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THE SLAC ACCELERATOR: FIRST YEAR OF OPERATION*

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Early performance of the SLAC Accelerator after initial turn-on has been described in a number of previous papers.[1-11] It is the purpose of this paper to summarize the performance achieved during the first full year of operation and to discuss briefly some of the improvement programs which are now underway.

Present Performance

Electron and positron beam performance is summarized in Table I. In general, all design expectations have been met for the electron beams. The only exception is the beam break-up threshold which, although now double the value originally obtained, is still slightly under the original specification of 50 mA peak.

Simultaneous interlaced beams are obtained on a routine basis, as illustrated in Fig. 1. The two sets of pulse trains shown here represent 120 and 240 pps, respectively. The B-beam shows a special type of double-pulse. The events taking place during the early short pulse are recorded by means of spark chamber pictures; those occurring in the later, longer pulse are counted.

A special "chopped" beam has been obtained with deflector plates driven at 40 MHz. These plates are located upstream of the first accelerator section, in the injector. Trains of bunches spaced 12.5 nsec apart and locked to the accelerator RF have thus been generated for time-of-flight experiments. A similar system is capable of operating at 10 to 20 MHz.

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Generation of positron beams has not as yet been easy. Most of the present difficulties can be traced to the perhaps overly ambitious early desire for high yields and flexibility, which required:

(a) a 300-kW "trolling wheel" radiator

(b) a 1 to 9 pulses/sec pulsating "wand" radiator

(c) up to 3700-ampere focusing solenoids

(d) simultaneous beams of positrons and electrons

While satisfactory positron beams have been obtained (see Fig. 2) with impinging electron beam powers up to 60 kW, the "wheel" radiator is still not complete because of bellows problems. A short circuit and misalignments have developed in some of the focusing coils. Because of the steering caused by these misalignments, simultaneous high current electron operation with positron "wand" operation is still not entirely satisfactory. These problems are presently receiving maximum attention and should be remedied in a few months. Overall redesign of the positron source for better capture is also being contemplated.

The first electron beam was delivered through the beam transport system to the research area on September 21, 1966. Since that time, several experiments have been completed[12,13,14,15] and others are in various stages of progress.

Figure 3 shows the arrangement of the Beam Switchyard and the present layout of experiments in the research area. At present, electron, positron, and bremsstrahlung photon beams are available on the A side. They are being utilized in experiments being performed with the 1.6 GeV/c, 8 GeV/c and 20 GeV/c spectrometers in End Station A and with a streamer spark chamber in a 2-meter magnet located outside of End Station A. In End Station B, a μ beam, a neutral K beam, and an annihilation photon beam are being used for various spark chamber and bubble chamber experiments. All of these experiments are progressing

satisfactorily. The central beam of the Beam Switchyard has recently been completed and a separated charged K beam is being constructed for use with an 82" bubble chamber.

Experimental studies of beam optics and beam isochronism indicate that the beam transport system behaves in agreement with the prediction of the SLAC TRANSPORT[16] computer program which was used to design the system. Figure 4 shows an energy spectrum of the electron beam from the accelerator obtained using the B transport system. Various checks on the momentum calibration of the transport system have been made by comparing the A and B transport systems, by using a quantameter and Faraday cup, by comparing the End Station A spectrometers with the A transport system, and by calorimeter measurement. These measurements indicate that the system satisfies the criterion of ± 0.1% momentum calibration. Beam momentum resolution as low as 0.05% has been used for experiments using the spectrometers in End Station A.

Problems which have hampered delivery of the beam have been the usual ones, e.g., interlock faults, power supply failures, vacuum failures, instrumentation failures, etc. Some damage of hardware by the electron beam has been experienced. Additional interlocks and protection devices have been installed to prevent repetition of this damage. In general, no serious radiation or radioactivity has been encountered at the average power levels run to date. In a few cases, redesign and additional general-purpose shielding have been required to reduce beam-produced radiation external to the end stations in the research area. When the intense electron beam is absorbed in water-cooled high-power beam dumps, slits, and collimators, 0.30 liter of free hydrogen is released per megawatt-sec of beam absorbed in the water. The lower explosive limit of a hydrogen-air mixture can be reached in a few minutes when operating

at high power. The simple solution of diluting the gases from the surge tanks and venting to the atmosphere is prohibited for any long-term operation by the presence of excessive amounts of O^{15} (2 minutes) and C^{11} (20.5 minutes) in the evolved gases. A recombination system (see below) has been designed to handle this problem. Some of the equipment close to the beam is becoming radioactive, and remote operations have been required in a few cases. It is too early to evaluate the radiation resistance of special components.

Operating Statistics

Statistics for the first year of operation (FY 67) are shown in Table II and Fig. 5.

The total manned hours include not only operating shifts but also shifts during which the machine was shut down for scheduled maintenance, equipment modifications, and search activities. The total number of klystron hours is $\int N(t)\,dt$ where N(t) is the number of klystrons in use at a given time t. Allowing about 5% reserve, approximately 13 klystrons are needed at low beam current for each GeV of beam energy. Thus, the number of klystron hours depends not only upon the total hours of operation but also upon the average beam energy. As noted in Table II, a total of 833,413 klystron hours were run during FY 67. This is an average of 3400 hours for each of the 245 klystron sockets on the accelerator.

The total productive beam hours given in Table II are the number of hours the accelerator was operated with one or more useful beams. Accelerator beam tune-up time and other nonproductive beam time have been excluded. The total experimental hours include actual beam hours and beam downtime requested by the experimenters. This total includes the sum of the operating times of simultaneous experiments.

Figure 5 shows the percentage times devoted to the various activities on a quarterly basis. It is significant to note that the fraction of the manned shift time utilized for particle physics increased from 0 in the first quarter to 58.1% in the last quarter of FY 67. During the same interval, the time devoted to machine physics dropped from 56% in the first quarter to 11.2% during the final quarter. It can also be noted from Fig. 5 that the time consumed in other essential but unproductive activities decreased from 44% to 30.7% during the year. Steps are now being taken to reduce this unproductive time even further. It is also anticipated that the fractional time spent unproductively will decrease further as the number of operating shifts per week is increased. This improvement is expected because the productive beam-time should be roughly proportional to the average number of operating shifts per week, while the times consumed in accomplishing several of the unproductive activities are essentially independent of the number of operating shifts.

