21. In these experiments, a Corning filter No. 3060, which cuts off light of wavelengths below 3800 Å, was placed between the photoreactivating light source and the tubes to be illuminated.
22. Strains R-03 and 002, obtained from Dr. S. Kondo, were used in these experiments. Both strains require arginine and are sensitive to ultraviolet, with a survival and frequency of induced prototrophy similar to that of WP2s; R-03 is *phr*+, 002 is *phr*−. Result for mutations from *arg*− to *arg*+ are those obtained by Kondo (personal communication); results for streptomycin-resistance observed by me. Both strains were derived from strain H/r30 (*28*).
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36. The parent strain (*mfd*+) is WU36-10, a di-auxotroph requiring tyrosine and leucine, derived from WU36(*15*). The *mfd*− mutant has the same requirements. In Figs. 7 and 9, mutations to tyrosine-independence are followed on SEM agar supplemented with 20 μg of leucine per milliliter.
37. J. Setlow, personal communication.
38. Research supported by grant AI-01240 from NIAID and conducted with the able assistance of N. A. Sicurella. I thank Dr. L. Gorini for supplying the "conditional streptomycin-dependent" strains, Dr. R. Hill for strain WP2s, and Dr. S. Kondo for the ultraviolet-sensitive *phr*+ and *phr*− strains (see *22*).

Electrons Accelerated to the 10- to 20-Gev Range

The first full-length operation of the Stanford Two-Mile Linear Electron Accelerator is reported.

W. K. H. Panofsky, R. B. Neal, and the staff of the Stanford Linear Accelerator Center

On 21 May 1966, electrons were accelerated for the first time through the full length of the Stanford Two-Mile Linear Electron Accelerator. Construction of this machine had begun in April 1962. Beam operation with the first two sectors (each sector 333 feet long) had initially taken place on 3 January 1965, and operation with two-thirds of the machine (6700 feet) started on 21 April 1966. The design objective of this machine is to accelerate a maximum electron current of 30 microamperes average to an energy of 20 Gev (10^9 electron volts). Detailed design characteristics of the accelerator may be found elsewhere (*1*).

During the first full-length operation, an energy of about 10 Gev was obtained, with 24 out of the 30 sectors contributing energy but operating at reduced power levels. Subsequently, during the two runs scheduled since that date, the energy has been increased to 16.4 Gev by activating 208 out of the total of 245 klystrons, by improving the phasing adjustments, and by increasing the peak power of the klystrons. Higher-energy operation will be approached cautiously until more experience with the life of the components has been obtained.

Overall Accelerator Performance

Overall accelerator performance to date has been good. Energy measurements have shown that the design goal of 20 Gev should easily be met. The attainable intensity is at present limited to about half the design value of 30 microamperes by the "beam breakup" limit discussed below. Corrective measures are under investigation. Below the beam-breakup threshold, at least 90 percent of the beam measured at a monitor 30 feet from the injector is transmitted through the entire length of the machine. At a pulse repetition rate of 360 pulses per second and a pulse length of 1.5 microseconds, a peak current of 10 milliamperes corresponds to an average current of 5.4 microamperes. With klystrons operating at a conservative output power of 15 megawatts peak, the stability of the machine has been very good. In the absence of any major changes in operating conditions, it has been possible to turn off the beam and reestablish it several hours later without retuning. The automatic phasing system in which the electron beam is used as a phase reference has functioned well. Typical energy spectra with and without beam loading, such as are shown in Fig. 1, have exhibited spectrum widths at half maximum of less than 1 percent. Microwave beam position monitors located at the end of each sector have indicated the transverse beam location with respect to the accelerator axis within ± 0.5 millimeter. Their use has greatly facilitated the functions of steering and focusing the beam along the machine. These functions have been further aided by the use of a 2-mile-long, argon-filled, coaxial line installed along the accelerator. This line works as a continuous ionization chamber and enables the operator to detect beam losses and, from the times of arrival of the ionization signals, to resolve their location within 100 to 200 feet. The capability of the laser alignment system to read out, remotely, the accelerator transverse coordinates to an accuracy of ± 0.010 inch has been demonstrated. Preliminary experiments with interlaced beams such as that illustrated in Fig. 2 have demonstrated the feasibility of transmitting beams of different energies, intensities, and pulse lengths through the accelerator. These beams can then be separated in the beam switchyard for experimental purposes.

Tests on the life of accelerator components, including klystrons, are in progress. In accordance with design,

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such tests and the associated maintenance and repairs are being carried out without interrupting beam operations.

