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PROGRESS REPORT ON BEAM BREAK-UP AT SLAC*

BY

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Introduction

The purpose of this paper is to review the progress that has been made in the last six months in understanding and remedying the beam break-up effect (BBU) at SLAC. No attempt will be made to give a comprehensive summary of earlier work on this subject published elsewhere.[1,2,3,4] As described in these references, the BBU effect observed and studied at SLAC is of the multisection cumulative type. The first few cavities of each of the 960 SLAC accelerator sections can sustain a series of beam-induced resonances in the HEM_{11} transverse deflecting mode, of which the lowest, at $\sim$ 4140 MHz, is predominant (see Fig. 1). The effect of this two-mile chain of "resonant cavities" is that of an amplifier in which the electron bunches and the beam-induced RF wave interact cumulatively as a function of distance and time, resulting in both a growing transverse electron bunch deflection and growing HEM_{11} resonant fields. When the transverse deflection of the electrons becomes equal to the accelerator aperture, the electrons strike the walls and the familiar effect of pulse shortening is observed. For long pulses (0.4 – 1.6 μsec), the effect occurs first in the vertical direction. This is due to the fact that in the vertical plane, perpendicular to the input couplers, the Q of the resonant mode is somewhat greater than in the horizontal direction.

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For short pulses ($< 0.1\ \mu$sec), multiple RF reflections do not have the time to build up and the break-up plane direction is random. Three examples of beam profiles for a $1.6\ \mu$sec pulse are shown in Fig. 2.

The natural input excitation to the two-mile amplifier is derived from noise, the sources of which will be discussed below. The effect can also be excited artificially by means of an external signal injected onto the beam. It is interesting to note that when this excitation is injected through the coupler of an early accelerator section, the final break-up plane rotates as the frequency of the signal is changed. This fact is explained by Fig. 3 which shows how coupler mode polarization varies with frequency.

Present State of Theory

Two types of theoretical approaches to the multisection BBU problem are presently available. One is analytic,[4-9] the other uses computer programs. The Panofsky analytic formulation, most readily applied to SLAC, has the limitations indicated in Refs. 3-5 but the solution has the advantage of yielding simple scaling laws which give physical insight into the gain mechanism. For constant acceleration and in the absence of focusing, the asymptotic solution for the transverse electron coordinate x is given by the expression

$$x = x_0 \exp \left\{ \frac{3\sqrt{3}}{2} \left(\frac{C\, I\, t\, z}{d\gamma/dz} \right)^{1/3} - \frac{\omega}{2Q}\, t - \frac{1}{4} \log \frac{\gamma}{\gamma_0} \right\} \tag{1}$$

where I is the beam current, t is time, z is axial distance, ω the break-up frequency, Q the cavity loss factor, $\gamma m_0 c^2$ = electron energy, and

$$C = \frac{e}{m_0 c^2} \frac{c\, r_t \ell_1}{LQ} \frac{\omega^2}{2 c^2}$$

where r_t is the transverse shunt impedance, L the distance between interaction regions, c the velocity of light, and ℓ_1 the effective interaction length. The input term x_0 , which represents the initial deflection, will be discussed below; $\gamma_0 m_0 c^2$ is the input energy and $d\gamma/dz$ is constant. The beam starts scraping the walls when x equals the accelerator aperture radius (0.8 cm). The first term in the exponent is dominant and of the order of 20. The second is the decay term: for a typical SLAC pulse (1.5 μsec), it is of the order of 2. The logarithmic term varies slowly with the parameters of interest. Thus, neglecting all terms except the first, it is seen that I varies linearly with $1/z$ and $d\gamma/dz$, which has been verified experimentally.[2,4] It also appears that the total transmitted charge [It] is approximately conserved. As will be seen below, this prediction is not quite verified and breaks down for short pulses where the theory no longer applies.

The computer treatment currently used at SLAC is similar to the Panofsky formulation but somewhat more general. The active portions of the structure are modeled as short, isolated resonant "cavities", and the beam interaction with these "cavities" is treated in impulse approximation. Data input provides for arbitrary configurations of elements such as "cavities", drift or accelerator sections, and lenses; the parameters describing every such element can be defined individually, so that actual accelerator conditions may be simulated fairly realistically in the computations.

The beam is represented as a series of delta-function bunches, which are ray-traced successively through the various elements of the structure. This ray-tracing feature allows treatment of beam interaction with misaligned cavities, in which case "shock excitation" of the break-up mode occurs. It also permits investigation of nonlinear focusing elements such as sextupoles. Beam bunching frequency, current envelope, and initial transverse modulation (if desired) are provided as input data to the computer program.

Impulse treatment of the beam-cavity interaction specifically excludes consideration of the regenerative type of break-up. However, this effect is not believed to be important at SLAC.* On the other hand, several of the normal modes of the actual structure may be taken into account by including appropriate cavity elements in the input data, thereby partially simulating the complicated nature of the actual interaction. Results of these computations are shown below.

<u>Present Experimental Results and Comparisons with Theory</u>

Figure 4 gives a plot of BBU charge per pulse and current vs. time to break-up. The experimental points were obtained under the best focusing conditions presently available on the machine. These include the newly-completed system[5] consisting of singlets every 40 feet in the first six sectors and strong doublets at the end of each sector from there on. With this system in operation, the corresponding betatron wavelengths are approximately 150 and 400 meters, respectively. Notice that for a pulse length of 1.6 μsec, the maximum current transmitted to date is approximately 42 mA, still somewhat short of the 50 mA current originally specified but more than twice as large as the current obtained when the machine was first turned on.[1,2] This improvement is entirely due to the new focusing system.

The computed curves were obtained by successively including 1, 2 and 3 of the normal modes in the calculation. It is seen that the effect of additional modes is increasingly marked as the pulses become shorter.

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*Earlier computations[3] based on a coupled-resonator model of the accelerator structure have shown that typical beam currents are far below the threshold for regenerative break-up.

Figure 5 shows a set of curves giving the transverse beam envelope amplitude $|x|$ as a function of $(Iz)^{1/3}$. The experimental points were obtained from the amplitudes of 4140 MHz signals induced in C-Band cavities installed at the ends of sectors 5, 13, 21 and 29 with a constant external excitation at 4140 MHz injected at the beginning of the accelerator. While the curves are very close to straight lines as predicted by Eq. (1), there are four distinct plots depending on the value of z that was used. The computer results, on the other hand, show very good agreement. Two different values of $R_{\perp}/Q$ were assumed and the computed points were normalized to the experimental points in the 10^{-2} cm range.

Figure 6 shows a set of curves of BBU current vs. betatron phase shift per sector, $k_{\beta}S$. The experimental data were taken before the installation of the 40-foot singlets. Results for four different values of $d\gamma/dz$ are shown. The agreement between experiment and computation is very good.

Present Hypotheses on Noise Sources

As discussed in detail in Ref. 4, three competing sources of noise seem to be responsible for starting BBU: klystron noise power (independent of beam current I), gun shot noise power (proportional to I) and shock excitation (proportional to I^2). Figure 7 shows measured and computed klystron output powers at 4140 MHz which have to be injected at various locations to affect beam break-up. At the beginning of the accelerator, these levels seem to be of the order of 10 μwatts. While the existence of outputs at these levels has not been checked experimentally, it seems sufficiently likely to justify installing 50 db filters at 4140 and 4428 MHz between the klystrons and the accelerator in Sector 1. At the time that this report is being written, five such filters are already installed but results are not yet conclusive.