The klystrons are rated at 21 MW peak and 21 kW average power output. Their design capability is somewhat higher than these ratings. A total of 452 tubes are being procured from three industrial companies and 54 tubes are being fabricated at SLAC. By August 31, 1967, 477 of these tubes had been delivered. Tubes from all sources are designed to be repairable. The total number of tubes being procured allows both for a quantity sufficient to fill the repair cycle and to provide a suitable reserve.

Klystron operating experience through August 31, 1967, is summarized in Table III. Tube operating hours are given by quarter and cumulatively. Also given are the number of failures and average life at failure on both a quarterly and a cumulative basis. In terms of the cumulative values, one klystron failure has occurred for each 8000 operating tube hours. This is, of course, not an

accurate measure of tube life expectancy except after many generations. An attempt to predict mean life on the basis of present experience is shown in Fig. 6, where age at failure for each tube has been plotted against the percentage of tubes which have failed. The horizontal scale is constructed so that a normal failure distribution will result in a straight line when life at failure is plotted as indicated above. The data plotted omits all failures of the tubes of one of the manufacturers since the failure rate for this company is about twelve times the average failure rate for the other two companies and SLAC. Where the line crosses the 50% failure coordinate, the corresponding mean time to failure may be read on the vertical scale. The predicted mean time to failure from this data is approximately 5300 hours. This prediction has to be hedged by the fact that up until now only a small percentage of tubes have failed from old age, i.e., from such causes as lack of emission. Between one-fourth and one-third of the total failures were caused by output window failure, and at least one-third were caused by tube gassiness as evidenced by excessive arcing, pulse break-up, pulse droop and/or oscillations. There were also a few failures caused by high voltage seal punctures. A plot of age distribution of tubes installed in the gallery is given in Fig. 7. This figure shows that the mean age on September 1, 1967, was 4000 hours, and the median age was 4250 hours.

Planned Improvements

As the laboratory enters its second year of full operation, the needs of the experimenters are resulting in an ever increasing diversity of beam requirements and flexibility of operation. These demands in turn have two effects: maximum use of original accelerator design capabilities and initiation of various machine improvement programs.

With the exception of the present beam break-up limitations and positron source problems discussed earlier, it can be said that accelerator performance is satisfactory. Thus, most of the improvement programs presently being contemplated relate either to increases in original scope or additions to the existing instrumentation and controls. Among the former, a study is underway to design a simple off-axis gun in order to obtain low energy beams with greater ease and less spectrum broadening due to beam loading. Among the latter, plans are being made to improve the reliability of the automatic phasing system and to use the existing high quality video cables along the accelerator to make available, in the Central Control Room, the RF outputs from all accelerator sections. The operator will then be able to diagnose individual klystron performance. This switched video transmission system will also allow the operator to look at video beam pulses from any of the 30 toroids along the machine. Further improvements are also planned to provide (a) better quality and more flexible voice communications, (b) remote calibration of beam position monitors, (c) improved monitoring of low beam currents (from 1 to 100 microamps peak) which are required by some experimenters, (d) insertable 180° phase shifters in every sector to permit acceleration and deceleration of the beam on a pulse-to-pulse basis, and (e) pulse steering at one or more places along the accelerator to facilitate simultaneous operation with positron and electron beams.

At present, the positron source can be controlled only locally at Sector 11. Provisions will be made to allow the source to be operated from the Central Control Room.

Now that overall accelerator operation is much better known and understood, the time seems to be appropriate to acquire a small or medium-sized computer for the Central Control Room. At first, this computer would be required to do

only simple jobs such as data logging and automatic klystron replacement functions which are presently performed manually. In the long run, other jobs will be added, such as beam guidance, set-up of new beams, scanning of the phasing system, beam spectrum control, scanning of protection interlocks, and key and door release operations.

SLAC has continued to do development work on klystrons during the construction and operating periods. Recently, an experimental SLAC klystron, when operated at a beam voltage of 300 kV, produced a peak power output of 42 MW with an efficiency of 45%. While tubes having these improved characteristics are a long way from production, this result indicates that at some time in the future a significant increase in the power output of production klystrons may be possible. Many questions relating to stability and life must, of course, first be resolved.

Certain requirements for improvement and further development of the Beam Switchyard and Research Area have also been revealed. In order to accommodate new control instrumentation, the size of the Data Assembly Building (DAB) which houses control equipment for the BSY and Research Area beam transport systems has been approximately doubled. Plans and design of improved instrumentation for operation of multiple beams are in progress. The sensitivities of beam position and current monitors are being improved. Independent interlocks for multiple beams are being installed. A cathode ray display will be used in conjunction with the BSY control computer for display of information to the operator.

Numerous improvements in BSY and Research Area beam transport hardware and facilities are being made. These include modification of access arrangements, improvement of facilities at two of the high power beam dumps,

and development of thicker beam-defining slits and collimators. To allow full power beam operation without venting gases from the radioactive water systems, a fully enclosed catalytic recombination system for H_2 and O_2 has been developed and is being installed. A major improvement being made is the development of a beam switching facility which will provide switched-pulse beam operation to three targets in End Station B. This will allow several simultaneous experiments (at equal energies) to be performed at this station.

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TABLE I

Summary of Electron and Positron Beam Performance.

