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Electrons Accelerated to 10-20 GeV Range

The first full-length operation of the
Stanford two-mile linear electron
accelerator is reported.

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Introduction

On May 21, 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 January 3, 1965 and operation with 2/3 of the machine (6700 feet) started on April 21, 1966. The design objective of this machine is to accelerate a maximum electron current of 30 microamperes average to an energy of 20 GeV. Detailed design characteristics of the accelerator can 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 component life 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 one half the design value of 30 microamperes by the "beam break-up" limit discussed below. Corrective measures are under investigation. Below the beam break-up threshold, at least 90% 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 ma corresponds to an average current of 5.4 microamperes. When operating klystrons at a conservative output power of 15 Mw 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 re-establish it several hours later without retuning. The automatic phasing system which uses the electron beam as a phase reference has functioned well. Typical energy spectra with and without beam loading such as shown in Fig. 1 have exhibited spectrum widths at half maximum of less than 1%. Microwave beam position monitors located at the end of each sector have indicated the transverse beam location with respect to the accelerator axis within $\pm$ 0.5 mm. 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 two-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 one to two hundred feet. The capability of the laser alignment system to read out remotely the accelerator transverse coordinates to an accuracy of $\pm$ 0.010 inch has been demonstrated. Preliminary experiments with inter-laced 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.

Life tests on accelerator components including klystrons are in progress. In accordance with design, such tests and the associated maintenance and repairs are being carried out without interrupting beam operations.

Beam Dynamics and Beam Break-Up

Considerable testing time has gone into beam dynamics studies. The bunch length at the 30-foot point has been measured to be $\approx 5^o$ of the operating frequency (2856 MHz). 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 times 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/c · cm) (expressed as a product integral of the transverse momentum in units of MeV/c 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 break-up sets in. Below beam break-up 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 using argon-filled Cerenkov cells after the end of the accelerator.

Beam break-up (BBU) 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 taken 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 BBU also increases; the measurements indicate that about 25 ma 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 BBU threshold.

The observed phenomenon of beam break-up, 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, BBU occurs typically over a 10-foot length for peak currents of $\approx$ 300 mA in uniform structures and $\approx$ 600 mA 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 build-up 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 BBU will occur at much lower current than in short machines. It had been expected that the non-uniform accelerator structure arising from the constant-gradient design adopted for the two-mile accelerator would prevent this difficulty. It now appears that the use of this structure has served to reduce but not to eliminate the break-up problem. The action described is the transverse analogy to the amplification of longtudinal bunching in a multi-cavity klystron.

RF measurements performed by means of a variety of coaxial and waveguide probes reveal that the onset of break-up is associated with the presence of transverse beam modulation at 4140 MHz. 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 MHz is also observed; it is simply a "beat note" of 4140 MHz with the third harmonic of the accelerator frequency, 2856 MHz. Self-excited break-up invariably seems to occur in the vertical direction, at 90° with the waveguide couplers. It has also been possible to lower the threshold current for BBU artificially by injecting a few milliwatts of 4140 MHz or 4428 MHz rf power into an early 10-foot section of the accelerator. Experimental and analytic work is underway, aimed at gaining an understanding of the mechanism of transverse modulation build-up from noise and to test alternate 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

$$V = (1 - e^{-2\tau})^{\frac{1}{2}} (P \ell r)^{\frac{1}{2}}$$

where P is the rf peak power input and τ is the net attenuation of the structure in nepers. In the SLAC accelerator, $\tau = 0.57$, $\ell = 305$ cm, and $r = 53$ megohms per meter. Using these values and correcting for the power loss of 0.54 ± 0.1 dB in the waveguide system between the klystrons and the accelerator, one obtains the energy gain per klystron, each feeding a power P into four ten-foot accelerator sections, of

$$V_{MeV} = 19.9 \sqrt{P_{MW}} \ .$$

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 $(MW)^{\frac{1}{2}}$. Thus, the measured constant in the above equation of 19.5 is in reasonable agreement with the theoretical value.