Beam Dynamics and Beam Breakup

Considerable testing time has gone into studies of beam dynamics. The bunch phase spread at the 30-foot point has been measured to be about 5 degrees (5/360 of the wavelength at the operating frequency of 2856 megahertz). The transverse phase space at the injector has been calculated by measuring the beam diameter at two positions, for one of which the beam has been focused to minimum spot size. The phase space is given approximately by the product of the beam diameter at the beam minimum and the angular divergence of the beam. This divergence can be inferred from the beam diameter at the second position. Eighty percent of the injected current was found in a phase space of 1.2×10^{-2} Mev cy^{-1} cm^{-1} [expressed as a product integral of the transverse momentum, in units of million electron volts per cycle, and the beam displacement, in centimeters]. This transverse phase space should be conserved along the whole machine up to currents where the phenomenon of beam breakup sets in. Below beam-breakup threshold the beam diameter was observed visually, at a final energy of 16 Gev, to be less than 1/8 inch and showed a negligible spread in 480 feet, the distance between two viewing points, as measured with argon-filled Cerenkov cells beyond the end of the accelerator.

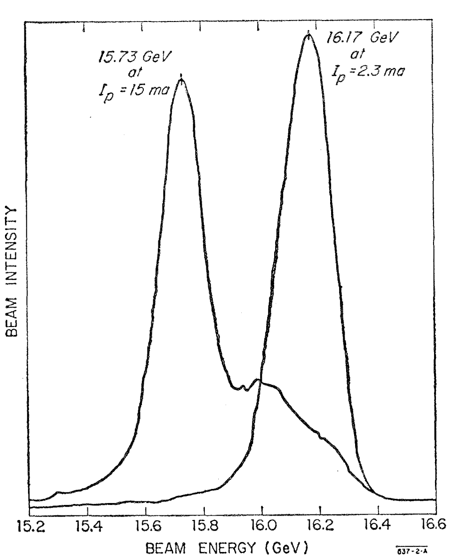

Fig. 1. Typical energy spectra measured at end of the accelerator with and without beam loading. Width at half maximum was measured at 1.33 percent, with 0.9 percent attributable to experimental resolution.

Beam breakup manifests itself through a progressive shortening of the transmitted beam pulse when a certain combination of peak beam current and accelerator length is exceeded. Among other extensive measurements, data have been obtained with the beam accelerated to 600 Mev through the first 333-foot sector and then permitted to coast through the remainder of the accelerator; these are shown in Fig. 3. As the number of activated sectors increases, the current which can be accelerated without beam breakup also increases; the measurements indicate that current of about 25 milliamperes can be accelerated at full gradient to the end of the accelerator, corresponding to an average current of 14 microamperes at the full 360-pulse-per-second repetition rate. Focusing adjustments have only small effects on the beam-breakup threshold.

The observed phenomenon of beam breakup, while undoubtedly related to the excitation of the higher-order, TM_{11}-like, deflecting mode, appears to be somewhat different from similar effects reported earlier (*2*) in other linear accelerators. In short machines with similar design parameters, beam breakup occurs typically over a 10-foot length for peak currents of $\sim$ 300 milliamperes in uniform structures and $\sim$ 600 milliamperes in constant-gradient, tapered structures. In a multiple-section machine it appears that the transmitted beam can successively interact with this higher-order transverse mode in each of the 960 accelerator sections. Subsequent bunches in the beam undergo transverse modulation while passing through the sections. This modulation is carried to the following sections, resulting in progressively higher excitation. The next portion of the beam entering the accelerator finds each section already pre-excited in this transverse mode, and the progressive buildup from section to section therefore proceeds from a higher value. For these reasons, the transverse modulation of the beam will in general increase exponentially *both* in time and with distance along the accelerator, and the onset of beam breakup will occur at much lower current than in short machines. It had been expected that the nonuniform accelerator structure arising from the constant-gradient design adopted for the 2-mile accelerator would prevent this difficulty. It now appears that the use of this structure has served to reduce but not to eliminate the breakup problem. The action described is the transverse analogy to the amplification of longitudinal bunching in a multicavity klystron.

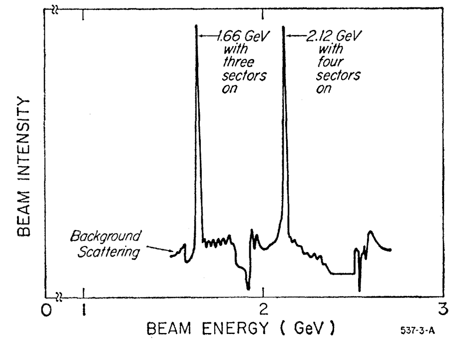

Fig. 2. Energy spectra of two interlaced beams displaced in time by 1/120 second, each beam operating at 60 pulses per second with 8-milliampere peak current. (Measured with beam through two-thirds of the accelerator.)