Maximum energy attained to date (limited by no. of klystrons and operating voltage stability).	20.16 GeV
Lowest usable energy attained to date (limited by beam loading and transmission).	0.9 GeV
Typical relative energy spectrum width (limited at high currents by beam loading and at low currents by klystron voltage jitter).	0.5 - 2%
Number of simultaneous beams (an energy ratio of at least 1:10 can be achieved; up to 6 beams will later be available).	2 - 4
Maximum beam current achieved to date for 1.6 μsec pulse length (present beam break-up limit).	43 mA peak
Usable current range	0.1 - 35 mA peak
Number of electrons for 1.6 μsec pulse length	$\sim 10^9$ to 4×10^{11} e^-/pulse
Number of simultaneous selectable gun pulse shapes	3
Chopped beams available	
at 40 MHz:	one 5 psec bunch every 12.5 nsec
at 10 MHz:	five 5 psec bunches every 50 nsec
Maximum beam power obtained to date (limited by energy, current, spectrum width and protection systems).	300 kW
Typical transverse phase space	
e^- Injector	$0.004\,\pi \left(\frac{\text{MeV}}{c}\right)$ (cm)
e^- BSY	$0.01\,\pi$-$0.03\,\pi \left(\frac{\text{MeV}}{c}\right)$ (cm)
e^+	$0.2\,\pi \left(\frac{\text{MeV}}{c}\right)$ (cm)
Positron beams	
Maximum yield to date	
at source	$\sim 3\%$
into BSY	$\sim 1.5\%$
to experimenter (within 1% spectrum)	$\sim 0.75\%$
Maximum electron current incident on positron source (limited by Beam Break-up)	~ 60 mA peak
Typical impinging e^- energy	6 GeV
Typical e^+ energy	4 - 10 GeV
Typical compatible energy of simultaneous e^- beam	10 - 16 GeV
Optimum relative e^- - e^+ RF phase	165°

TABLE II

OPERATING STATISTICS FOR FY-67

MANNED HOURS	5,700
KLYSTRON HOURS	833,413
TOTAL PRODUCTIVE BEAM HOURS	2,874
LOW ENERGY (< 3 GeV)	709
MACHINE PHYSICS	698
PARTICLE PHYSICS	11
HIGH ENERGY	2,165
MACHINE PHYSICS	493
PARTICLE PHYSICS	1,672
TOTAL EXPERIMENTAL HOURS	3,466
MACHINE PHYSICS	1,342
PARTICLE PHYSICS	2,124

TABLE III

KLYSTRON USAGE AND FAILURE

DATES	OPERATING HOURS		QUARTER		CUMULATIVE	
	QUARTER	CUMULATIVE	NUMBER FAILED	AVG. LIFE AT FAILURE	NUMBER FAILED	AVG. LIFE AT FAILURE
TO 12/31/65		27,000			10	297
TO 3/31/66	11,000	38,000	13	252	23	272
TO 6/30/66	118,000	156,000	16	234	39	256
TO 9/30/66	127,000	283,000	14	594	53	350
TO 12/31/66	176,000	459,000	23	1070	76	575
TO 3/31/67	228,000	687,000	28	1670	104	860
TO 6/30/67	303,000	990,000	26	2166	130	1130
TO 8/31/67	223,000	1,213,000	21	3118	151	1408

FIGURE CAPTIONS

1. Beam Pulses at End of Accelerator showing 120 pps (time slots 1 and 3) for A-beam and 240 pps (time slots 2, 4, 5, and 6) for B-beam.
2. Electron and Positron Beam Transmission. The height of the dots is proportional to beam intensity at the end of each sector. One electron beam (22×10^{10} e^-/pulse incident at Sector 11) and two positron beams at 4 and 10 GeV (0.4×10^{10} e^+/pulse at end of accelerator) are shown. Notice that electron and positron dot heights are differently normalized.
3. Layout of Beam Switchyard and Research Area.
4. Electron beam energy spectrum.
5. Operating statistics during FY 1967.
6. Klystron failure distribution to September 1, 1967.
7. Klystron age distribution (all vendors) in 200-hour increments on September 1, 1967.

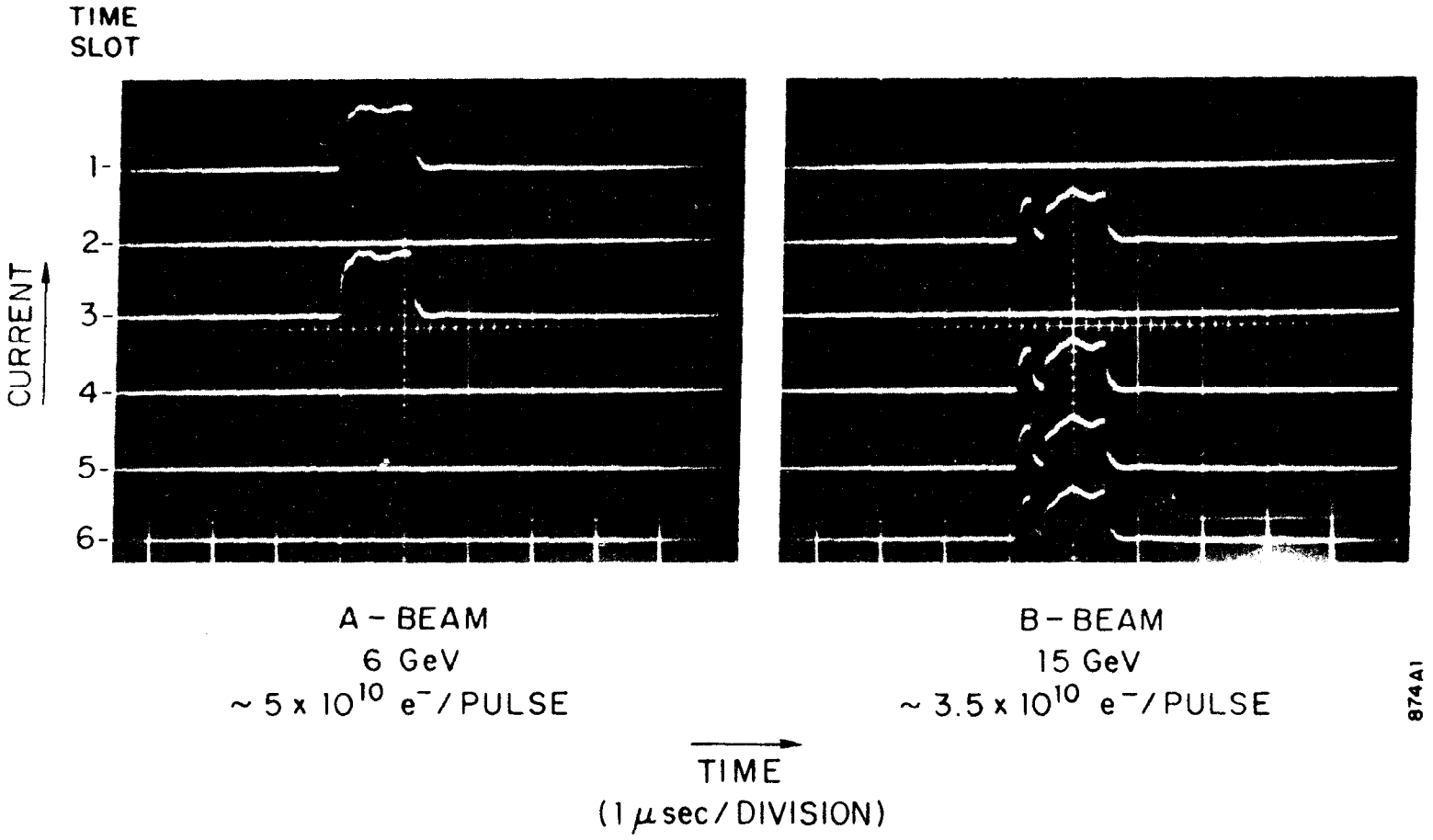
TIME
SLOT
1-
2-
3-
4-
5-
6-
CURRENT
A - BEAM
6 GeV
~ 5 x 10^10 e⁻/PULSE
B - BEAM
15 GeV
~ 3.5 x 10^10 e⁻/PULSE
874A1
TIME
(1 μsec/DIVISION)

