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SINGLE BUNCH BEAM LOADING EXPERIMENTS ON THE SLAC TWO-MILE ACCELERATOR*

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Introduction

In September 1971, the authors presented a paper on "Single Bunch Radiation Loss Studies at SLAC."[1] Aside from its academic interest, the main motivation behind this work was its relevance to the design of electron ring accelerators (ERA). Indeed, at that time a number of laboratories throughout the world were hoping to build these new types of machines but the theories of how much energy the ring would radiate to its accelerating structure were not on firm ground and had not been tested. The SLAC two-mile accelerator seemed to be one of the few vehicles where the dependence of single bunch radiation loss as a function of energy could be measured.

The SLAC experiments were successful in leading to some specific conclusions, namely : (a) the radiation loss seemed to be independent of energy in the range between 900 MeV and 19 GeV; (b) the dependence of radiation loss on charge in the bunch appeared to be linear; and (c) the energy lost per electron for a single bunch of 10^9 electrons traversing 86,000 cavities of the linac was measured to be 35 MeV. Admittedly, the experiment had several shortcomings having to do with unknown bunch shape and bunch phase with respect to the accelerating field. In spite of this, the results seemed to agree with E. Keil's predictions at CERN[2, 3] and his later paper[4] strengthened the general confidence that theory and experiment were converging.

In the ensuing years since 1971, three relevant developments took place : (1) enthusiasm for electron ring accelerators decreased considerably because their physical realizability became hampered by a number of theoretical and practical difficulties; (2) the problem of radiation loss or beam loading reappeared on the scene because of its relevance to high current storage rings: indeed the beam energy loss to higher order modes can have a major effect on the cost of the RF system of these machines and their operation (see for example Refs. 5 - 10); and (3) the authors of the present paper, in their desire to remove some of the shortcomings of their earlier work, came up with some significant experimental improvements and obtained a considerable amount of new data. This in turn prompted them to develop an empirical theory to explain their results. Both are presented here.

Review of Experiment

The entire experiment is illustrated in Fig. 1. A single electron bunch of adjustable charge is generated in the 35 MeV injector, accelerated to 4 GeV in the accelerator and momentum-analyzed in the Beam Switchyard (BSY). The resultant energy spectrum is displayed on an x-y recorder in the Main Control Center (MCC). Since details of the instrumentation can be found in Refs. 1 and 11, only the highlights of the set-up are described here.

The single bunch beam is formed by the combination of two devices ahead of the 35 MeV injector section. One is a grid pulser which limits the normal 1.6 μs gun pulse to approximately 5 ns. The other is a resonant system which uses transverse deflecting plates. The frequency of the system is 39.667 MHz, the 72nd subharmonic of the accelerator frequency, i.e., 2856 MHz. The voltage applied to the plates is high enough that the only bunches that reach the accelerator are the ones that pass through at zero crossing time, i.e., every 12.5 ns. The combination of the two devices working in concert generates single bunches. After these single bunches of about 5×10^8 electrons are formed, bunched and accelerated to 35 MeV, they are relativistic enough that their length (about 5 to 10 electrical degrees) and their charge distribution can no longer be affected substantially by subsequent accelerating fields. It is at this point that a new "sieve" collimator is installed to control the charge of the transmitted bunch. The collimator is a slab with four "rest" positions, each consisting of an identical circular area punctured with a different set of holes. The greater the hole size and density, the greater the charge transmitted in the bunch. By choosing identical circular areas, one is certain to preserve overall beam shape. Since the beam is already "stiff," the relative charge distribution and phase remain undisturbed. The relative ratios of transmitted charge have been experimentally checked to be 0.08, 0.4, 0.7 and 1.

After the collimator, the beam is injected into the machine and accelerated to 4 GeV. This requires approximately 40 klystrons beyond which the beam is permitted to drift. The accelerator structure is entirely modular and repeats itself every 3 meters (960 so-called constant-gradient sections with a total of 86,000 cavities). By superposition, it is assumed that the accelerating fields and the beam loading fields are set up independently.

