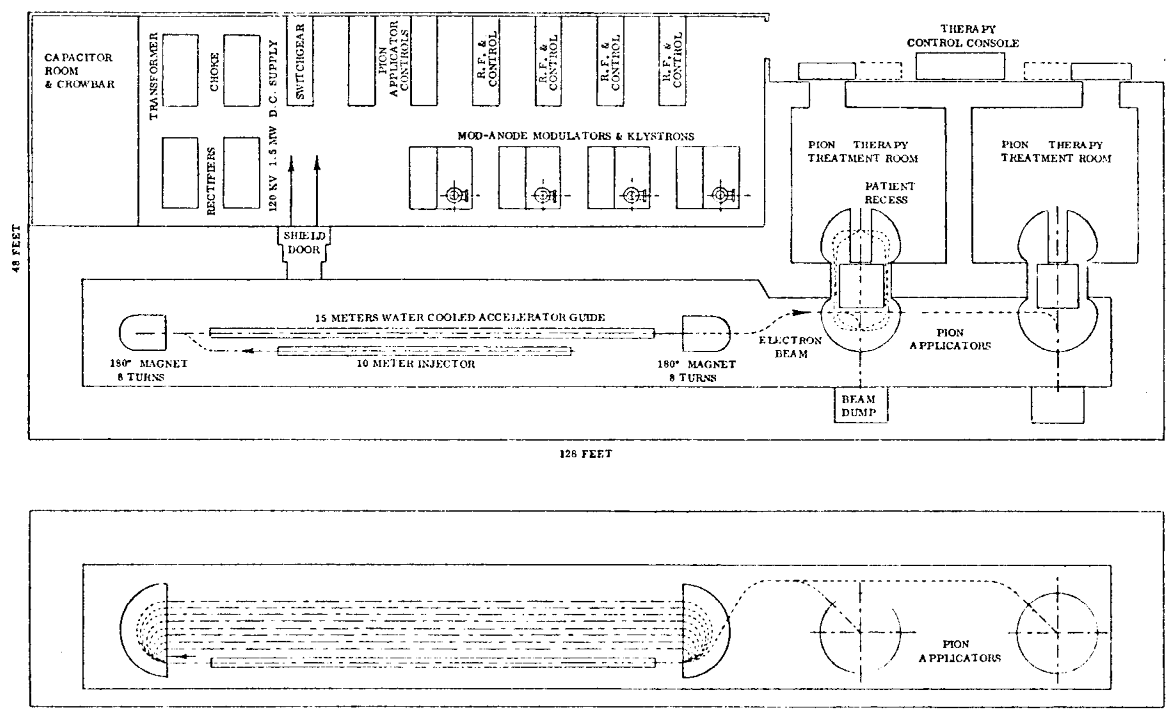

FIG. 9--Layout of a pion therapy facility using a racetrack microtron.

SLED

Recently a method has been proposed[22] for increasing SLAC's energy by adding passive microwave energy storage networks in the output waveguide line of each klystron. The overall system is called SLED (SLAC Energy Doubler) for convenience. High Q cavities in the microwave networks store energy over a large fraction of the klystron output pulse length, and then deliver it to the accelerating sections during a much shorter period. By this means peak power is enhanced at the expense of pulse length. It will also be advantageous to lengthen the klystron modulator pulse in order to take full advantage of the SLED concept. Parameters for SLAC after the installation of SLED, compared to the present SLAC parameters, are given in Table III. The SLED method could also

TABLE III

Comparison of SLED and Present SLAC Parameters
(Computed assuming 30 MW klystrons)

		Present SLAC	SLED
Unloaded Energy	(GeV)	26	48
Loaded Energy	(GeV)	23.5	43
Repetition Rate	(pps)	360	180
Rf Pulse Width	(μsec)	2.7	5.4
Beam Pulse Width	(μsec)	1.6	0.33
Average Current	(μA)	40	13
Peak Current	(mA)	70	220
Duty Cycle		6×10^{-5}	6×10^{-6}
Energy Spread	(%)	1.0	0.5*
Average Beam Power	(kW)	940	560

*Assumes 280 mA pulse for the first 0.16 μsec, then 170 mA for the next 0.16 μsec. For constant 220 mA peak current, estimated energy spread is 1.8%.

be used to increase the energy of medical accelerators and other electron linacs having rf pulse lengths of a few microseconds.

