(1969 National Particle Accelerator Conference,
Washington, D.C., March 5-7, 1969.)

SLAC-PUB-563
March 1969
(ACC)

RECENT BEAM PERFORMANCE AND DEVELOPMENTS AT SLAC*

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Summary. The purpose of this paper is to describe recent developments at SLAC which have contributed to improvements in beam operation. The paper will be divided into two parts. The first will summarize overall beam performance and operational efficiency in delivering beams to various experiments. The second will be devoted to specific developments such as the achievement of higher energies, increasingly narrow energy spectra, higher beam breakup current thresholds, chopped beams and improvements in pulse-to-pulse operation. The discussion will include a description of various new pulsed devices such as pulsed quadrupoles, improvements in the positron source and new beam loading measurements obtained for very short pulses.

Operating Experience

The Stanford Two-Mile Linear Accelerator has been in operation since April, 1966 and has been engaged in physics research since November, 1966. A general trend during the past nine quarters has been an increase in the fraction of the available shifts devoted to particle physics research and a decrease in the fraction used for machine physics.

An operations summary giving the percentages of manned operating time devoted to particle physics and to machine physics and the percentages required to satisfy various functions and contingencies is shown in Table I. Fortunately, it has been possible to reduce the non-productive portion of the manned hours in a reasonably steady manner during operations to date.

TABLE I
ACCELERATOR OPERATION SUMMARY

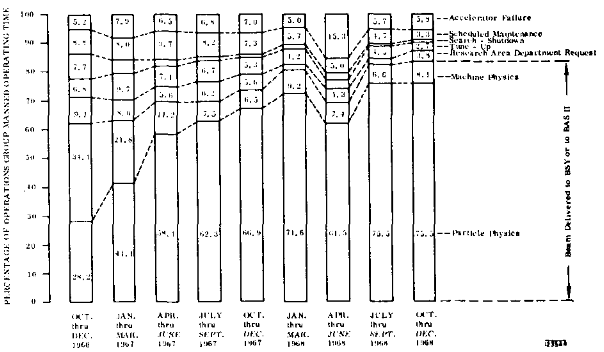

Table II is a display of machine operations giving the actual hours devoted to productive and non-productive categories of work. Because of multiple-beam operations whereby several experiments can be conducted simultaneously, the total experimental hours exceed the total beam hours by a factor which has increased more or less steadily during the past six quarters. In the most recent quarter reported this factor is 3.4.

Performance and life of the SLAC high power klystrons are reported in a separate report[1] to this conference. At this date, 122 of the 245 tubes attached to the accelerator still perform satisfactorily after 10,000 hours of operation. Mean life of all tubes is predicted to be 12,000 to 15,000 hours.

Table II
MACHINE OPERATIONS

	FY 1968				FY 1969	
	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter	1st Quarter	2nd Quarter
A. MANNED HOURS						
Physics Beam Hours						
Machine Physics	130	82	74	142	68	121
Particle Physics	909	735	958	879	979	1,117
TOTAL	1,039	817	1,032	1,021	1,047	1,238
Non-Physics Hours						
Scheduled Downtime	136	98	70	137	55	49
Unscheduled Downtime Due to Equipment Failure	163	134	107	230	108	104
All Other (Machine Tune-Up, etc.)	286	215	170	212	150	113
TOTAL	585	447	347	579	313	266
TOTAL MANNED HOURS	1,624	1,264	1,379	1,600	1,360	1,504
B. EXPERIMENTAL HOURS						
Machine Physics	164	104	103	194	153	106
Particle Physics	1,498	1,162	1,971	1,956	2,616	4,066
TOTAL EXPERIMENTAL HOURS	1,662	1,266	2,074	2,150	2,769	4,172

Electron Beam Performance

Overall beam performance is summarized in Table III. The maximum energy of 21 GeV was reached on an experimental performance run on September 13, 1968. It corresponds to a contribution of about 90 MeV per klystron. Typical physics runs require simultaneous interlaced beams between 5 and 18 GeV. Most experiments use the maximum available pulse length (1.6 μs) with typical current requests varying between 500 μA and 40 mA peak. The new gun modulator is now capable of delivering such widely varying currents on a pulse-to-pulse basis. The recently achieved maximum beam breakup threshold of 55 mA peak is discussed in detail below. An increasing number of experiments use time-of-flight techniques to "tag" their events. This requires