In order to study the electron energy distribution in the bunch, the beam is momentum-analyzed in the A-branch of the BSY and transmitted through a 0.1% slit. At three locations along the accelerator, there are fast pick-up monitors which can resolve the RF structure of the beam. At the 1 km point and past the slit, these pickups are connected to sampling scopes which allow one to monitor bunch intensity and to check that one is not getting a pre-bunch or post-bunch. A third pickup is available at Sector 27. Beam charge transmission along the accelerator is monitored on another scope as shown. In order to display beam energy spectrum, there are two options. One is to sweep the momentum analyzer magnets over the range of interest but this method is cumbersome and suffers from hysteresis. The other is to sweep the energy of the beam by changing the phase ϕ_V of the so-called vernier klystron 27-5. The energy of this klystron can be calibrated accurately and its phase can be set so that it is swept ±60 degrees around zero energy contribution. A potentiometer analog of ϕ_V can then be used for the x-energy axis of the x-y recorder. The y-axis is obtained by generating a DC signal from the peak of the sampling scope display, downstream of the 0.1% slits as shown.

The machine contains a synchronizer which locks the klystron pulse triggering time and hence the klystron video envelope to the single bunch timing : as a result the effect of klystron timing jitter is not a source of energy jitter on a pulse-to-pulse basis. The stability of the sampling scope displays has been improved. The trigger is derived by counting down the main drive line 476 MHz signal available at each scope to about 10 MHz. The zero crossing of this signal is combined with the machine trigger to form an RF sync trigger which can be applied to the scope sweep. As a result, no time jitter is seen on either scope when viewed on a 100 picosecond/cm sweep.

The last feature of this set-up which is noteworthy has to do with ϕ_{cl}, the so-called "phase closure" of the injector klystron. If we consider the total RF wave resulting from the addition of all 40 accelerating klystrons, there is a net angle between the electron bunch and this 4 Gigavolt electric field vector. This angle is settable by adjusting the phase

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shifter ϕ_{cl}. It determines the relative position of the bunch with respect to the wave crest (see Fig. 2). As will be seen, this angle plays a subtle role in the results given below.

Theory

As mentioned in the introduction, the question of burning importance to the designers of high current storage rings is : "What is the energy lost by the circulating bunches to the RF cavities and other metallic pipes constituting the ring vacuum envelope?" In order to answer this question, it is necessary to understand the apparently simpler problem of the energy loss due to a single bunch making a single passage through a cavity or array of cavities. In this connection, two basic questions may be considered. The first has to do with the average energy lost per electron traversing the structure. If one knows the total number of electrons in the bunch, one can then calculate the total energy lost. This energy must reappear as microwave energy distributed over a number of modes which eventually get dissipated in the structure and in the loads. The second has to do with the actual energy lost by each electron as a function of its position in the bunch.

The theoretical treatment discussed by Keil[4] and used by others[9, 12] is based on the modal analysis model. In this model, one assumes a given geometry for the cavity array and the bunch, and the fields are expanded in terms of the set of normal modes of the cavity. The total energy delivered by the electrons in the bunch to all the cavity modes with their proper RF phases is the total energy lost by the bunch. While the method could yield the configuration in space and time of the fields induced by the bunch, the calculations published so far have not done so. Indeed, if one considers that in the SLAC experiment the highly relativistic bunch is only about 0.5 mm or 2° long at FWHM while the cavities are 35 mm or 120° long, it appears that the bunch is long gone before the energy left behind has bounced off the walls of a particular cavity and distributed itself amongst the modes of the set.

In the approach taken in this paper, we attempt to unravel the available experimental evidence to come up with an empirical formula which should give some insight into the real fields accompanying the bunch.

Referring again to Fig. 2, the fields seen by an electron located at phase θ_o result from the superposition of the sinusoidal accelerating field and the beam loading field left behind by the electrons preceding it.

In the absence of beam loading, i.e., small charge, the total energy of an electron is simply $E = E_o \cos\theta$ where $E_o = 4$ GeV. Because of the finite slit width $\Delta E/2$, the transmitted electrons actually exist over a finite angular interval $\theta_2 - \theta_1$ such that

$$E + \frac{\Delta E}{2} = E_o \cos\theta_2$$

$$E - \frac{\Delta E}{2} = E_o \cos\theta_1$$

where $\Delta E = 4$ MeV for $\frac{\Delta E}{E} = 0.1\%$.

For a bunch with uniform charge distribution, the charge transmitted through the slits is directly proportional to $\theta_2 - \theta_1$. For a non-uniform distribution, the phase interval must be multiplied by an appropriate distribution function of the form $f(\theta_o - \theta)$ extending from θ_o to $\theta_o - \phi$.