The result of another experiment[4] which attempted to identify the dominant term is illustrated by the dotted points in Fig. 8. It is seen that no clear conclusion can be drawn and that all three above hypotheses are equally plausible!

Some information about the nature of the noise sources at 4140 MHz can be gained by observing the power induced by the beam in one of the in-line cavities mentioned earlier. Numbers of counts as a function of RF pulse height are shown in Fig. 9 for three cases. If the normal beam modulation is due to the statistical noise in gun emission, the current amplitude should exhibit a half gaussian distribution. The pulse height distributions are proportional to the square of the current amplitudes and should have an exponential distribution. This seems to be borne out by Fig. 9(a). The sharp peak in Fig. 9(b) was obtained with a stimulated input. Figure 9(c) shows a case of slight saturation where the beam was occasionally breaking up in Sector 28, ahead of the detector cavity.

Figure 10 shows how the BBU threshold current diminishes when the injected beam is chopped at 20 MHz and the ratio of currents before and after chopping is increased from 1 to 32. Because the beam chopper introduces a broad spectrum of harmonics and also imparts some transverse momentum to transmitted bunches, it is not certain to what extent the curve of Fig. 10 strengthens the shock excitation hypothesis.

Conclusions

The present status of the beam break-up problem at SLAC can be summarized as follows:

1. The laws of growth of the instability are now reasonably well understood and can be predicted with good accuracy.
2. Overall understanding of the noise problem is still incomplete.
3. Remedies frequently suggested such as RF feedback, time varying quadrupoles or nonlinear focusing, do not seem to work for SLAC.

4. Further increases in beam break-up thresholds may be obtained through additional quadrupole focusing, at the cost, however, of operational flexibility. Another fairly promising RF solution is suggested by the computed curve of Fig. 11. However, while similar solutions have already been proposed earlier,[3,4,10] it should not be implemented without some prior partial experimental verification.

REFERENCES

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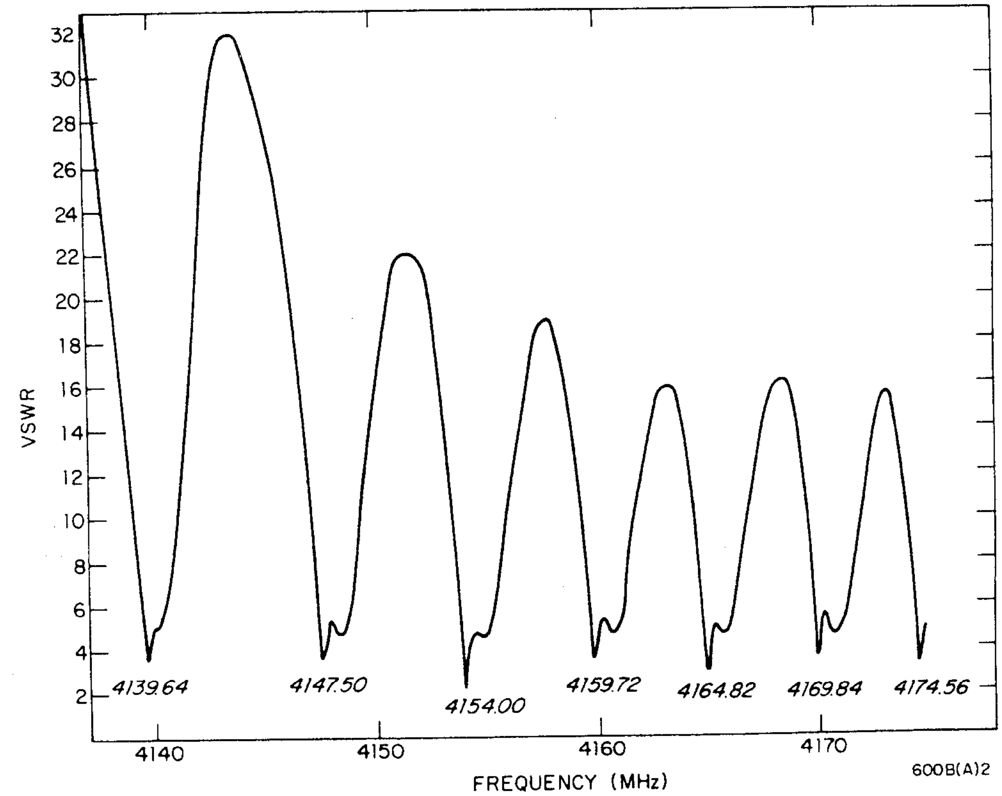
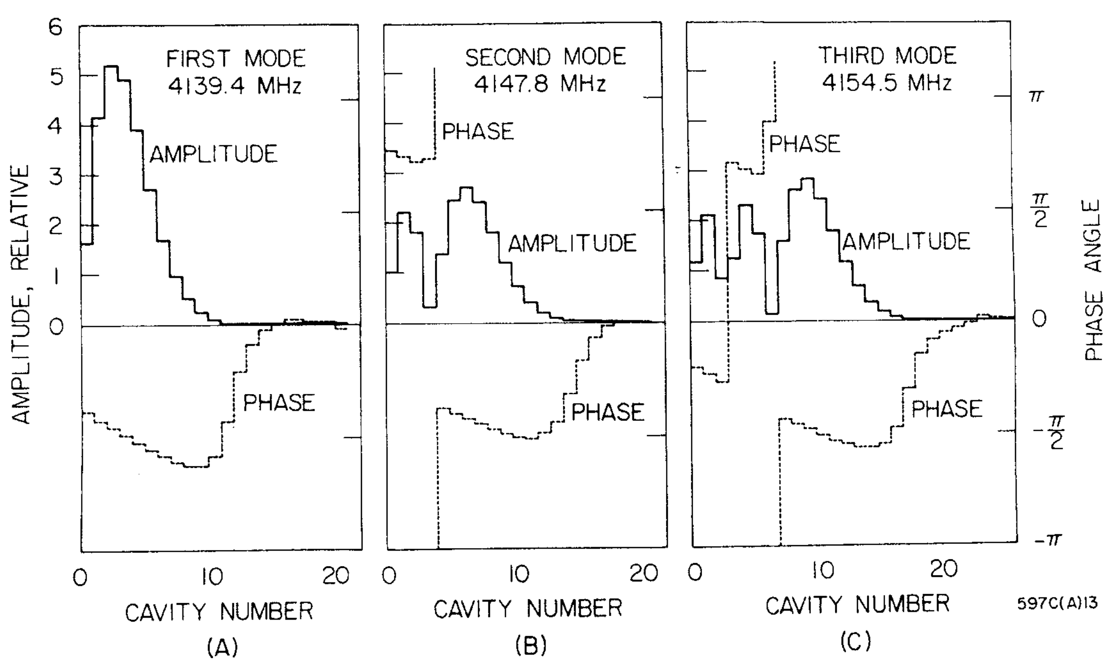
FIGURE CAPTIONS