TABLE III
ELECTRON BEAM PERFORMANCE

Energy range	1 - 21 GeV
Typical energy spectrum	0.2 - 2%
Maximum peak current into BSY (Limited by beam breakup)	55 mA at 1.6 μsec pulse length
Repetition rate	1 - 360 pps
Pulse length	0.050 - 1.6 μsec
Maximum beam power	500 kW
Number of simultaneous beams	6
Typical transverse phase space	
Injector	$0.004\pi \left(\frac{\text{MeV}}{c}\right)$ (cm)
BSY	0.01π to $0.03\pi \left(\frac{\text{MeV}}{c}\right)$ (cm)

*Work supported by U.S. Atomic Energy Commission.

various beam-chopping modes which are also described below. The combination of higher currents and energies has made it possible to obtain beam powers up to 500 kW. Multiple beam operation has greatly improved and has become more flexible, but it is also the area where many experimenter-requests are forcing new developments such as pulsed steering, pulsed focusing, "gulch filling" and computer control described below. Some difficulties are still experienced with trouble shooting minor energy and position instabilities which sometimes appear on the beam. These are often caused by jitter on one or more klystron outputs, which are difficult to locate. Another problem is the increase in transverse phase space along the accelerator. One theory is that this increase is due to RF steering effects caused by coupler asymmetry. However, this explanation cannot be complete because the steering effects seem to be current dependent.

Positron Beam Performance

A new mode of operation of the positron source has recently been successfully demonstrated. This will permit interlacing high repetition rate positron beams with high current, high repetition rate electron beams. The former method of producing interlaced electron and positron beams utilized a moving "wand" target which moved rapidly across the accelerator aperture periodically when a positron beam was desired. This operating mode was limited to about 10 pulses of positrons per second. The new method uses a fixed target which only partially fills the beam aperture. The beam is allowed to hit the target when positrons are desired, and is steered around the target with 3-pulsed steering dipoles when electrons are desired. The beam aperture in the vicinity of the positron target is 19 mm in diameter and the beam is normally focused to about 2 mm diameter at the target. Thus it is not difficult to steer one beam so that it hits a target at the center of the aperture, and to steer a second beam so that it misses the target.

To test the method, a target was inserted so that it included slightly more than half the aperture, extending 1.5 mm beyond the center. A 25 mA, 6 GeV electron beam and a 1 mA 8.5 GeV positron beam were satisfactorily interlaced with this configuration.

Improvements in Beam Breakup Current Threshold

The maximum beam current at SLAC is limited by cumulative beam breakup (BBU), which has been discussed in previous publications.[2-7] Briefly, the effect involves interaction of the beam with a transverse deflecting mode of the HEM_{11} type, such that small amplifications of transverse displacements occur in successive accelerator sections. This results in very large overall amplification of any initial transverse noise, and eventual deflection of the beam to the walls of the structure.

The first major attempt at improving the BBU threshold was based on strengthening the focusing system. Redistribution of quadrupole magnets was carried out in 1967 and improved the threshold from an original 20 mA up to about 40 mA peak pulse current.[4,5]

Another BBU improvement program known as "dimpling" has been implemented during the latter part of 1968. This scheme depends on the fact that in the tapered accelerator structure used at SLAC, the dominant breakup interaction is with a resonant mode at ~ 4140 MHz, which exists only in the first 20 cm or so of each 10-ft structure. Hence by indenting or "dimpling" only a few of the cavities in a given 10-ft section, it is possible to detune the BBU resonance by several MHz so that the amplification in that section is no longer coherent with the rest of the machine. Since only a small fraction of the 10-ft section is affected, the energy gain in the accelerating mode is reduced only slightly. Computer analysis[7] predicted that if, for example, sectors 1 and 2 were detuned by 4 MHz in the 4140 resonance, the breakup threshold should increase by about 30%.

On the strength of the computer predictions, the dimpling program was carried out in sectors 1 and 2.