Fig. 1

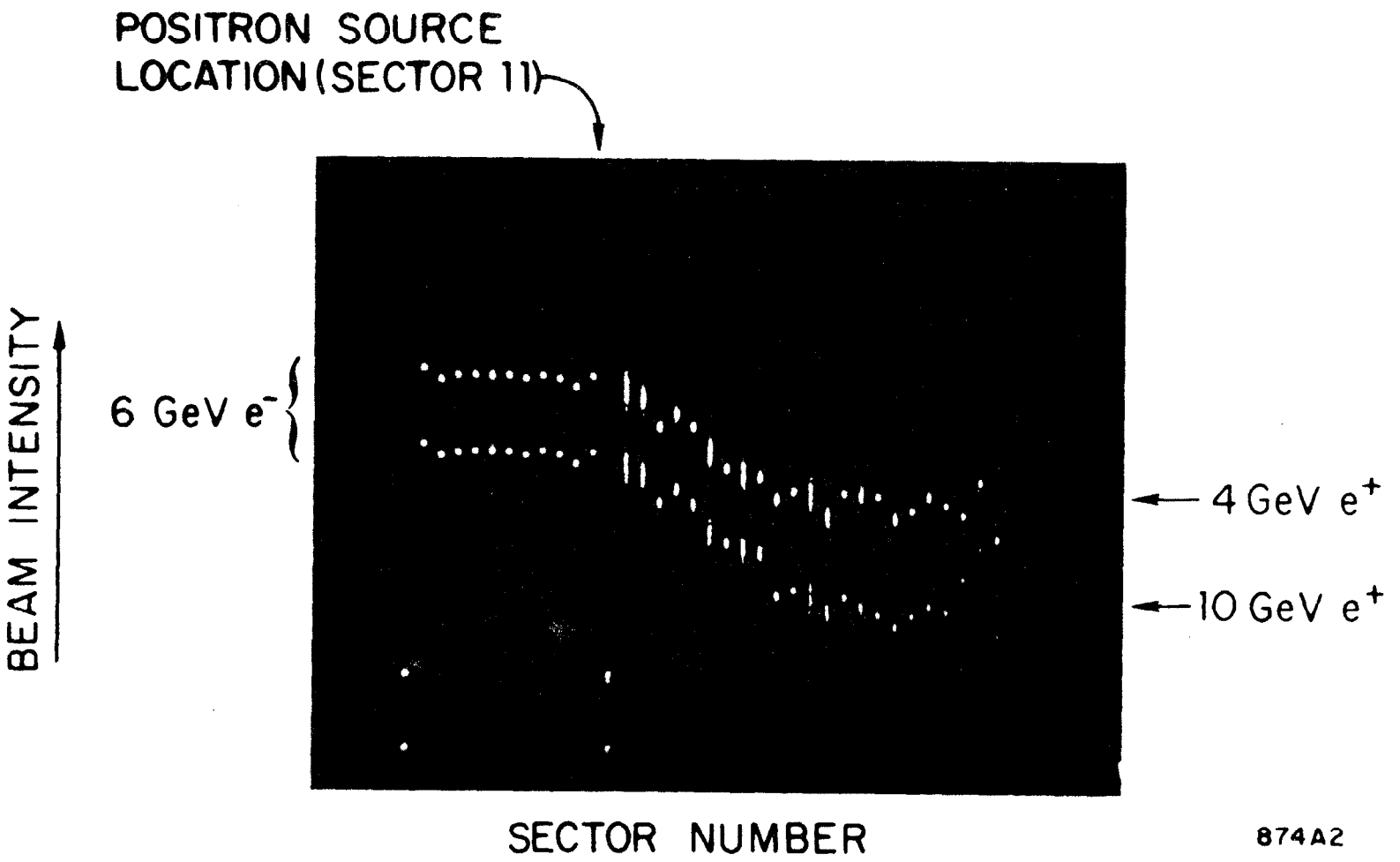
POSITRON SOURCE
LOCATION (SECTOR 11)
BEAM INTENSITY
6 GeV e⁻
4 GeV e⁺
10 GeV e⁺
SECTOR NUMBER
874A2