1. Measured and computed HEM_{11}-mode resonances in SLAC Constant-Gradient sections.
2. Beam profiles at the end of the accelerator for three different currents (Energy: 16 GeV, beam pulse width: 1.6 μsec). The large grid width is 1 cm.
3. Axial electric field amplitude as a function of azimuthal angle in first accelerator section cavities as a function of frequency. (Data taken at 1/4-inch radius with metal bead using frequency perturbation method.)
4. Beam break-up charge and current vs. time to break-up. The experimental points were obtained recently (8/24/67) under the best focusing conditions presently available and at an energy of 16 GeV.
5. Transverse beam envelope amplitude $|x|$ as a function of $(Iz)^{1/3}$ (Energy: 16 GeV, beam pulse width: 1.6 μsec).
6. Beam break-up current vs. betatron phase shift per sector (Sector 19, pulse width: 1.5 μsec). Data taken in February 1967, before completion of installation of 40-foot singlets.
7. 4140 MHz power at klystron output required to affect pulse shortening at the end of Sector 19 (Beam energy: 2.2 GeV, Beam current: 18 mA). Data taken in February 1967, before completion of installation of 40-foot singlets.
8. Relative noise source power as a function of beam current. Data taken by comparison with 4140 MHz beam induced signal at Sector 29 (Energy: 16 GeV, pulse length: 1.6 μsec).
9. Number of counts vs. pulse height of rectified 4140 MHz beam induced power.
10. Beam break-up threshold at end of accelerator as a function of 20 MHz beam chopper rejection ratio (Energy: 16 GeV, beam pulse length: 1.6 μsec).
11. Computed improvement in beam break-up current threshold by "detuning" the 4140 MHz mode in Sectors 1 and 2. Only the first few cavities in each 10-foot section would be affected. Focusing as of August, 1967(Pulse width: 1.6 μsec, Beam energy: 16 GeV).

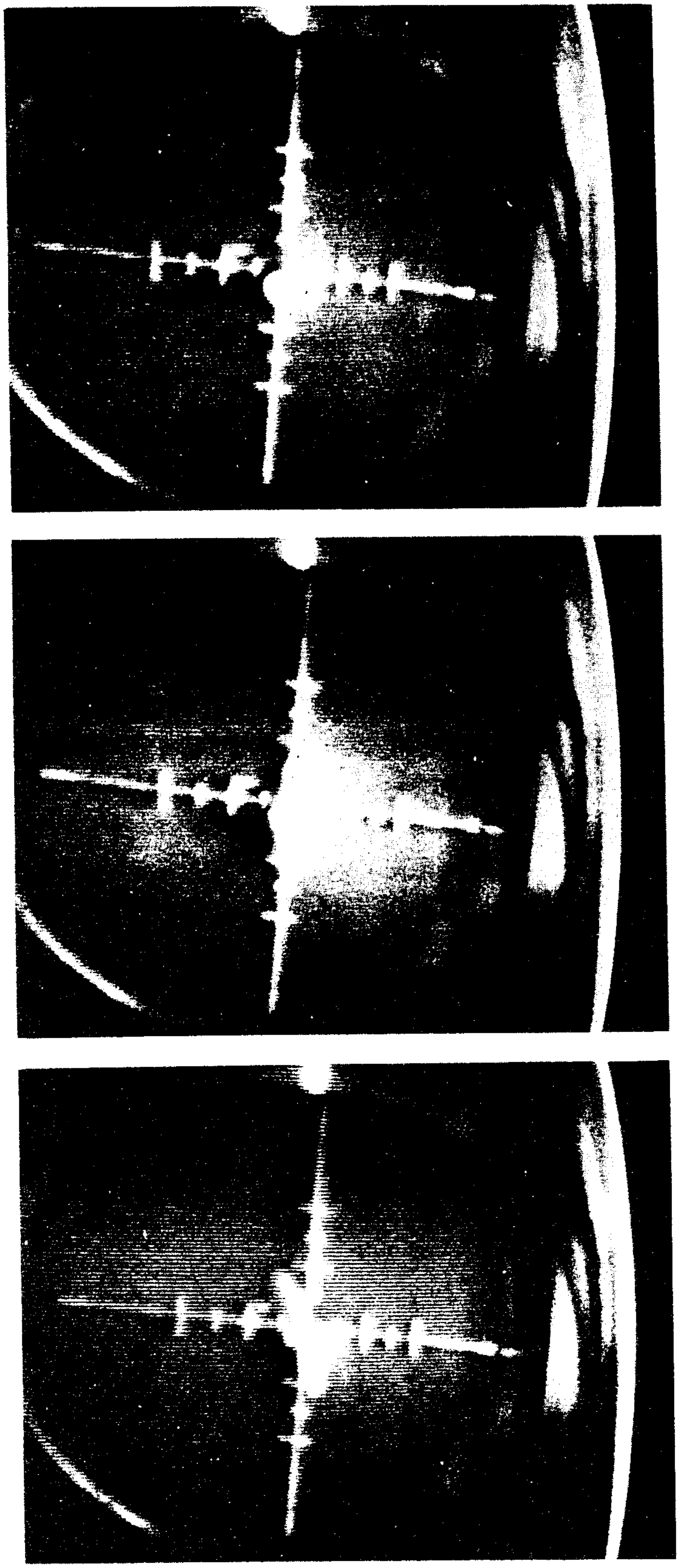


a) VSWR LOOKING INTO SECTION INPUT



b) EXAMPLES OF COMPUTED AMPLITUDE AND PHASE DISTRIBUTION

FIG. 1



(a) CURRENT BELOW BREAKUP (35 mA)

(b) CURRENT FOR PREDOMINANTLY VERTICAL BREAKUP (45 mA)

(c) CURRENT WHERE BREAKUP BEGINS TO OCCUR IN RANDOM DIRECTION (75mA)