Relativistic Electron Beams as Research Tools

A relativistic electron beam can be useful as a tool to investigate effects of interest for accelerator technology, as well as to perform experiments of a more basic nature not directly related to nuclear or particle physics. The use of the SLAC beam to investigate radiation into higher-order cavity modes is an example of the first kind. In this experiment,[14] a single bunch of electrons, produced by the beam knock-out systems described earlier, is sent through the length of the SLAC accelerator. The short burst of electrons excites higher-order resonances in the disk-loaded structure, as well as the fundamental mode. Power dissipated in these higher-order modes represents a loss not taken into account by the usual beam loading formulas that apply to a continuous train of bunches. For example, at SLAC a bunch of 10^9 electrons loses about 40 MeV passing through the 3 km length of structure. For the same total charge passing through the length of the accelerator in the form of a train of many bunches spaced apart by the rf wavelength, a loss of 7 MeV would be expected. Thus losses are enhanced by more than a factor of 5 for single-bunch beam loading. This information is important in the design of high energy storage rings. If the revolution time of a single bunch, or the time between the passage of successive bunches in a multi-bunch machine, is comparable to the cavity filling time, then an enhancement in beam loading due to excitation of higher-order modes is to be expected.

The microwave structure of the beam from an electron linear accelerator makes possible timing measurements with picosecond resolution. Taking advantage of this beam property, an experiment[21] is underway at SLAC to search for changes in the velocity of light for high energy photons. The experimental layout is shown in Fig. 10. Gamma-rays with an energy $\leq$ 15 GeV are

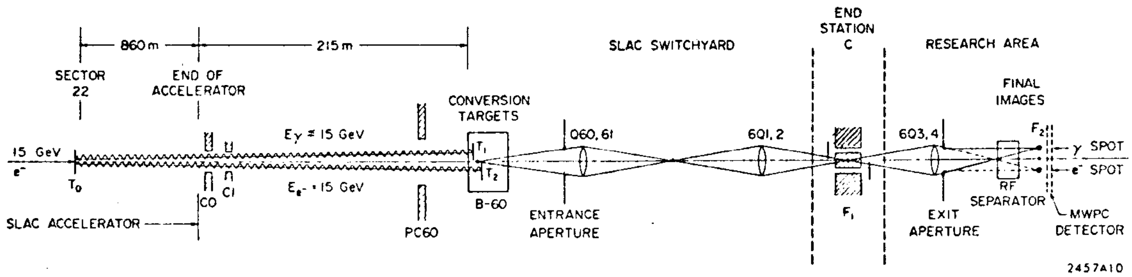

FIG. 10--HEPL/SLAC velocity of light experiment (after Z.G.T. Guiragossian, et al.[21]).

produced at the radiator T_0 in Sector 22 and travel a distance of 1075 meters along with 15-GeV electrons. The principal element of the detector is an rf separator in the research area which converts any velocity difference, which shows up as a slip in the microwave phase between the electron and photon beams, into a time difference. A difference in velocity between electrons and photons on the order of one part in 10^7 can be detected.

Generation and Amplification of Infrared through X-ray Frequencies

A number of methods have recently been suggested for generating or amplifying radiation in the infrared through X-ray frequency range using relativistic electron beams in the 10- to 500-MeV energy range. At HEPL, a free-electron laser has been proposed.[15] In this device, stimulated emission of Bremsstrahlung in a periodic magnetic field provides a new mechanism for the amplification of radiation. The principle is shown schematically in Fig. 11. The wavelength of the radiation is related to the magnet period, λ_q, by $\lambda = \lambda_q/2\gamma^2$, where γ is the electron energy in units of the rest energy. The gain per unit length that can be achieved increases as the energy spread in the electron beam is reduced. Thus a beam with good energy homogeneity, such as that from a superconducting linac or a microtron, is desirable. Initial measurements at HEPL are proposed at a wavelength of $10\,\mu$ utilizing a 50-MeV beam from the superconducting linac. A time-averaged gain of 0.015 db per pass is expected. This gain may be sufficient to sustain oscillation in an appropriate optical resonator.

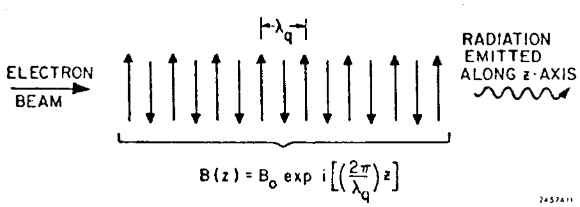

FIG. 11--Radiation by a relativistic electron beam in a periodic magnetic field (after J.M.J. Madey, et al.[15]).

The possibility of using stimulated Compton scattering to obtain laser action has also been considered.[16] For this process, the ratio of output to input wavelength is given by $\lambda_0/\lambda_i = 1/4\gamma^2$. Lasers based on stimulated Compton scattering might be constructed to provide coherent radiation in portions of the frequency spectrum where other sources are not readily available. Furthermore, it would be possible to tune the output signal over a large frequency range by changing the accelerator voltage.