Fig. 2

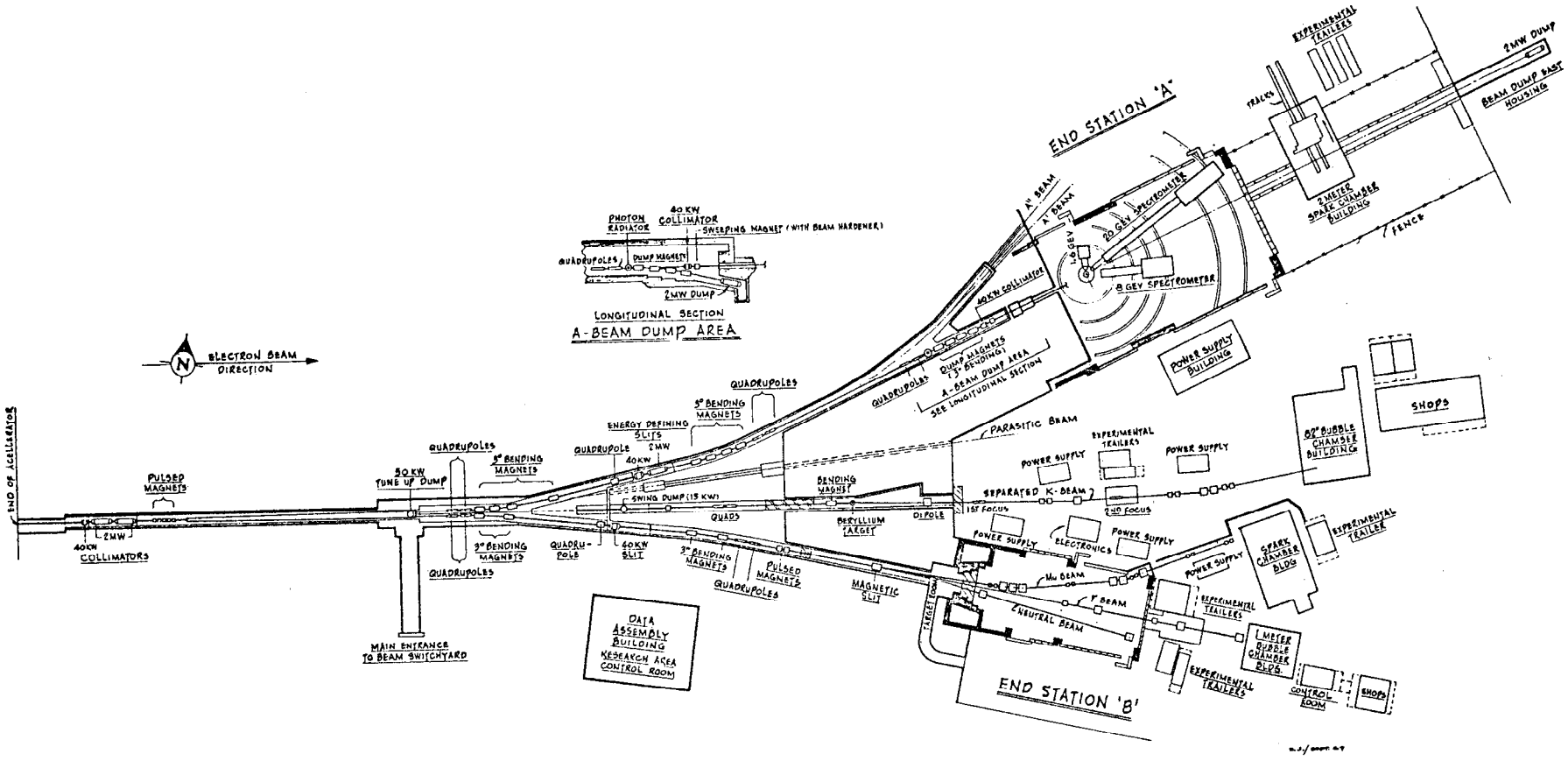
END OF ACCELERATOR
ELECTRON BEAM DIRECTION
PULSED MAGNETS
40KW
2MW
COLLIMATORS
50 KW TUNE UP DUMP
QUADRUPOLES
3° BENDING MAGNETS
MAIN ENTRANCE TO BEAM SWITCHYARD
QUADRUPOLES
3° BENDING MAGNETS
QUADRUPOLES
ENERGY DEFINING SLITS
40KW
2MW
SWING DUMP (15 KW)
QUADS
QUADRU-POLE
40KW SLIT
3° BENDING MAGNETS
QUADRUPOLES
PULSED MAGNETS
DATA ASSEMBLY BUILDING
RESEARCH AREA CONTROL ROOM
PHOTON RADIATOR
40 KW COLLIMATOR
SWEEPING MAGNET (WITH BEAM HARDENER)
QUADRUPOLES
DUMP MAGNETS
2MW DUMP
LONGITUDINAL SECTION
A-BEAM DUMP AREA
BENDING MAGNET
BERYLLIUM TARGET
DIPOLE
MAGNETIC SLIT
TARGET ROOM
NEUTRAL BEAM
π BEAM
μ BEAM
A" BEAM
A' BEAM
40KW COLLIMATOR
QUADRUPOLES
DUMP MAGNETS (3° BENDING)
A-BEAM DUMP AREA
SEE LONGITUDINAL SECTION
END STATION 'A'
20 GEV SPECTROMETER
8 GEV SPECTROMETER
POWER SUPPLY BUILDING
PARASITIC BEAM
SEPARATED K-BEAM
1ST FOCUS
2ND FOCUS
POWER SUPPLY
ELECTRONICS
EXPERIMENTAL TRAILERS
POWER SUPPLY
82" BUBBLE CHAMBER BUILDING
SHOPS
SPARK CHAMBER BLDG
EXPERIMENTAL TRAILER
EXPERIMENTAL TRAILERS
1 METER BUBBLE CHAMBER BLDG.
CONTROL ROOM
SHOPS
END STATION 'B'
EXPERIMENTAL TRAILERS
TRAILERS
2 METER SPARK CHAMBER BUILDING
FENCE
2MW DUMP
BEAM DUMP BAST HOUSING