876A1

Fig. 2

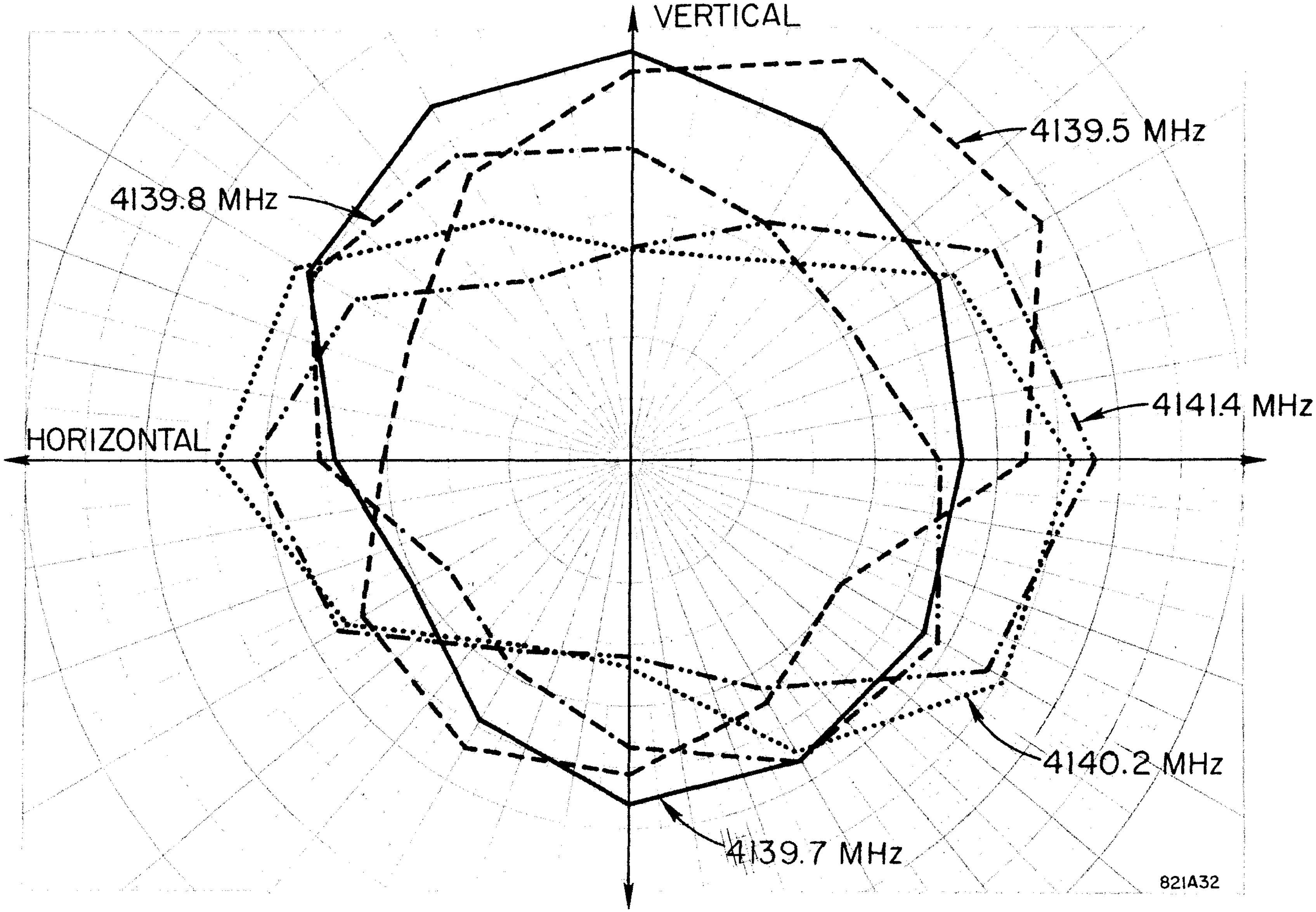
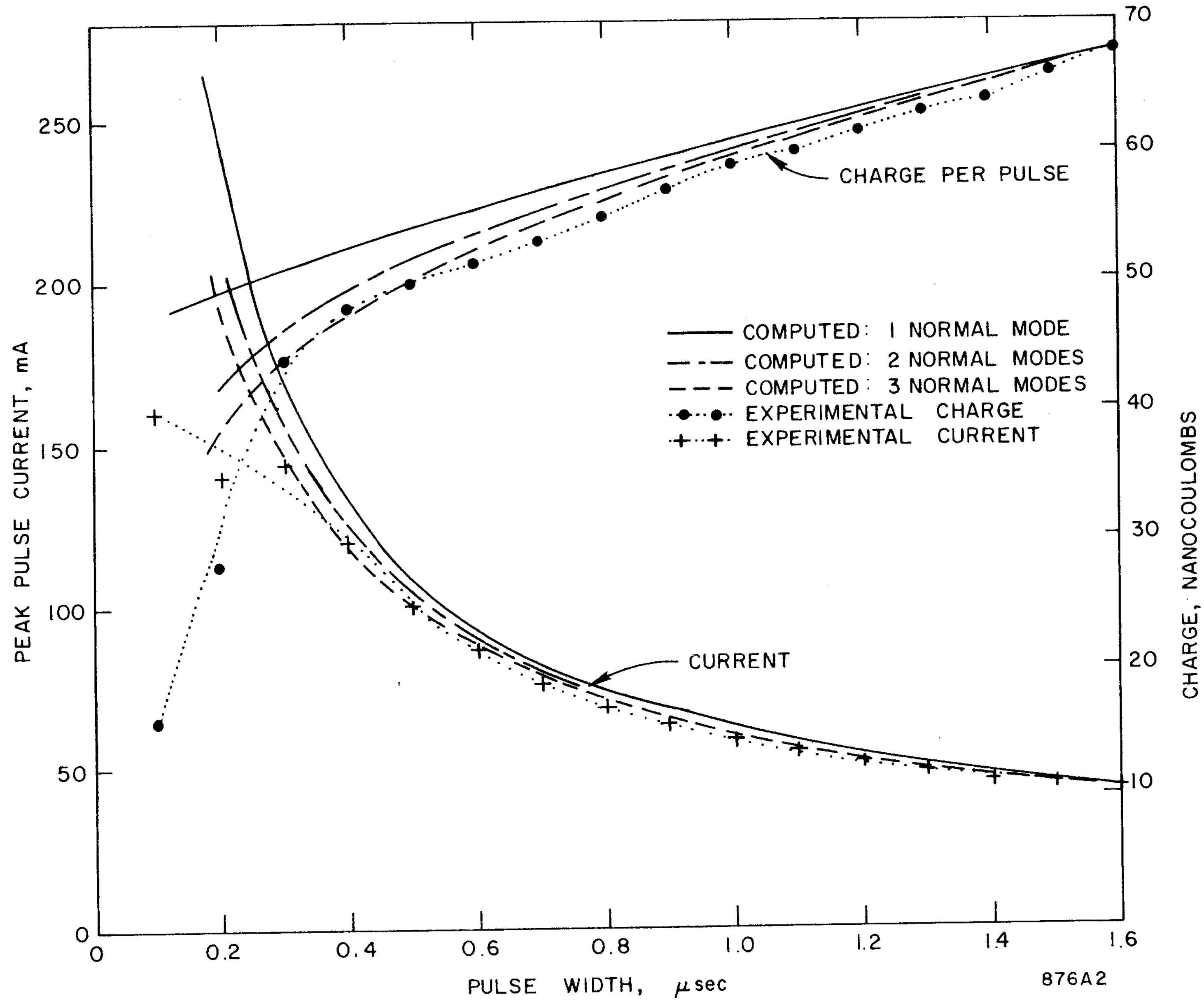
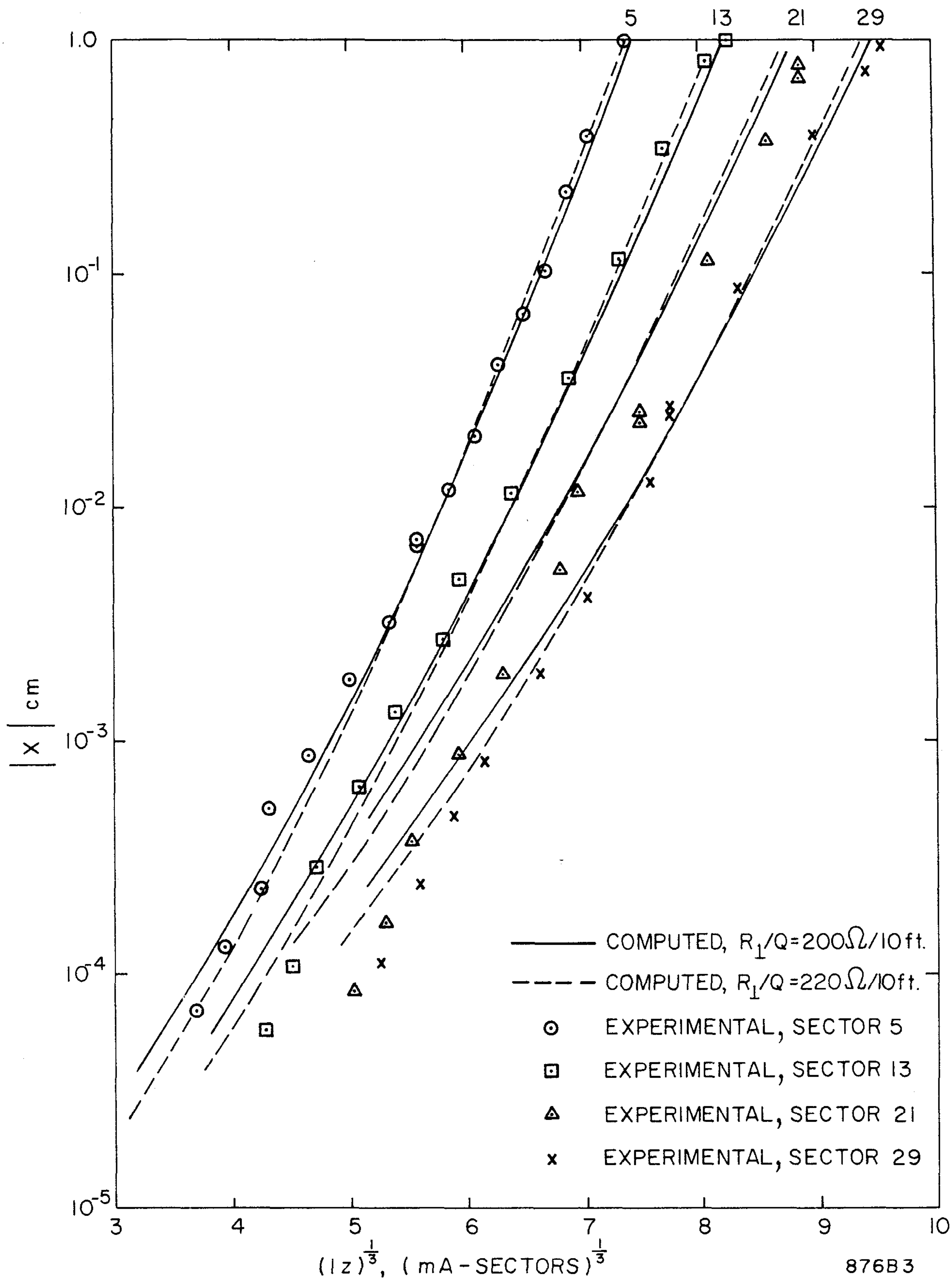