Extensive laboratory tests were made to determine the optimum dimpling pattern for detuning the HEM_{11} resonance. Dimpling was simulated by the insertion of brass screws through tapped holes in the walls of an old accelerator section. The preferred dimpling pattern was required to give maximum HEM_{11} frequency shift for minimum S-Band phase shift and VSWR deterioration. It was finally decided to dimple cavities 3, 4 and 5 in the 45° planes. This pattern gave 4 MHz frequency shift at 4140 MHz for approximately 27° phase shift at 2856 MHz.

A tool was made to clamp over the accelerator pipe, as shown in Fig. 1. The cavities were dimpled by

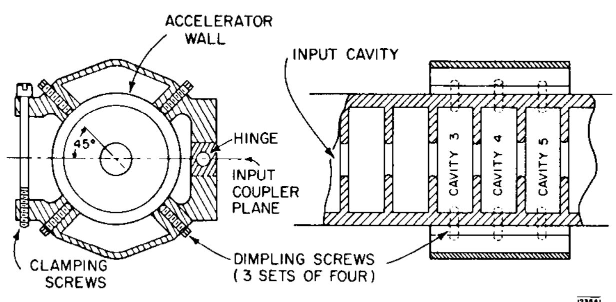

FIG. 1--Detuning SLAC beam breakup resonance.

means of the hardened-steel screws in the tool. Three reject accelerator pipes were detuned with this tool in the laboratory to confirm the correctness of the procedure. Then, during a shutdown week in May 1968, a single 10-ft accelerator section near the injector was dimpled. Since no unforeseen difficulties arose, the remaining 30 sections in sector 1 were detuned during the August 1968 shutdown. After dimpling, the phase relationship between accelerator sections fed by the same klystron was rechecked for each klystron, and waveguide feeds were adjusted where necessary. Subsequent accelerator tests showed a 7% increase in BBU threshold current, with negligible loss in energy.

Sector 2 has recently been detuned, using the same technique. A further increase of 8% in the threshold current has resulted.

Figure 2 summarizes the history of breakup threshold improvement to date. In general there has been fair agreement between computer predictions and experimental results.

Recent Beam Loading Measurements

High-current beams require beam-loading compensation to reduce energy spread. A convenient way of providing such compensation, which has been used for

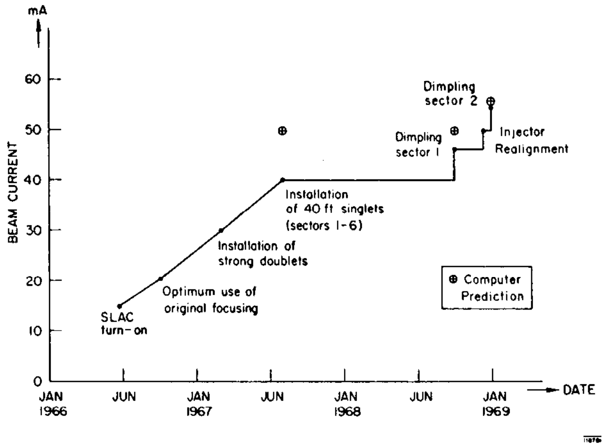

FIG. 2--Improvement of beam breakup threshold at SLAC (at maximum energy and 1.6 μs pulse length).

some time at SLAC, is to delay the turn-on of some klystrons. The rising field in the accelerator pipes associated with these klystrons then approximately balances the falling beam energy due to transient loading of the rest of the accelerator. This form of compensation has reduced the initial 5% energy spread in a 40 mA beam down to an energy spread of 0.7%. Most of this remaining energy spread is in the form of an energy depression or "gulch" about 0.6 μs wide centered about 0.6 μs after the electron pulse starts. The gulch manifests itself as a gap in the beam pulse transmitted through energy resolving slits less than 0.5% in width. Quantitative mean energy measurements have recently been made, and are summarized in Fig. 3. A 17 GeV, 40 mA beam was