Further Plans

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

Footnotes

1. See e.g., R. Borghi, A. Eldredge, G. Loew, and R. Neal, "Design and Fabrication of the Accelerating Structure for the Stanford Two-Mile Accelerator," Stanford Linear Accelerator Center, Stanford, California, SLAC-PUB-71, (January 1965) (to be published in Advances In Microwaves, Academic Press, Inc., New York, N.Y.); or J. Ballam, G. Loew, and R. Neal, Proceedings of the Fifth International Conference on High Energy Accelerators, Frascati, Italy, September 9-16, 1965.
2. See e.g., T. R. Jarvis, G. Saxon, and M. C. Crowley-Milling, Proc. IEE 112, 1795 (1965).

FIGURE LIST FOR SLAC ARTICLE FOR JUNE 3rd ISSUE OF "SCIENCE"

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

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 ma peak current. (Measured with beam through two-thirds of the accelerator.)

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

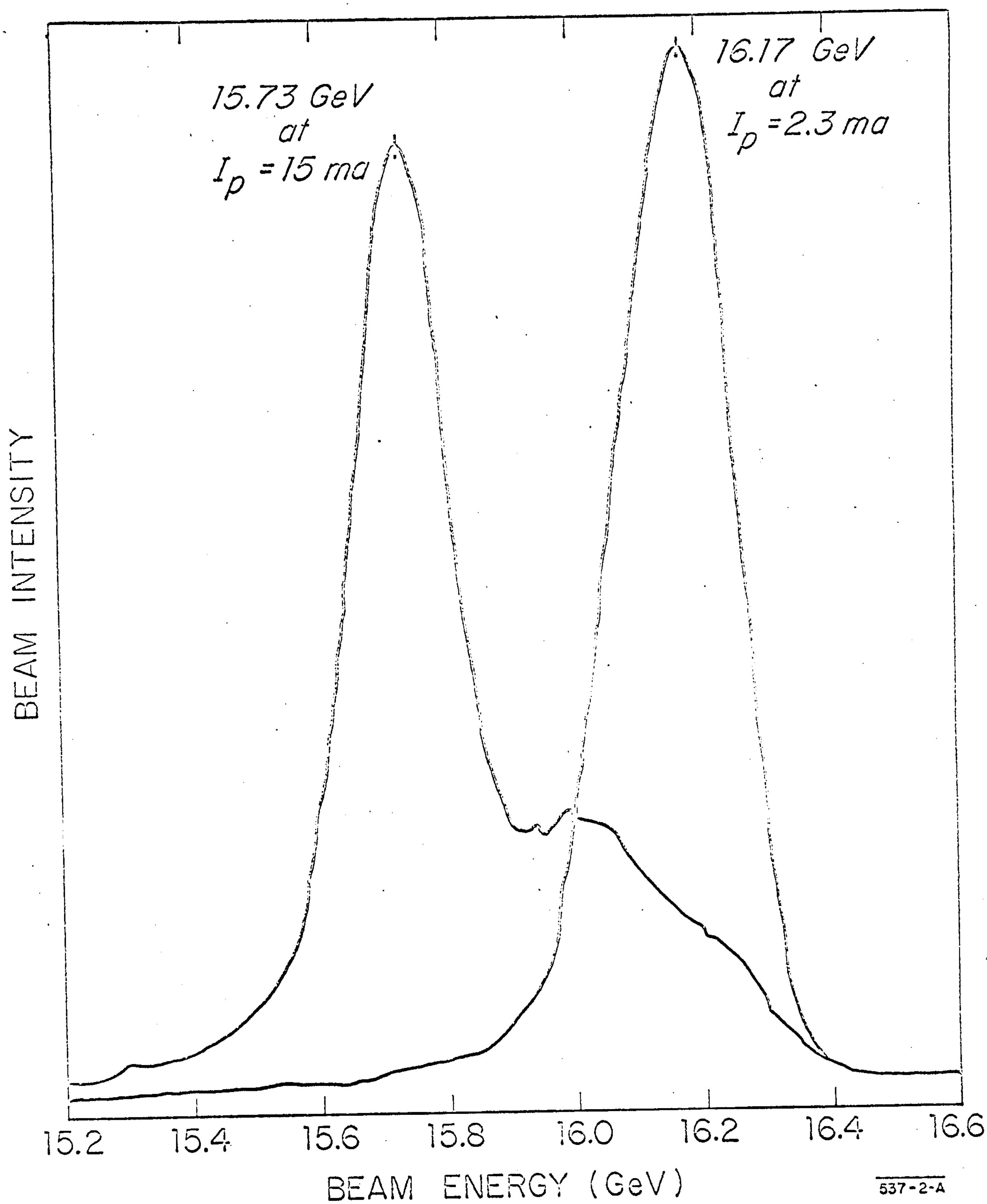

15.73 GeV
at
I_p = 15 ma
16.17 GeV
at
I_p = 2.3 ma
BEAM INTENSITY
15.2
15.4
15.6
15.8
16.0
16.2
16.4
16.6
BEAM ENERGY (GeV)
537-2-A