VERTICAL
HORIZONTAL
4139.5 MHz
4139.8 MHz
4141.4 MHz
4140.2 MHz
4139.7 MHz
821A32

FIG. 3



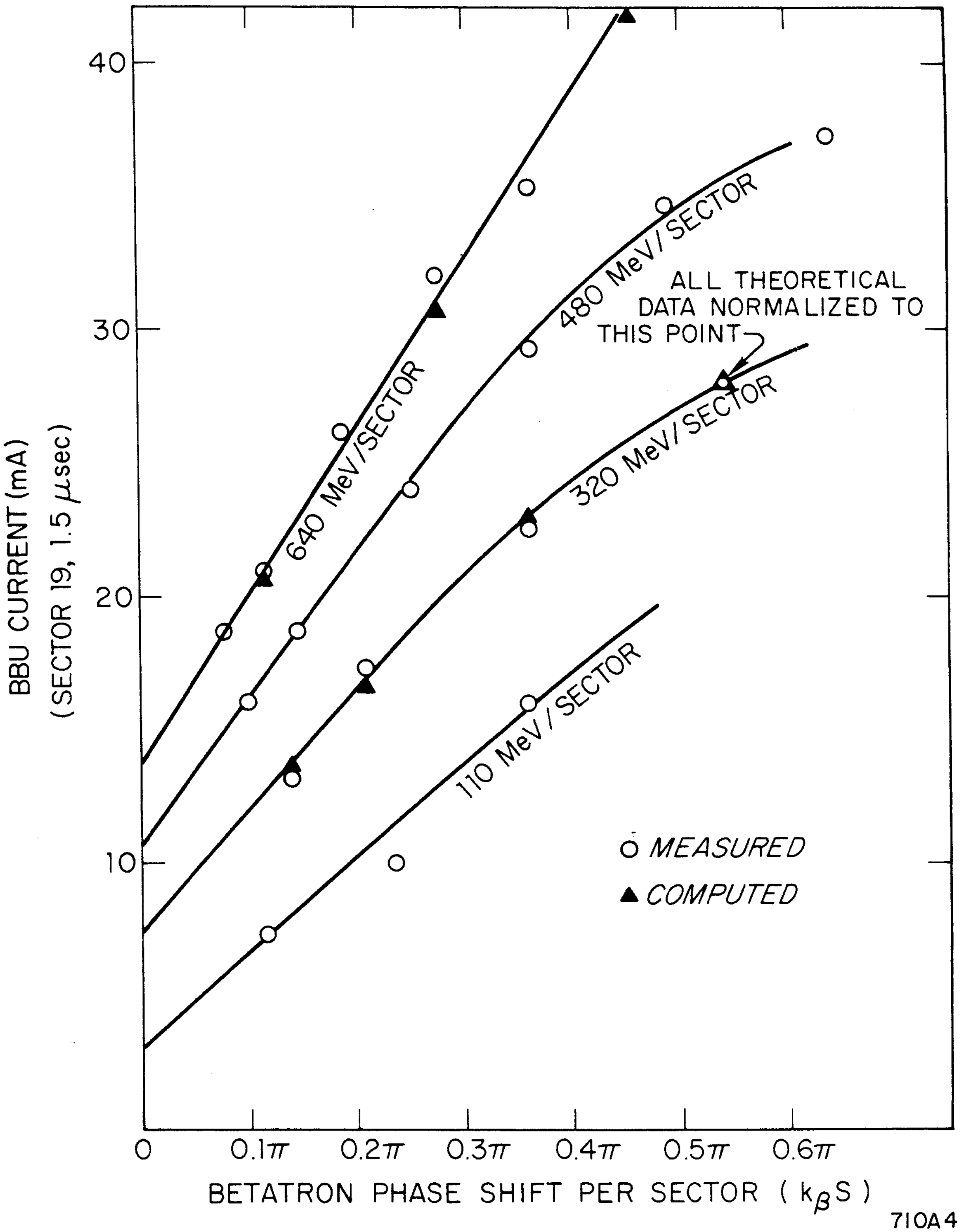
CHARGE PER PULSE
COMPUTED: 1 NORMAL MODE
COMPUTED: 2 NORMAL MODES
COMPUTED: 3 NORMAL MODES
EXPERIMENTAL CHARGE
EXPERIMENTAL CURRENT
CURRENT
PEAK PULSE CURRENT, mA
CHARGE, NANOCOULOMBS
PULSE WIDTH, μsec
0
50
100
150
200
250
10
20
30
40
50
60
70
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
876A2