FIG. 3

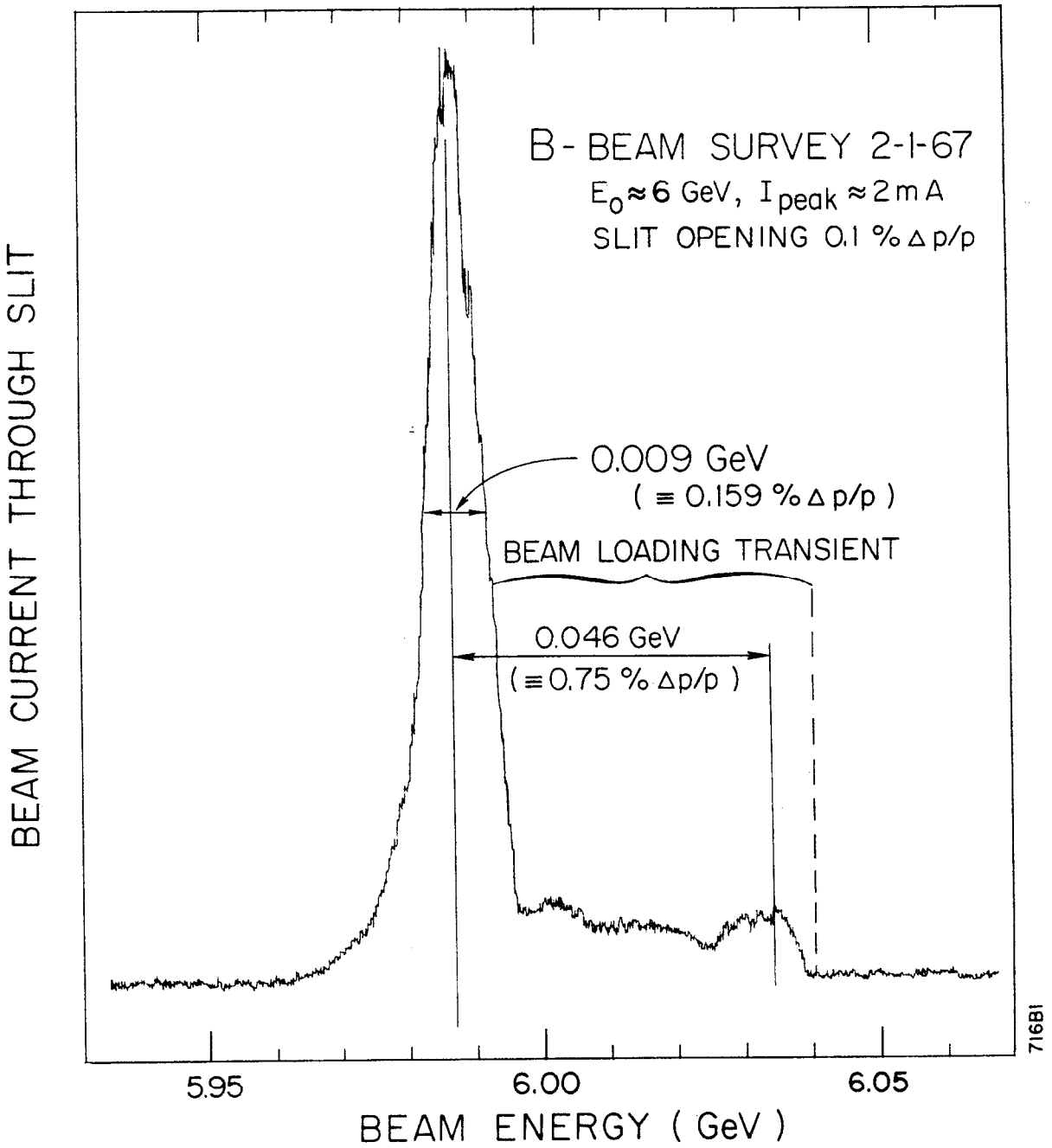
B-BEAM SURVEY 2-1-67
$E_0 \approx 6$ GeV, $I_{peak} \approx 2$ mA
SLIT OPENING 0.1 % Δ p/p
0.009 GeV
(≡ 0.159 % Δ p/p)
BEAM LOADING TRANSIENT
0.046 GeV
(≡ 0.75 % Δp/p)
BEAM CURRENT THROUGH SLIT
5.95
6.00
6.05
BEAM ENERGY (GeV)
716B1