Radiofrequency measurements made by means of a variety of coaxial and waveguide probes reveal that the onset of breakup is associated with the presence of transverse beam modulation at 4140 megahertz. This frequency corresponds to the π-mode of the input end of each constant-gradient accelerator section in the TM_{11} mode. A second frequency of 4428 megahertz is also observed; it is simply a "beat

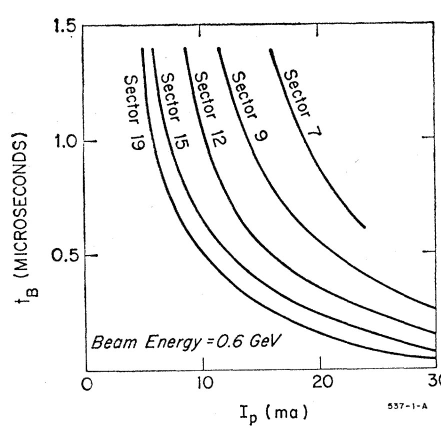

Fig. 3. Foreshortened pulse length, t_B, after beam breakup as a function of peak current, I_p. The sector number where breakup is observed is shown as a parameter; the distance from the injector is 333 feet times the sector number. A low-energy beam was used to permit extended range of parameters.

note" of 4140 megahertz with the third harmonic of the accelerator frequency, 2856 megahertz. Self-excited breakup invariably seems to occur in the vertical direction, at 90 degrees with the waveguide couplers. It has also been possible to lower the threshold current for beam breakup artificially by injecting a few milliwatts of 4140-megahertz or 4428-megahertz radiofrequency power into an early 10-foot section of the accelerator. Experimental and analytic work is under way, aimed at gaining an understanding of the mechanism of transverse modulation buildup from noise and to test alternative corrective measures.

Detailed Energy Measurements

Both cumulative and incremental energy measurements have been made over two-thirds of the length and over the full length of the machine to verify the relation between energy gain and radiofrequency power input to the accelerator.

For a constant-gradient structure with negligible beam loading, the energy gain V in a length l having a shunt impedance r per unit length is given by

$$V = (1 - e^{-2\tau})^{\frac{1}{2}} (Plr)^{\frac{1}{2}}$$

where P is the radiofrequency peak power input and τ is the net attenuation of the structure, in nepers. In the Stanford 2-mile accelerator, $\tau = 0.57$, $l = 305$ centimeters, and $r = 53$ megohms per meter. Using these values and correcting for the power loss of 0.54 ± 0.1 decibel in the waveguide system between the klystrons and the accelerator, one obtains the energy gain V per klystron, each klystron feeding a power P into four 10-foot accelerator sections, of

$$V = 19.9\ P^{\frac{1}{2}}$$

where V is measured in Mev and P is measured in megawatts.

For the highest energy run to date (16.4 Gev), the sum of the square roots of all the power inputs from the 208 contributing klystrons was 840 $(\text{Mw})^{\frac{1}{2}}$. Thus the measured constant of 19.5 is in reasonable agreement with the theoretical value of 19.9 given in the above equation.

Further Plans

Accelerator test runs will continue for about 3 months while construction of the beam switchyard and the experimental areas is progressing. After survey experiments on secondary beam production have been made, a scheduled program in elementary particle physics will begin, by late fall 1966.

References and Notes

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NEWS AND COMMENT

House: Increases for Education, NIH a New Formula for Research Funds

Memorial Day is one of those conveniently spaced national holidays which provide traditional breathers in the congressional schedule. Most legislators go back home, make a ceremonial appearance or two, and tap grass-roots opinion. The congressional mood before and after this Memorial Day long weekend can be described as uneasy.

Anxiety, of course, is a natural state for politicians in an election year. But this year senators up for election and all the congressmen must deal with Vietnam and inflation as live, if unclearly defined, political issues. Inflation seems to favor the outs, but the ins are hoping that full employment will outweigh it.

Vietnam is a principal national concern, but the primaries haven't shown which way it is likely to cut most deeply at the polls. President Johnson's popularity is reportedly down from its record peaks, but in off-year elections, candidates of a President's party seldom lash themselves politically to their national leader.

Present uncertainties and the awareness that it's a long, long way from May to November have dampened the appetite for early adjournment evident —particularly among Democrats—at the end of last year's long session.

Relations between the President and his majority in Congress seem to have frayed slightly, although normal wear and tear could account for it. The President's speech in Chicago 2 weeks ago was interpreted by some legislators as an ultimatum to members of his party to go all the way with LBJ on Vietnam or else, and was resented. And while the administration continues to prevail remarkably often legislatively, Congress has been taking many more liberties in committee this year than last.

Memorial Day marks a legislative watershed in most congresses. Many money bills have moved through the appropriations process, and the rough outline of what Congress is likely to accomplish can be discerned.

Major appropriations bills affecting science and education were sent on their way when the Labor–HEW and Independent Offices appropriations bills passed the House. The Senate has not acted, but radical changes are unlikely, particularly since extension and expansion of existing programs are involved, rather than enactment of new legislation.

The Independent Offices bill included appropriations of \$4.95 billion for the National Aeronautics and Space Administration, a reduction of some \$62 million in the budget request. More than \$4.2 billion of the total was ear-