FIG. 4



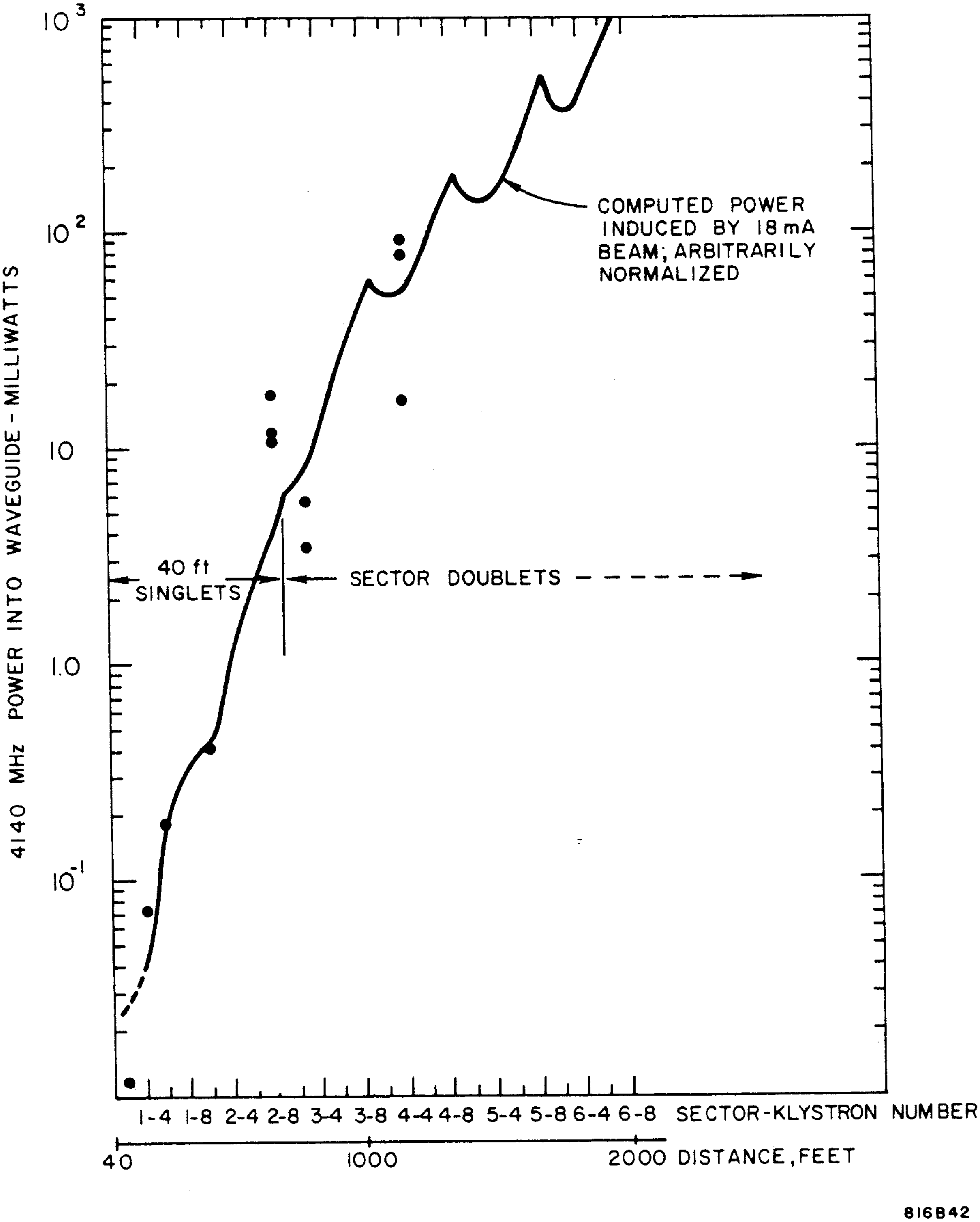
5
13
21
29
1.0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$|X|$ cm
3
4
5
6
7
8
9
10
$(Iz)^{\frac{1}{3}}$, (mA-SECTORS)$^{\frac{1}{3}}$
COMPUTED, $R_{\perp}/Q=200\Omega/10$ft.
COMPUTED, $R_{\perp}/Q=220\Omega/10$ft.
EXPERIMENTAL, SECTOR 5
EXPERIMENTAL, SECTOR 13
EXPERIMENTAL, SECTOR 21
EXPERIMENTAL, SECTOR 29
876B3

FIG. 5



BBU CURRENT (mA)
(SECTOR 19, 1.5 μsec)
40
30
20
10
0
0.1π
0.2π
0.3π
0.4π
0.5π
0.6π
BETATRON PHASE SHIFT PER SECTOR ($k_\beta S$)
640 MeV/SECTOR
480 MeV/SECTOR
320 MeV/SECTOR
110 MeV/SECTOR
ALL THEORETICAL DATA NORMALIZED TO THIS POINT
MEASURED
COMPUTED
710A4

FIG. 6



10^3
10^2
10
1.0
10^{-1}
4140 MHz POWER INTO WAVEGUIDE - MILLIWATTS
COMPUTED POWER INDUCED BY 18 mA BEAM; ARBITRARILY NORMALIZED
40 ft SINGLETS
SECTOR DOUBLETS
1-4 1-8 2-4 2-8 3-4 3-8 4-4 4-8 5-4 5-8 6-4 6-8 SECTOR-KLYSTRON NUMBER
40 1000 2000 DISTANCE, FEET
816B42