Fig. 4

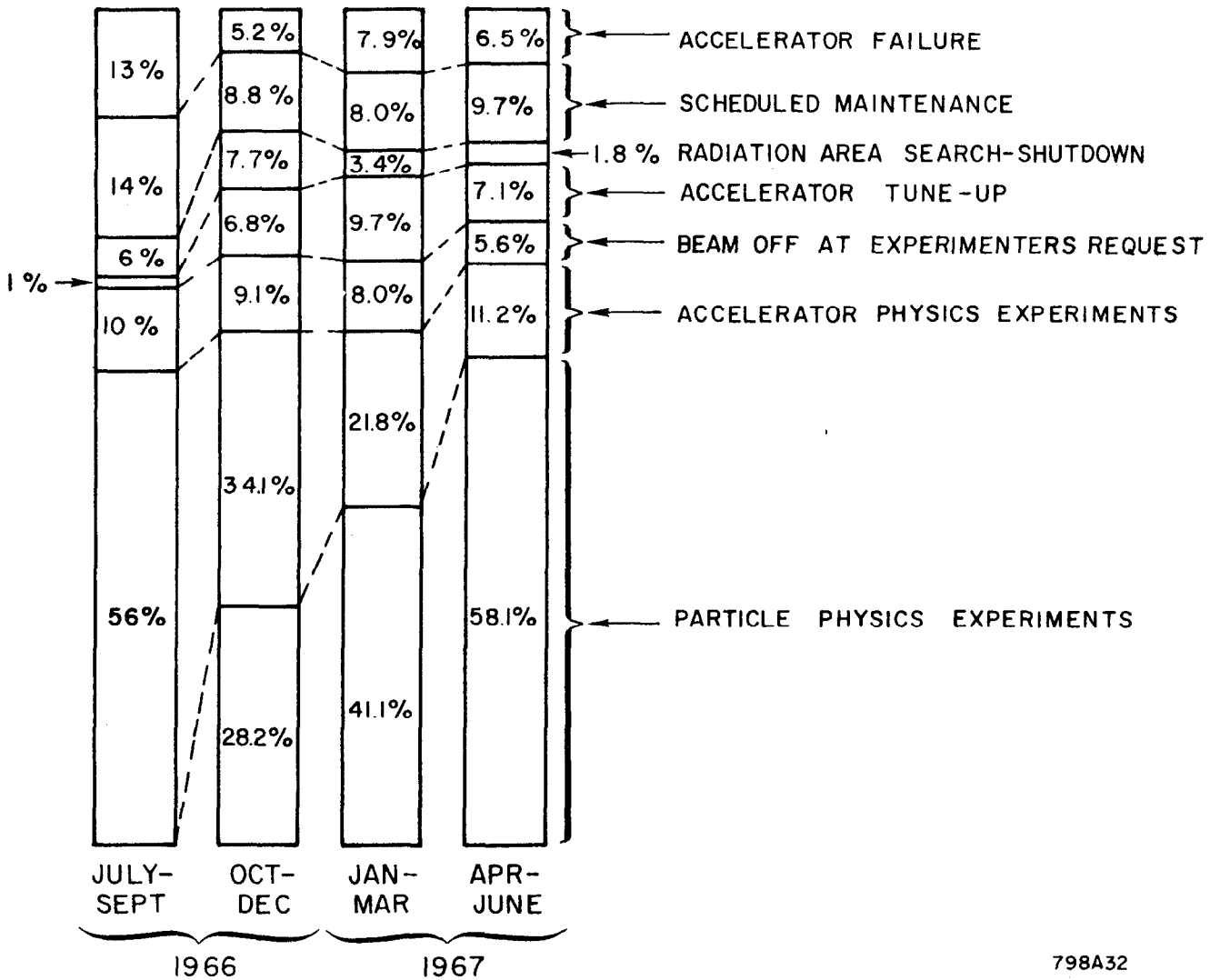
13 %
14 %
6 %
1 %
10 %
56%
5.2 %
8.8 %
7.7%
6.8%
9.1%
34.1%
28.2%
7.9%
8.0%
3.4%
9.7%
8.0%
21.8%
41.1%
6.5 %
9.7%
1.8 %
7.1%
5.6%
11.2%
58.1%
ACCELERATOR FAILURE
SCHEDULED MAINTENANCE
RADIATION AREA SEARCH-SHUTDOWN
ACCELERATOR TUNE-UP
BEAM OFF AT EXPERIMENTERS REQUEST
ACCELERATOR PHYSICS EXPERIMENTS
PARTICLE PHYSICS EXPERIMENTS
JULY-SEPT
OCT-DEC
JAN-MAR
APR-JUNE
1966
1967
798A32

Fig. 5

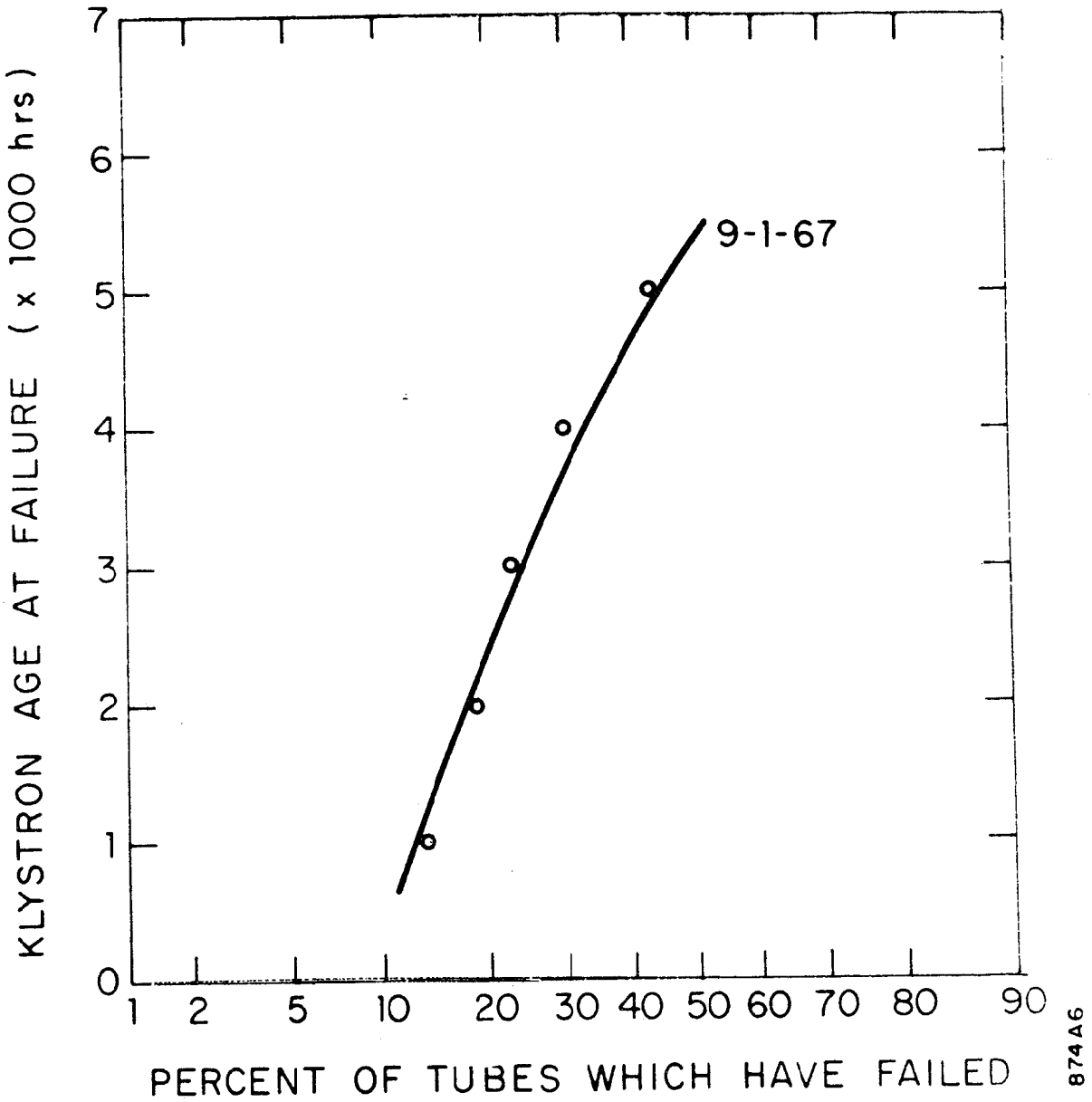
KLYSTRON AGE AT FAILURE (x 1000 hrs)
7
6
5
4
3
2
1
0
9-1-67
1
2
5
10
20
30
40
50
60
70
80
90
PERCENT OF TUBES WHICH HAVE FAILED
874A6