High electron and photon density and small energy spread are also desirable for a laser based on stimulated Compton scattering. At S-band, a high Q superconducting resonator might be used to provide a high photon density on a CW basis. For an input wavelength of 10 cm and a photon density of 10^{20} cm^{-3}, the gain for a 1-meter interaction length is calculated to be 78 db for an electron energy of 8 MeV and an output wavelength of 100 μ. The physical arrangement of such a laser is illustrated in Fig. 12, which also gives other values for gain and output wavelength.

Output Wavelength	dB Gain	Electron Energy
250μ	315	5 MV
100μ	78	7.9 MV
20μ	7	17.8 MV

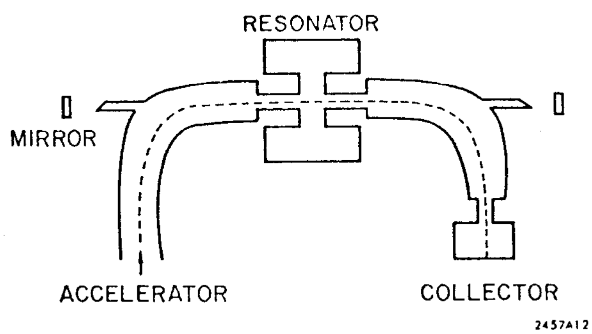

FIG. 12--Physical configuration for stimulated Compton scattering at infrared wavelengths (after Richard H. Pantell, et al.[16]).

Cerenkov radiation can provide a bright, well-collimated light source in the far ultraviolet and vacuum ultraviolet portions of the spectrum. A comparison between the spectral power densities (measured in power per unit wavelength per electron) from Cerenkov and synchrotron radiation shows that the former is two to three orders of magnitude greater in the visible and ultraviolet.[17] A 100 MeV beam with a peak current of 70 mA passing through 1 m of helium at STP produces radiation with a peak spectral density of 0.3W/Å at 650 Å. A 500-MeV, 400μA beam from a superconducting accelerator would provide a continuous source with a spectral density of 1.7 mW/Å at 650 Å.

Recently, Pantell[18] has made an interesting proposal to use the inverse Cerenkov effect for the coherent energy modulation of a relativistic electron beam by visible light. The resulting velocity modulation may be converted to current modulation by allowing the beam to drift. A Cerenkov output coupler may then be used to extract energy at the fundamental or at a harmonic frequency. Microwave klystrons provide high amplification and high efficiency. It is reasonable to expect that similar properties would apply to an optical klystron. Some potential applications are: a high-power tuneable pump source for parametric devices; an amplifier for lasers; a possible source for laser-induced fusion. If velocity modulation of a relativistic beam by a laser can be demonstrated, this also presents the possibility of using a laser for electron acceleration.[19]

In an initial experiment (see Fig. 13) proposed for HEPL by Pantell[18] and his associates, high energy (~100 MeV), monoenergetic ($\Delta E/E \simeq 0.1\%$) electrons are injected into an interaction region filled with helium gas, where they