FIG. 7

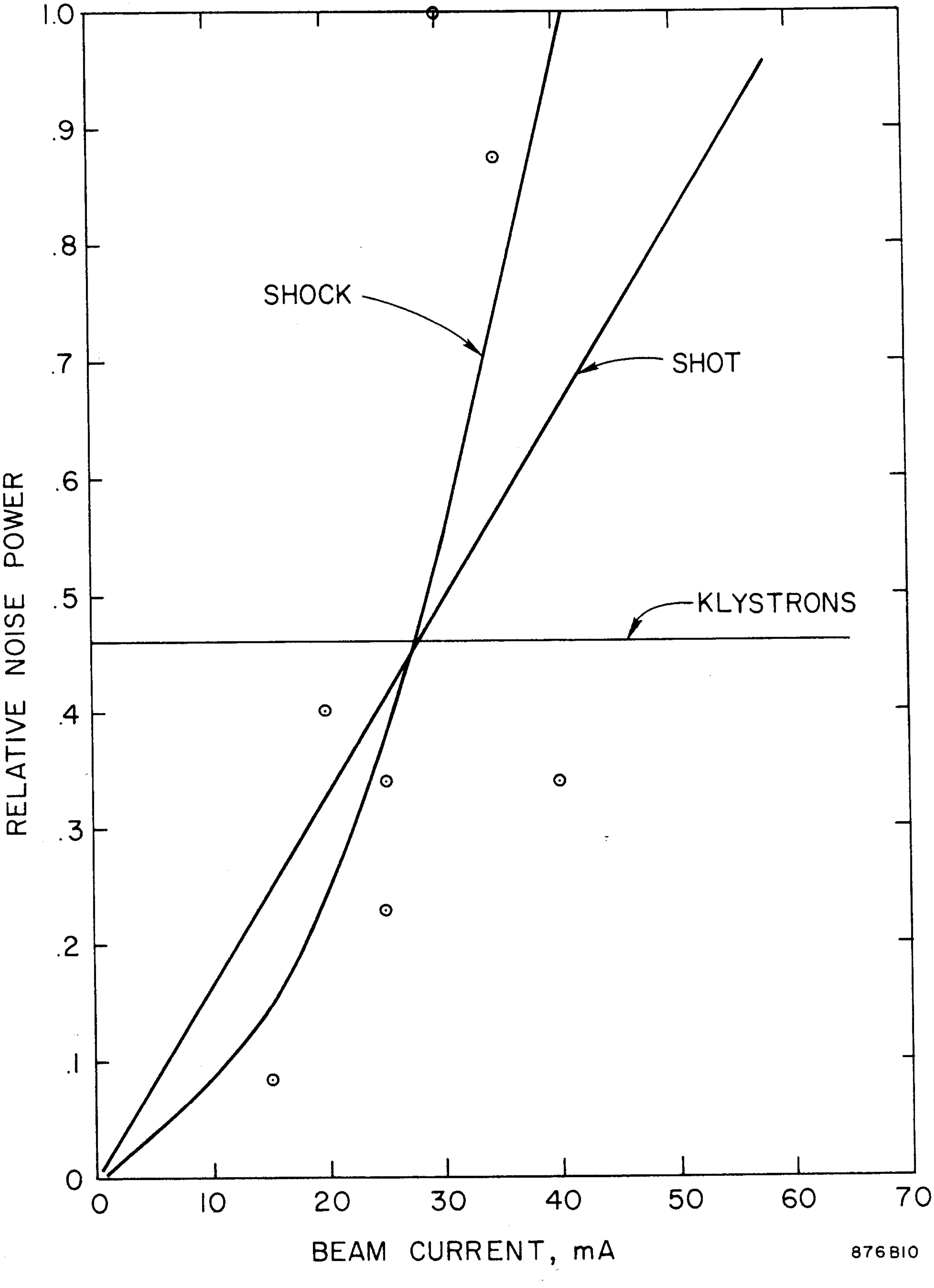
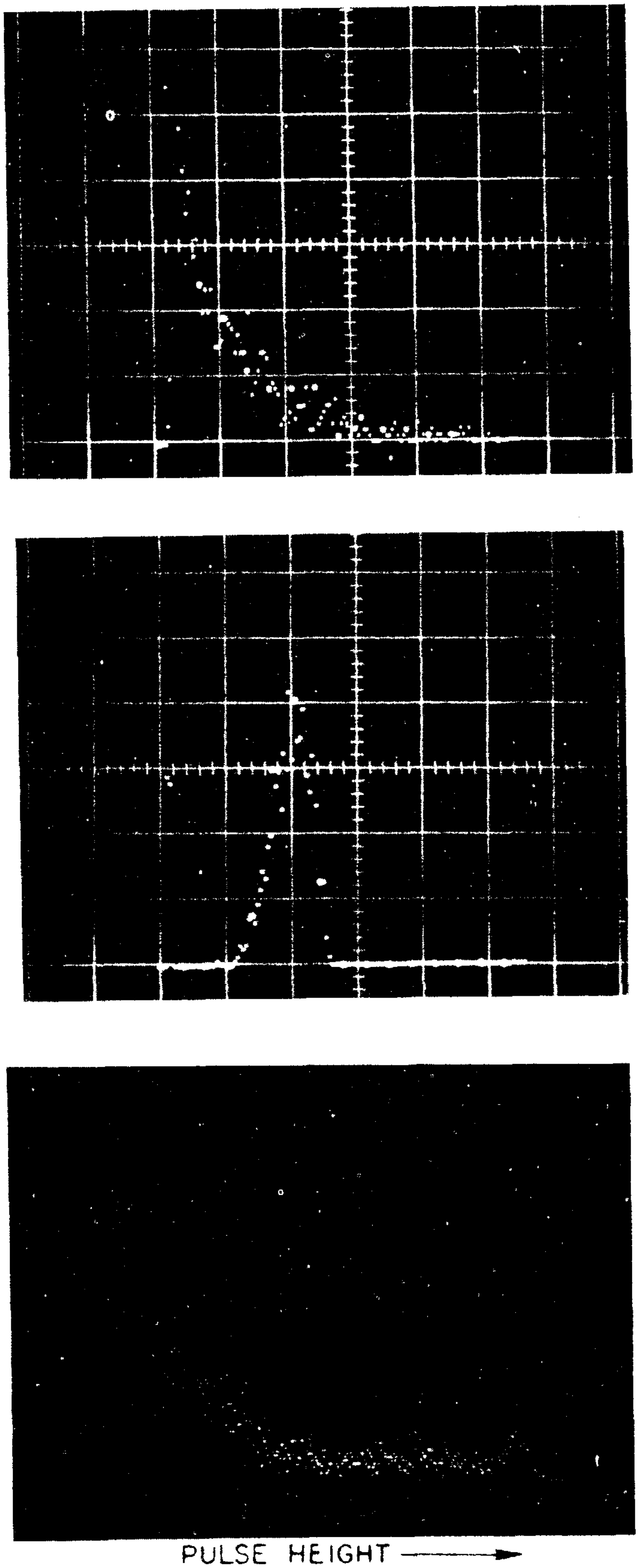

1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
RELATIVE NOISE POWER
SHOCK
SHOT
KLYSTRONS
0
10
20
30
40
50
60
70
BEAM CURRENT, mA
876B10