In the presence of beam loading, the above equations have been modified in the following way :

$$E + \frac{\Delta E}{2} = E_o \cos\theta_2 + \frac{\alpha \Delta V \beta}{\phi} \int_{\theta_o}^{\theta_2} f(\theta_o - \theta)\, e^{-\frac{(\theta_2 - \theta)^2}{\psi^2}}\, d\theta$$

$$E - \frac{\Delta E}{2} = E_o \cos\theta_1 + \frac{\alpha \Delta V \beta}{\phi} \int_{\theta_o}^{\theta_1} f(\theta_o - \theta)\, e^{-\frac{(\theta_1 - \theta)^2}{\psi^2}}\, d\theta$$

Here α is a factor proportional to bunch charge, ΔV is a constant voltage and β is a normalization constant. The exponential term takes into consideration the decay of the beam loading field left by electrons having passed earlier. ψ is the time constant or "decoherence angle" which has been used as a matching parameter.

In order to obtain the empirical spectra for the energy interval between $E + \Delta E/2$ and $E - \Delta E/2$, a computer program has been written to obtain the corresponding values of $\theta_2 - \theta_1$. This program actually inverts the process and searches for the appropriate angular "excursions" of θ between slit edges $\pm\Delta E/2$. These are then multiplied by the proper density function $f(\theta_o - \theta)$. Using the simple relation $E = E_o \cos\theta$, the final spectra are given in terms of E in the x-axis.

Results

In order to obtain $f(\theta_o - \theta)$, it is necessary to know the charge distribution within the bunch. This has been done by calculating the predicted spectrum for a uniform charge distribution at low current (i.e., negligible beam loading) and given θ_o, and comparing this spectrum with the same θ_o, low current experimental spectrum. The real distribution can be deduced by simple normalization. A typical distribution function is shown in Fig. 3. Fig. 4 shows comparisons of experimental and theoretical results for different values of phase closure, i.e., $\theta_o = -2$, $\theta_o = +2$ and $\theta_o = +7$. These results were chosen as typical samples of a total set of about 12 measured and calculated cases. As seen, the agreement between theory and experiment is fair for $\psi = 7^\circ$, taking $\Delta V = 35$ MeV for 5×10^8 electrons per bunch. Notice that the choice of the above Gaussian is based on the physical assumption that the beam induced field packets left behind are made up of many frequencies and that they wash out in a time represented by the phase angle ψ. The authors considered functions other than the Gaussian, for example

$$\left[1 - \left(\frac{\theta_2 - \theta}{\psi}\right)^2\right]$$

However, this function could undergo a sign reversal which would indicate physically that the beam induced energy blob contains only a few frequencies which, given the proper time delay, can produce acceleration rather than deceleration. This model, although not impossible, seems unlikely.

It should be mentioned that the experimental data displayed here was taken over a period of about 3 hours. During this time interval, it is probable that small drifts in absolute energy ($E_o \sim$ few MeV), phase closure ($\theta_o \sim 1^\circ$) and total charge ($\sim 10\%$) took place between data sets. An attempt was made in the analysis to average these out. The maximum charge per bunch ($\alpha = 1$) was in all cases taken to be equal to 5×10^8 electrons. Another shortcoming which was not taken into account in the empirical model for the slit is the finite diameter of the bunch (perhaps as large as 5 mm) at the slit. This compares with a slit opening (0.1%) of roughly equal width, which has the effect of rounding off the edges of the observed spectra.

In order to compare these results with those obtained earlier[1, 4], the average energy loss per electron over all experimental points was also calculated. A value of

ΔV = 47.1 MeV for 10^9 electrons/bunch was obtained with a σ = 4 MeV. This result compares with a value of ΔV = 9.47 MeV derived from a simple steady-state beam loading calculation. Such a calculation takes into account only the fundamental mode (2856 MHz) and is based on an r/Q = 4400 ohms/m (where r is the shunt impedance per unit length and Q is the cavity quality factor). As is seen, the fundamental only accounts for about 20 % of the average energy loss. The loss of a median electron (35 MeV) assuming linear loss is only ~75% of the observed average loss (47.1 MeV).