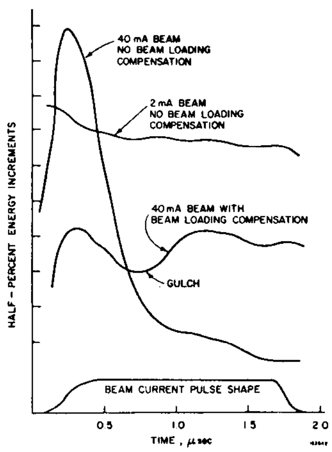

FIG. 3--Mean electron energy as a function of time, for a 17 GeV beam.

energy-mapped first with no beam loading compensation, and then with delayed turn-on klystrons as previously described. A 2 mA low current beam was also mapped to look for energy holes unconnected with beam loading. This 2 mA beam showed only the 0.5% energy drop-off predicted by normal beam loading theory. The energy gulch is apparent in the 40 mA compensated beam.

Gulch Filling

The gulch probably arises from imperfect matching between the leading edges of the beam-loading waveform and the accelerating voltage waveform in the delayed sectors. It is possible to "fill the gulch" by adding an accelerating pulse of the correct amplitude, shape and timing. This may be done in several ways: for instance, a short accelerator section (having a filling time less than half the gulch width) could be energized at the appropriate time. However, it is possible to produce a short acceleration pulse with standard SLAC 10-ft accelerator sections if the long filling-time (0.83 μs) is defeated by running a "cancelling" deceleration pulse, appropriately delayed, through the same section or an adjacent section, as shown in Fig. 4.

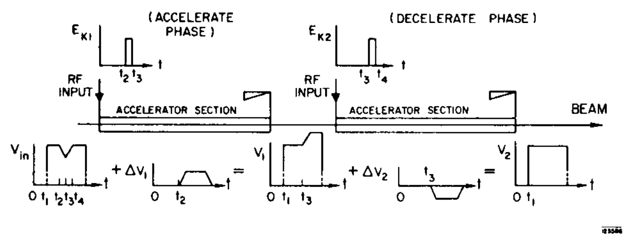

FIG. 4--Illustrating energy gulch-filling by means of short RF pulses in successive accelerator sections.

This has been done on an experimental basis by gating the drive to two adjacent klystrons with fast, high-power PIN diode switches, and adjusting the drive phases to give cancellation. The improvement in beam pulse transmitted through 0.2% slits is shown in Fig. 5.

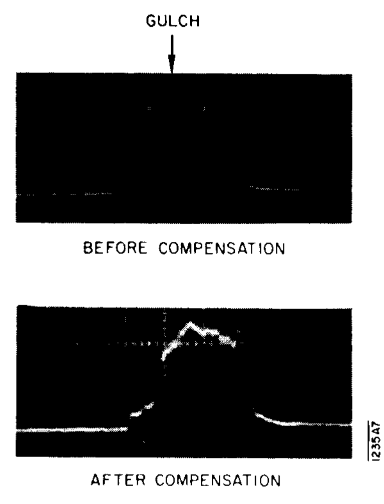

FIG. 5--Gulch-filling on a 17 GeV beam analyzed through 0.2% slits, using two klystrons.

An alternative and more flexible approach, using fast varactor phase-modulation of one or more klystrons, is being developed. This scheme will provide for additional energy compensation on the leading and trailing edges of the beam pulse, and will avoid running klystrons with reduced drive.

Pulsed Steering and Focusing

The present steering dipoles and focusing quadrupoles along the accelerator are dc. As a result, interlaced beams of different energies follow different trajectories along the accelerator, have different profiles and may enter the beam switchyard at slightly different angles. These effects often require that the operators make difficult compromises to optimize transmission and define energy. To remedy this situation, it has been decided to provide pulsed steering and pulsed focusing along the accelerator. Pulsed steering will be achieved with pulsed power supplies feeding the existing steering dipoles in the current range of ± 9 A on a pulse-to-pulse basis, at any repetition rate up to 360 pps. Six different levels within this range will be available.

Pulsed focusing will be achieved with new laminated quadrupole doublets, to be installed adjacent to the existing dc quadrupoles. The power supply will operate on the principle of resonant discharging of a parallel capacitor through the quadrupole coils and recharging through an auxiliary coil. The discharging and recharging process will take place at a constant frequency of 600 Hz. Pulse-to-pulse current variations will be obtained by using a constant sinusoidal amplitude (61.5 A) and variable adjustable time delays to trigger the discharge with respect to the onset of the beam pulse. The core aperture diameter of the quadrupoles is 2.9 cm, and the gradient for a current of 61.5 A is 2.92 kG/cm. The core length is 12.7 cm.