FIG. 8



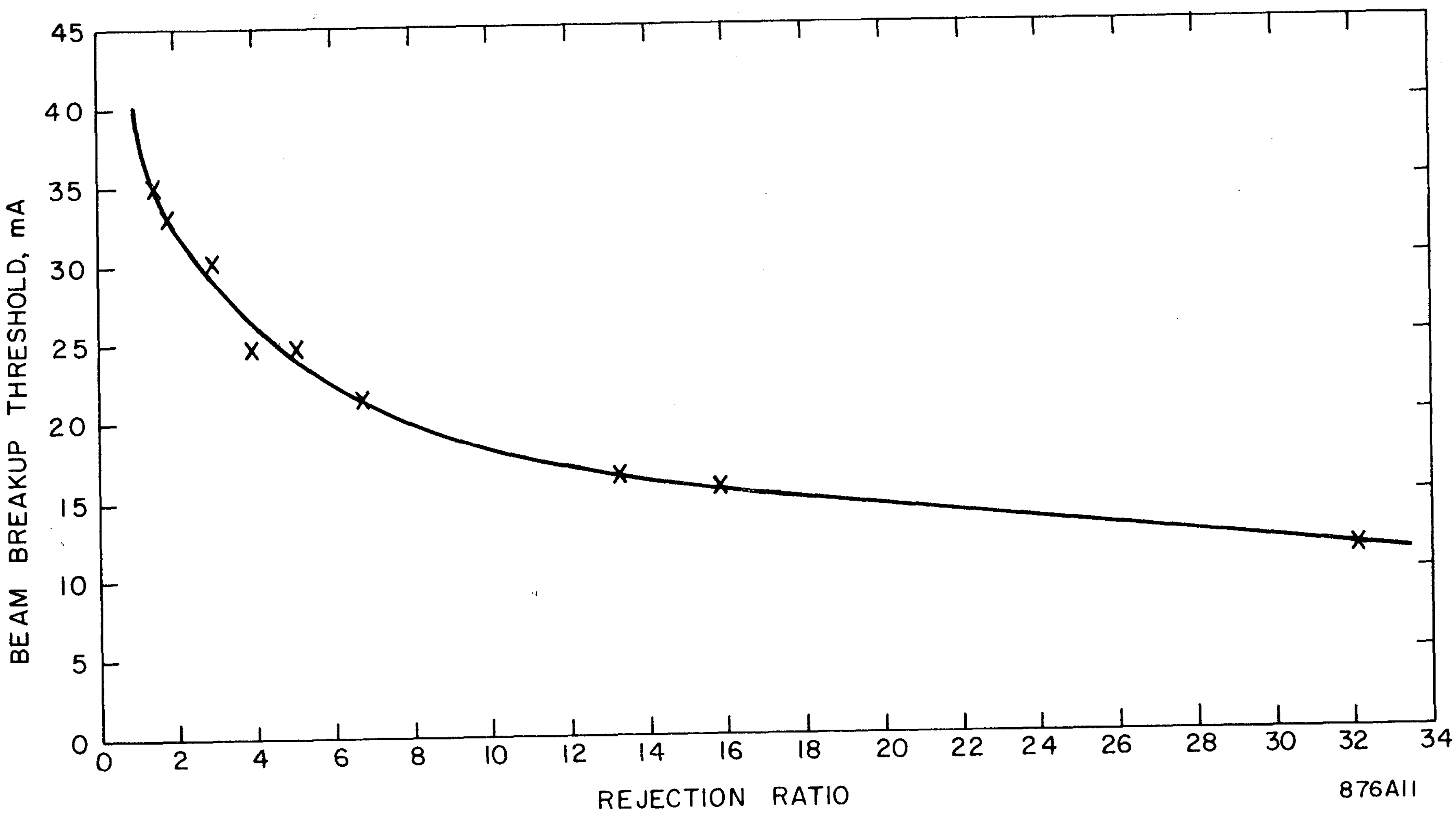
(a) NATURAL BBU, 23 mA, SECTOR 5 (FEBRUARY 1967)

(b) STIMULATED BBU, 18 mA SECTOR 5 (FEBRUARY 1967)

(c) NATURAL BBU, 40 mA, SECTOR 29, DATA SHOWING SLIGHT SATURATION (AUGUST 1967)

876A9

FIG. 9



BEAM BREAKUP THRESHOLD, mA
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
REJECTION RATIO
876A11

FIG. 10

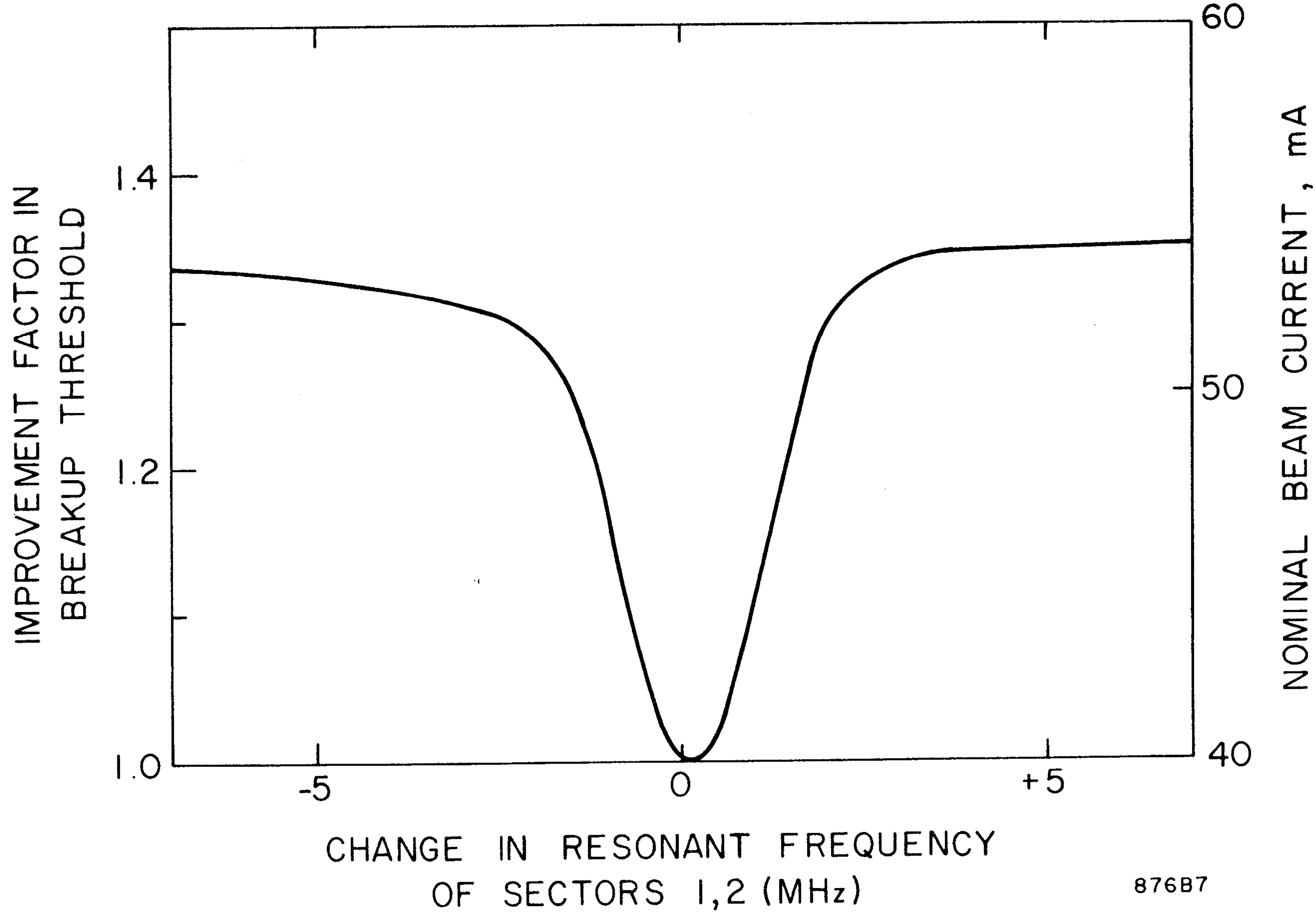

IMPROVEMENT FACTOR IN BREAKUP THRESHOLD
1.4
1.2
1.0
-5
0
+5
60
50
40
NOMINAL BEAM CURRENT, mA
CHANGE IN RESONANT FREQUENCY OF SECTORS 1,2 (MHz)
876B7

FIG. 11