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References

1. R. F. Koontz, G.A. Loew, R.H. Miller, "Single Bunch Radiation Loss Studies at SLAC," Proc. VIIIth Int. Conf. on High Energy Accelerators, CERN, Geneva, Switzerland, 1971, pp. 491 - 495.
2. E. Keil, "Energy Loss of an Electron Ring Passing Through a Cylindrical Cavity with End Tubes -- Part 1: The Method," CERN ISR-TH/68-49 (November 1968).
3. E. Keil, "Radiation Loss at SLAC II," CERN ISR-TH/EK (March 1971).
4. E. Keil, "Diffraction Radiation of Charged Rings Moving in a Corrugated Cylindrical Pipe," CERN, Geneva, Switzerland (December 27, 1971).
5. P. Wilson, "Beam Loading in High-Energy Storage Rings," Proc. IXth Int. Conf. on High Energy Accelerators, SLAC, Stanford, California, May 2-7, 1974. (CONF-740522, available NTIS)
6. A. Papiernik, "Fast Beam-Cavity Interaction and its Effect on Bunch Shape in Storage Rings," Proc. IXth Int. Conf. on High Energy Accelerators, SLAC, Stanford, Calif., 1974 (CONF-740522, available NTIS), p. 375.
7. G.H. Rees, "Design and Status of EPIC," Proc. IXth Int. Conf. on High Energy Accelerators, SLAC, Stanford, Calif., 1974 (CONF-740522, available NTIS), p. 548.
8. J.R. Rees, "PEP Electron-Positron Ring - PEP Stage I," Proc. IXth Int. Conf. on High Energy Accelerators, SLAC, Stanford, Calif., 1974 (CONF-740522, available NTIS), p. 564.
9. M. Sands, PEP Note 90.
10. P. Morton, "Implications of High Beam Currents for Accelerator and Component Design," "Experiments in Electron Cooling of Proton Beams;" M.A. Allen et al., "Beam Energy Loss to Parasitic Modes in SPEAR II;" and M.H.R. Donald, "RF Beam Loading in EPIC;" these Proceedings.
11. R. F. Koontz and R.H. Miller, "Nanosecond Electron Beam Generation and Instrumentation at SLAC," these Proceedings.
12. P. Wilson, private communications.