Figure 1

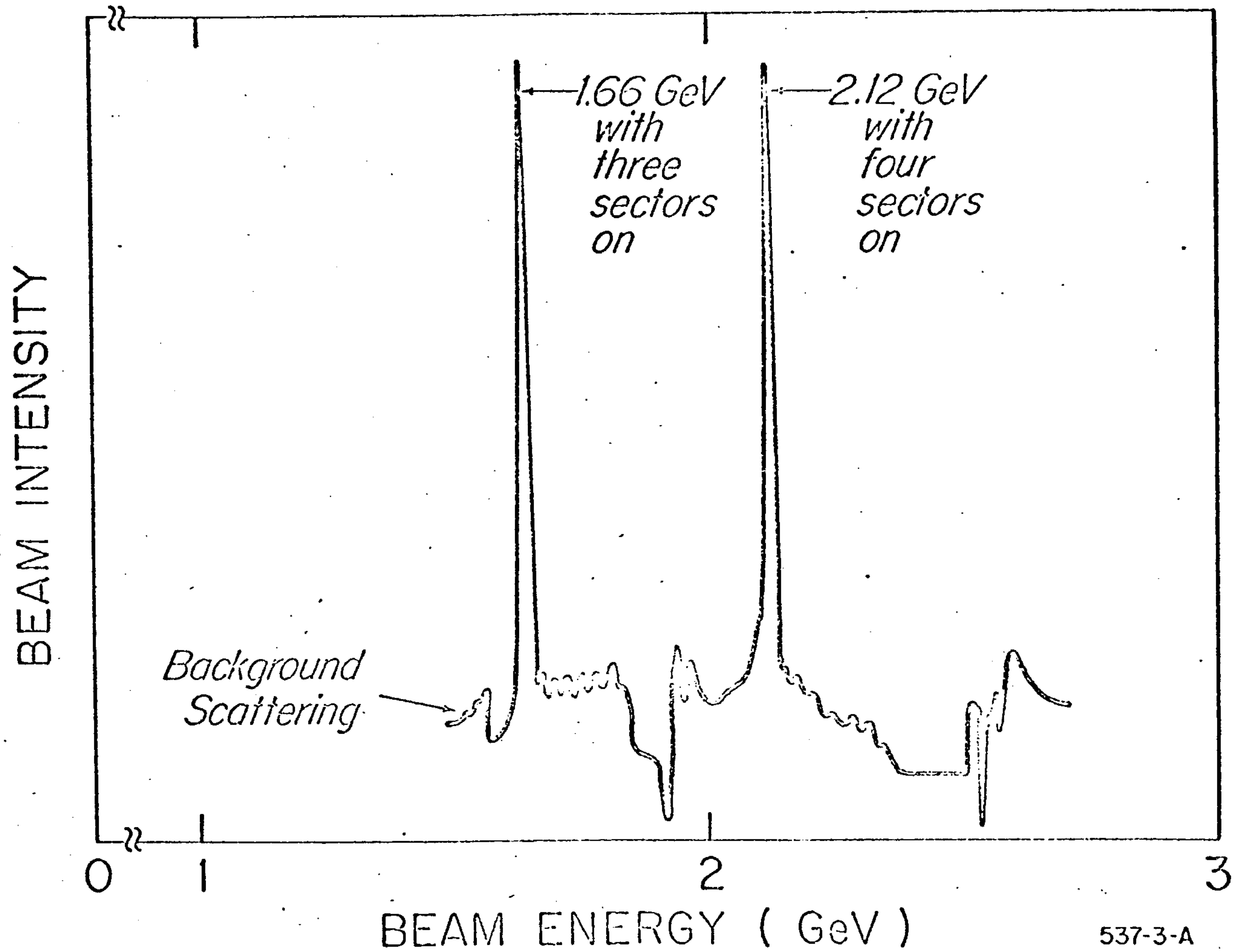
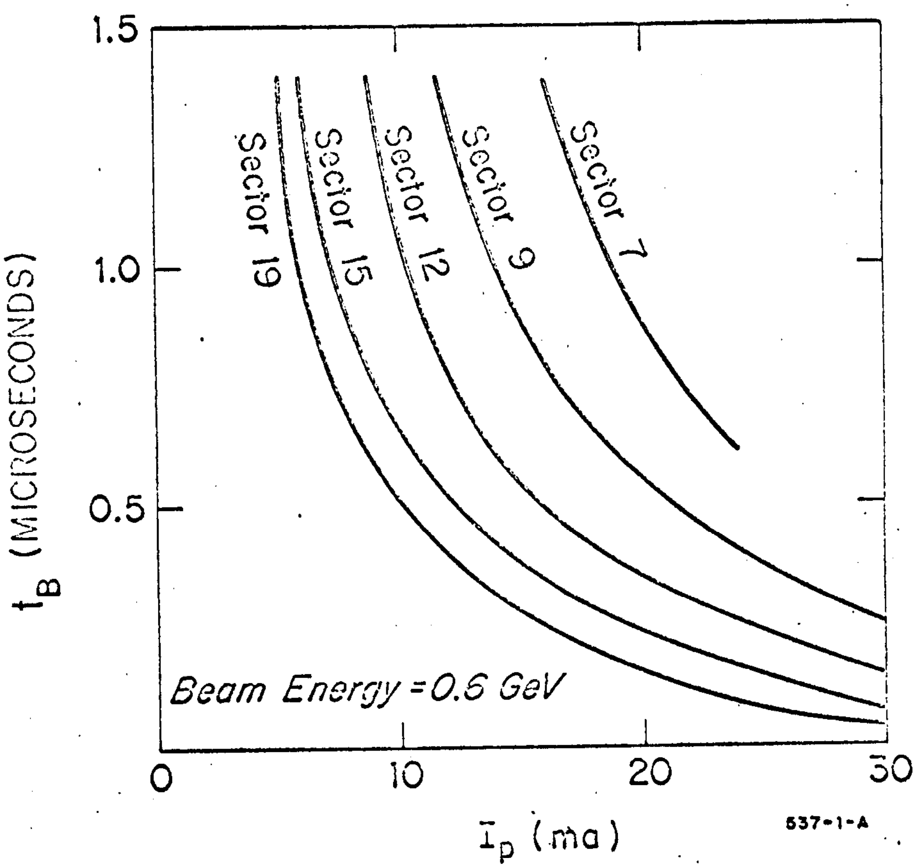

1.66 GeV with three sectors on
2.12 GeV with four sectors on
Background Scattering
BEAM INTENSITY
0
1
2
3
BEAM ENERGY (GeV)
537-3-A

Figure 2



1.5
1.0
0.5
t_B (MICROSECONDS)
Sector 19
Sector 15
Sector 12
Sector 9
Sector 7
Beam Energy = 0.6 GeV
0
10
20
30
I_p (ma)
537-1-A

Figure 3