Initially four pulsed dipoles and quadrupole doublets will be installed at selected locations.

Chopped Beams for Time-of-Flight Experiments

The term beam knockout (BKO) has become attached to various methods of eliminating all but selected electron bunches from the machine. By these schemes, the delta function nature of the bunches is preserved, but the spacing is made variable to suit the users' requirements.

Table IV lists the capability of equipment presently in use.

TABLE IV

BEAM KNOCKOUT: CHOPPED BEAM CAPABILITY

Chopper Frequency	Burst Spacing	Max. Average Pulse Current
40 MHz	12.5 nsec (single bunch)	~ 10 mA
40 + 20 MHz	25 nsec (single bunch)	~ 8 mA
40 + 20 MHz	25 nsec (several bunches)	~ 12 mA
40 + 10 MHz	50 nsec (single bunch)	~ 4 mA
40 + 6.6 MHz	75 nsec (single bunch)	~ 3 mA
6.6 - 20 MHz (continuously variable)	75 - 25 nsec (several bunches)	1 - 15 mA (gun limited)
40 + 10 MHz + 50 nsec Gun Pulse	One bunch (~ 10 psec long)	~ 10^9 electrons

A combination of RF chopping of the bunched beam, and the usual gun grid modulation is used to produce the various beam profiles. A 40 MHz subharmonic chopper in the injector imposes a 12.5 nanosecond spacing on the bunch structure. Operating at high level, this chopper selects single bunches from the beam structure. These bunches get through the chopping plates when the sinusoidal wave driving them goes through zero. Operating at reduced level, the chopper can produce bursts of several bunches for experimenters who need more total current but lack resolution to make use of single bunches. The beam chopper and its level selection are programmed by trigger patterns. This allows the chopped beams to be used interspersed with other normal beams.

A second chopper system capable of being subharmonically locked to the 40 MHz chopper operates downstream of the 40 MHz chopper plates. This system, a nonresonant traveling-wave stripline structure, cannot be driven hard enough to gate single bunches out of the beam. However, when operated at subharmonics of the 40 MHz chopper, it can eliminate selected bunches in the 12.5 ns structure to produce beam bunch trains with 25 ns, 50 ns, or 75 ns spacings as shown in Table IV. In addition a pulsed steering dipole has been installed at the nonresonant stripline deflector. When this steering dipole is appropriately adjusted to cancel the peak RF deflection, beams with 50 ns, 100 ns, or 150 ns structures can be produced. Operating in an unlocked mode, this chopper can produce bursts of electron bunches with any spacing between 25 ns and 150 ns. This chopper also is pattern-programmed so that it may be interspersed with other beams.

The BKO choppers are being used in conjunction with a short gun pulse to produce single electron bunches in the machine. This mode of operation is currently being used in machine studies of transient beam loading effects. These effects, and further transient phenomena at the threshold of beam breakup, limit the average BKO currents to the values given in the table.

Control Room Improvements

In addition to improved instrumentation and control along the accelerator, a concerted effort to improve beam operation is being made in the Central Control Room (CCR) and in the Data Assembly Building (DAB). Following a detailed study, immediate consolidation of the two control rooms in a single location was abandoned in favor of better individual computer control, both in CCR (PDP-9 recently acquired[8]) and in DAB (SDS-925 installed in 1966). The plan is first to increase the efficiency of beam setup and control in the two respective areas and then to produce de-facto consolidation by linking the two computers. In the meantime, both consoles are being rearranged in order to permit dual control so that under peak demand conditions, operators can work in parallel on separate beams in both CCR and DAB. The dual control feature is of course relatively easy to instrument in the beam switchyard where the beams are physically separated. In the accelerator this task will gradually be facilitated through the installation of the various pulsed devices which have been described above.

Acknowledgment

The authors would like to acknowledge the many significant contributions of their co-workers at SLAC to the measurements and improvements of beam performance reported in this paper.

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