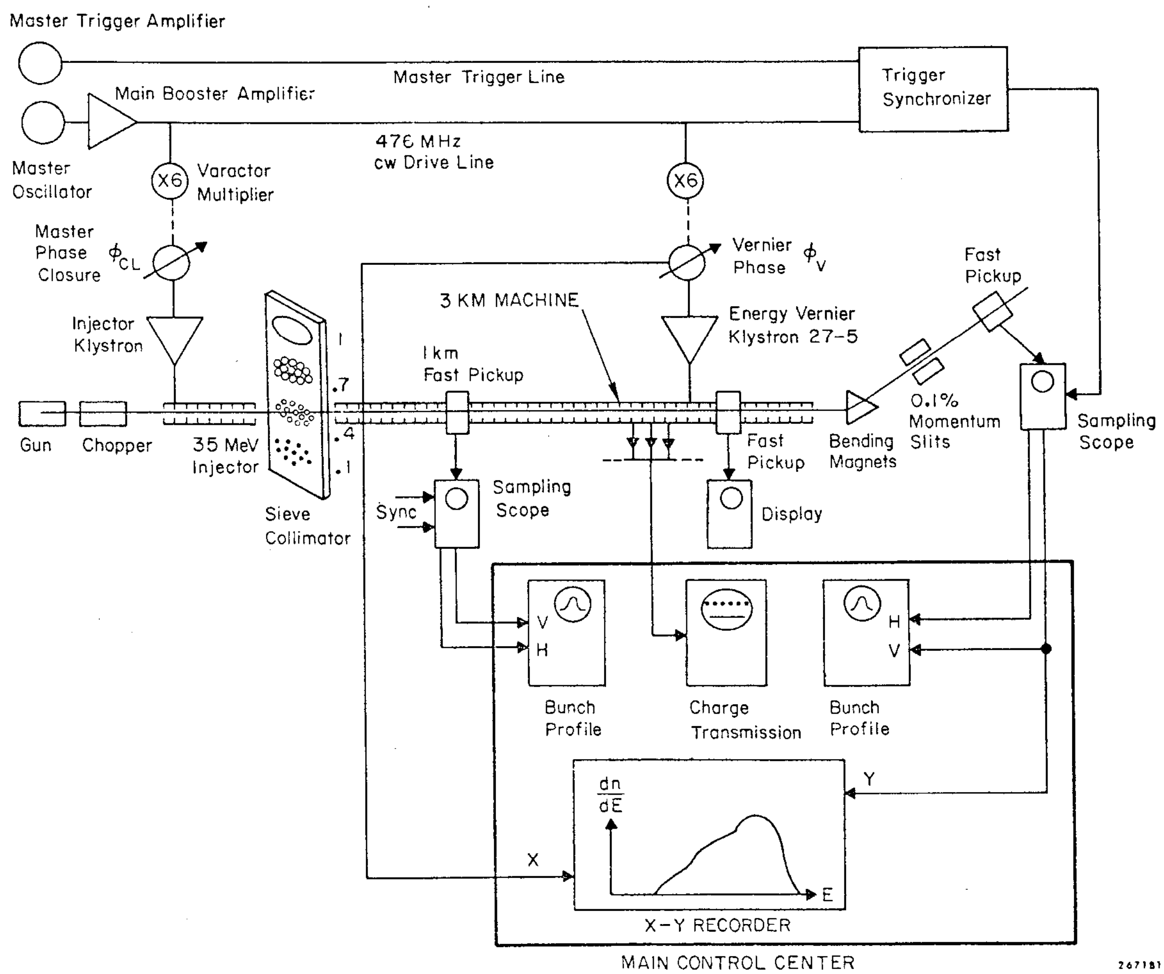

FIG. 1--Layout of single bunch experiment.

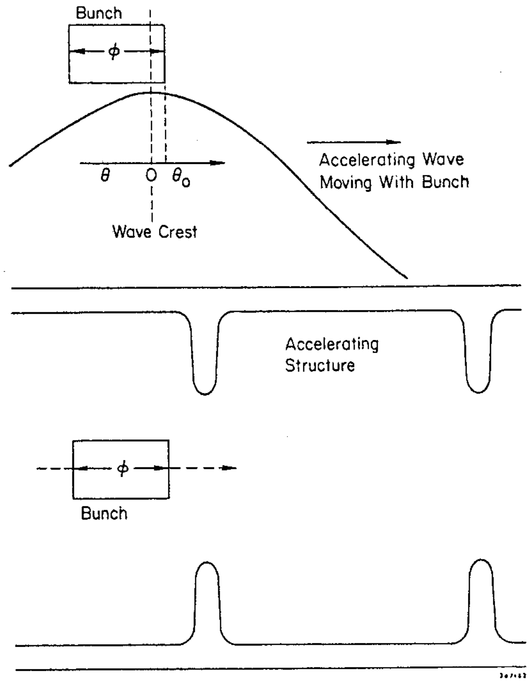

FIG. 2--Geometry of bunch with respect to wave crest and accelerator structure.

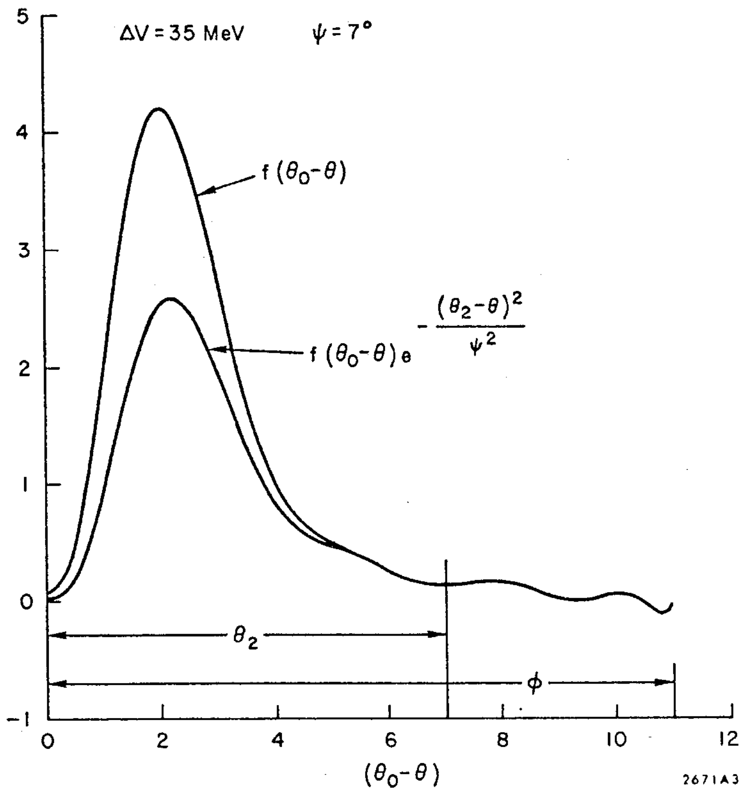

FIG. 3--Charge distribution within bunch.