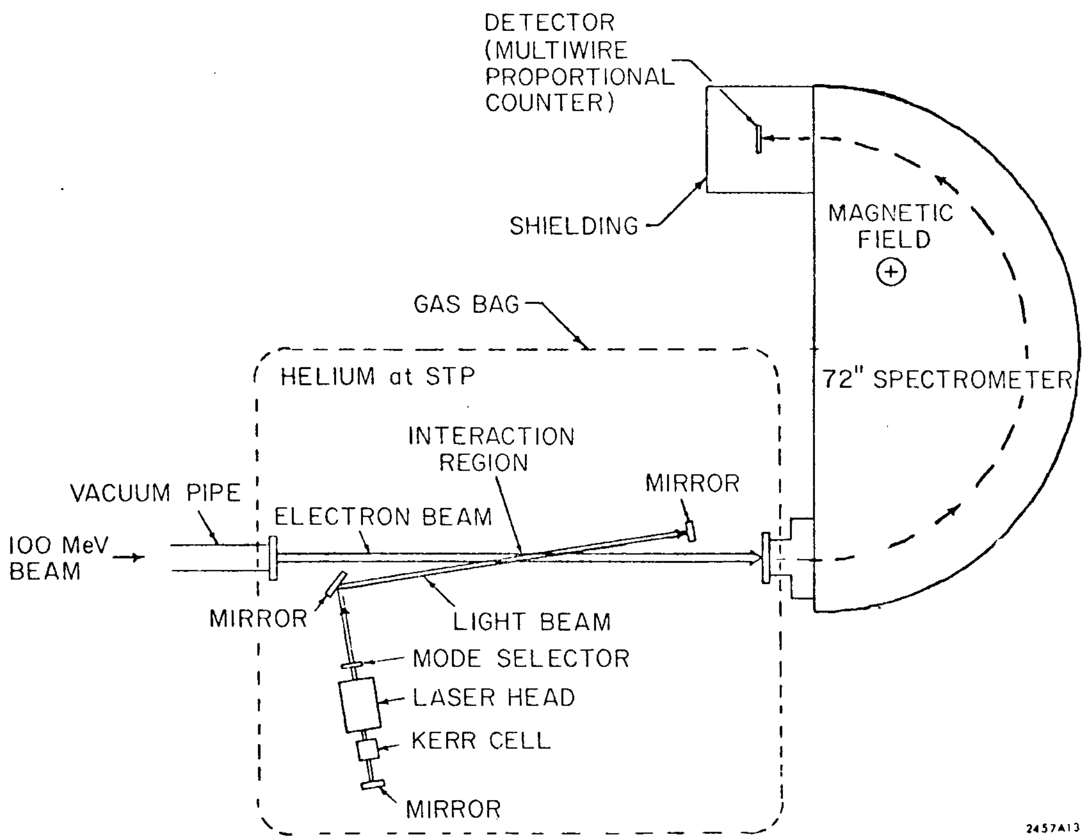

FIG. 13--Experimental arrangement for electron velocity modulation (after Richard H. Pantell[18]).

are modulated by a 10 MW peak power laser beam at the Cerenkov angle. The increase in energy spread due to modulation will be detected by a high resolution spectrometer. A superconducting accelerator would be capable of providing a beam with a smaller energy spread, which would make it easier to detect velocity modulation in this type of experiment.

A final proposal to be discussed here, also due to Pantell[18] and his associates, is the generation of X-ray radiation by electron beam pumped parametric emission. In this experiment, a beam in the 100-MeV to 1-GeV energy range is incident on a gaseous or solid (quartz or sapphire) target. A Q-switched CO_2 laser provides the input light source. Initial measurements have been proposed at the Mark III accelerator.

References

1. V.W. Hughes, R.L. Long, Jr., M.S. Lubell, M. Posner and W. Raith, Phys. Rev. 5A, 195 (1972).
2. Tom Elioff, IEEE Trans. Nucl. Sci. NS-20, No. 3, 1039 (1973).
3. R.H. Miller, Stanford Linear Accelerator Center, private communication.
4. M.A. Allen and R.A. McConnell, IEEE Trans. Nucl. Sci. NS-20, No. 3, 373 (1973).
5. M.A. Allen and P.B. Wilson, Proceedings of the 1972 Proton Linac Conference (Report LA-5115, Los Alamos Scientific Laboratory, Los Alamos, New Mexico), p. 279.
6. W.B. Herrmannsfeldt, IEEE Trans. Nucl. Sci. NS-20, No. 3, 910 (1973).
7. R.E. Rand, IEEE Trans. Nucl. Sci. NS-20, No. 3, 938 (1973).
8. B.H. Wiik and P.B. Wilson, in Linear Accelerators, P.M. Lapostolle, ed. (North Holland, Amsterdam), p. 553.
9. L. Gonella, Proceedings of the 8th Int. Conf. on High Energy Accelerators (CERN Scientific Information Service, Gevena, 1971), p. 557.
10. J.S. Allen, et al., Particle Accel. 1, 239 (1970).
11. C.J. Karzmark and Neil C. Pering, Phys. Med. Biol. 18, 321 (1973).
12. D. Reistad and A. Brahme, Phys. Med. Biol. 17, 692 (1972).
13. Perry B. Wilson and Craig S. Nunan, IEEE Trans, Nucl. Sci. NS-20, No. 3, 1018 (1973).
14. R.F. Koontz, G.A. Loew and R.H. Miller, Proceedings of the 8th Int. Conf. on High Energy Accelerators (CERN Scientific Information Service, Geneva, 1971), p. 491.
15. J.M.J. Madey, H.A. Schwettman and W.M. Fairbank, IEEE Trans. Nucl. Sci. NS-20, No. 3, 980 (1973).
16. Richard H. Pantell, G. Soncini and Harold E. Puthoff, IEEE J. Quantum Electronics QE-4, 905 (1968).
17. M.A. Piestrup, R.H. Pantell, H.E. Puthoff and G.B. Rothbart, to be published in J. Appl. Phys.
18. Richard H. Pantell, Stanford University, private communication.
19. K. Shimoda, Appl. Optics 1, 33 (1962).
20. R. Bangerter, A. Garren and L. Smith, IEEE Trans. Nucl. Sci. NS-20, No. 3, 786 (1973).
21. Z.G.T. Guiragossian, G. Rothbart, M.R. Yearian, IEEE Trans. Nucl. Sci. NS-20, No. 3, 994 (1973).
22. P.B. Wilson, "SLED — a method for doubling SLAC's energy," TN-73-15, Stanford Linear Accelerator Center (December 1973).