Fig. 6

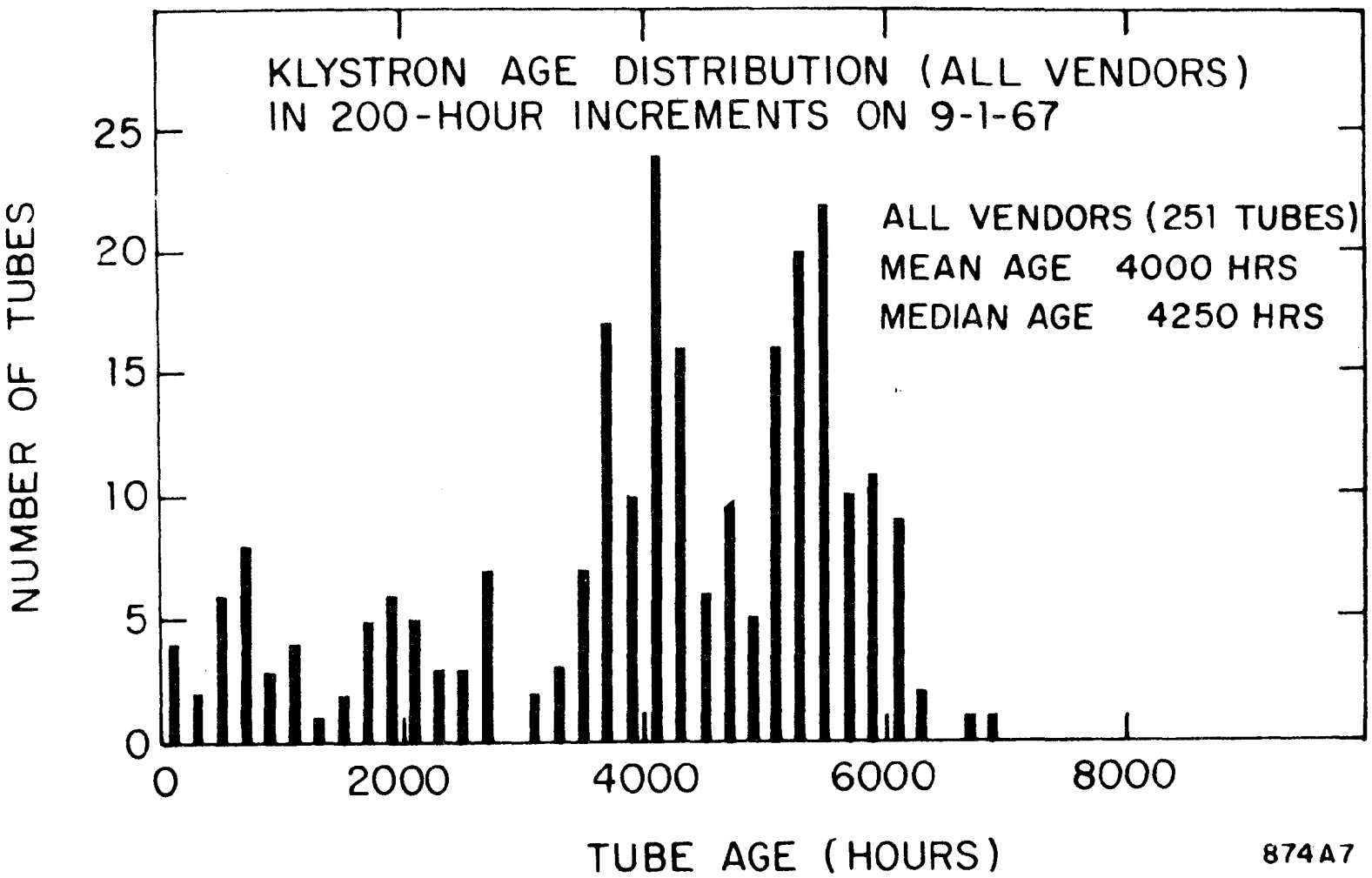
KLYSTRON AGE DISTRIBUTION (ALL VENDORS)
IN 200-HOUR INCREMENTS ON 9-1-67
ALL VENDORS (251 TUBES)
MEAN AGE 4000 HRS
MEDIAN AGE 4250 HRS
NUMBER OF TUBES
0
5
10
15
20
25
0
2000
4000
6000
8000
TUBE AGE (HOURS)
874A7

Fig. 7