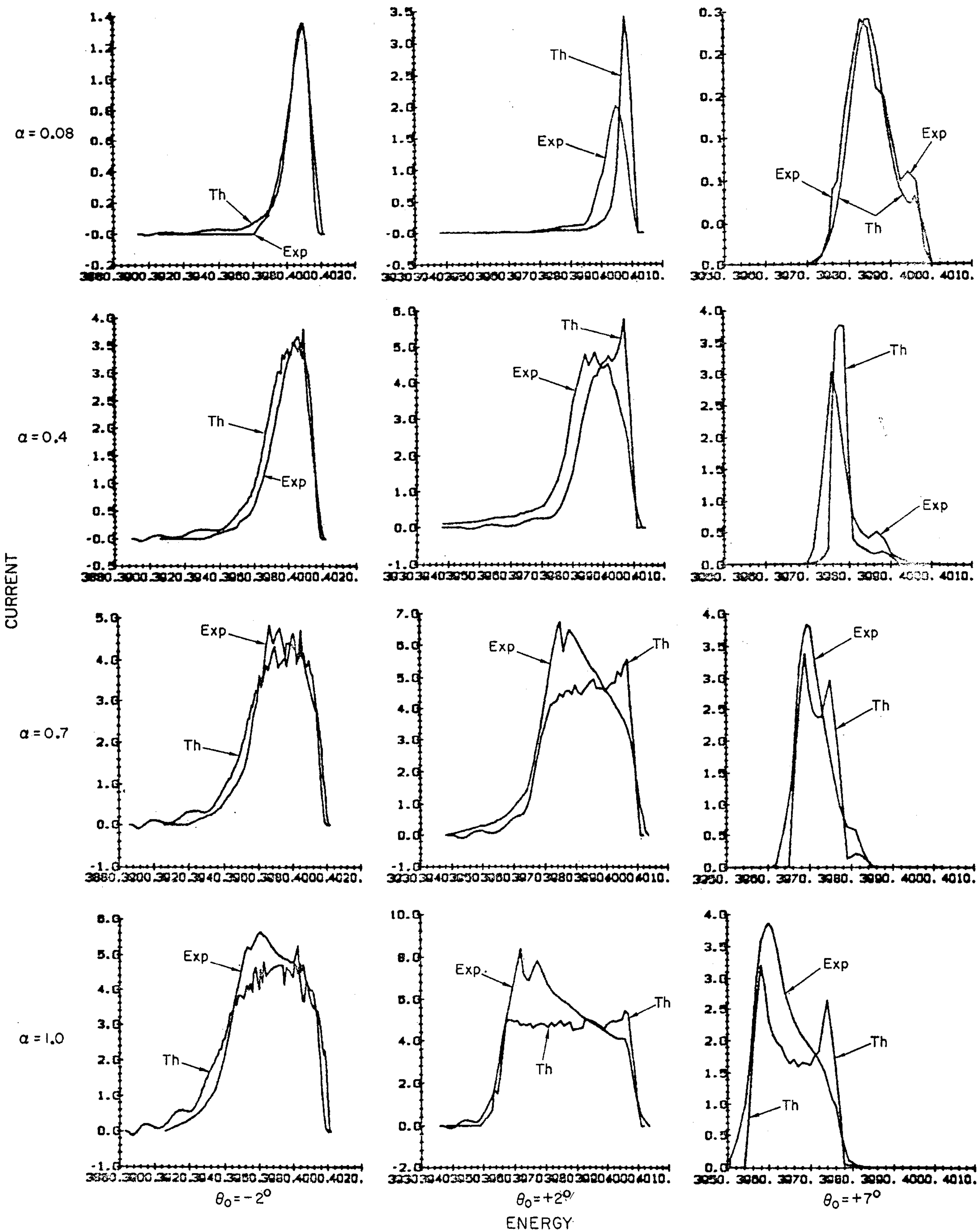

FIG. 4--Experimental and calculated spectra for three different values of phase closure ($\theta_o = -2^o, +2^o, +7^o$), each for 4 different values of bunch charge (α = 0.08, 0.4, 0.7, and 1.0).