DEPENDENCE OF PHASE INSTABILITIES ON BUNCH LENGTH AT THE CEA*

R. Averill, R. Eddy, A. Hofmann,† R. Little, H. Mieras, G. Nicholls, J. M. Paterson,‡ K. Strauch, G.-A. Voss§ and H. Winick

Cambridge Electron Accelerator
Harvard University and Massachusetts Institute of Technology
Cambridge, Massachusetts

Summary

Betatron and phase instabilities have been observed at the CEA during multicycle filling and dc storage. The betatron instabilities[1] are caused by the head-tail effect and have been controlled with sextupoles which make the chromaticity zero or slightly positive. The phase instability at present limits the electron and positron current which can be accumulated. We have made measurements of the threshold currents required to observe the onset of phase instabilities. These measurements show:

a. The threshold current required to observe the onset of this phase instability is independent of the number of bunches down even to one bunch. (Here and throughout this paper, current is defined as the current in one bunch averaged over one rf period, ie., 1 mA = 1.4×10^7/bunch.)

b. The threshold current for the onset of this instability first decreases with increasing bunch length, goes through a minimum, then increases again for long bunch length.

A cavity operating at the third harmonic of the main accelerating system frequency, thus providing increased nonlinearity of the total rf voltage waveform (hence increasing the Landau damping), increased the threshold current for the onset of these instabilities.

Introduction

The CEA operates as a colliding beam facility in the following way:[2]

First positrons are injected at 145 MeV, accelerated to 2 GeV, and decelerated back to injection energy. During this cycle radiation damping reduces the phase space occupied by the beam thus making injection at 60 Hz possible. After positrons are accumulated, electrons are injected with an injection energy of 265 MeV. The ac component of the synchrotron magnet excitation is then turned off and the beams are stored at a constant energy, and switched through the bypass.

The rf frequency is 475 MHz and the harmonic number 360. The electron or positron sausage occupies about one third of the circumference and each contains about 120 bunches. Betatron and phase instabilities have been observed in the cycling mode as well as during dc storage.

CEA is the only high-energy storage ring with ceramic vacuum chambers; these may have a significant effect on the threshold of instabilities.

Betatron Instabilities

Horizontal and vertical betatron instabilities have been observed as coherent signals on transverse-position-sensitive monitors as well as by observing an increase of the beam width or height on TV monitors of the synchrotron light. Such instability is caused by the head-tail effect and its characteristics have been described previously.[1,3] The threshold for betatron instabilities has been significantly raised (to > 350 mA) by the use of distributed sextupole magnets which keep the chromaticity zero or slightly positive. During multicycle filling it is necessary to program the currents in some of these sextupoles in order to satisfy this chromaticity requirement.

Phase Instabilities

At present, phase instabilities during multicycle injection limit the maximum accumulated current to about 25 mA for positrons and about 350 mA for electrons. The latter limit is larger because of the higher injection energy and the higher injection rate for electrons. The phase instabilities have been observed (as described in Ref. 1) to cause bunch lengthening as well as bunch widening indicating that not only the phase spread but also the momentum spread is increased. These instabilities also are observed in position monitor signals, as phase modulation of intensity monitor signals and as widening of the beam on a synchrotron-light TV image.

Measurement Technique

The primary method of determining the threshold of phase instabilities is by the observation of a sideband to a harmonic of the rotational frequency. The sideband is separated from the fundamental by the synchrotron oscillation frequency. The signal is derived from a position-sensitive rf loop and is displayed on a spectrum analyzer. This system is very sensitive to phase instabilities and is able to detect an excited synchrotron oscillation which is unobservable on previously mentioned devices. As a matter of fact, instabilities are observed before they have any effect on beam lifetime. Figure 1 shows the frequency analysis of the signal of a single bunch given by a horizontal displacement monitor (the

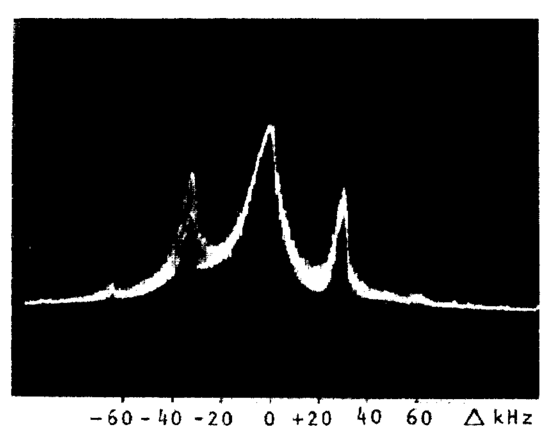

Figure 1

Oscilloscope Trace of Spectrum-Analyzed Signal from Horizontal Rf Monitor Showing Synchrotron Instabilities signal is proportional to intensity x |displacement|). The large central peak represents a multiple (in this case the 288th multiple) of the orbital frequency (1.32 MHz), and indicates an orbit distortion at the location of the monitor. The first sidebands are displaced from the central peak by the synchrotron oscillation frequency (typically $\sim$ 30 kHz). The fact that the first sideband is observed indicates that the instability is a coherent motion of the center of charge. Frequency analysis made with a beam consisting of many bunches gives the same result.

Investigation

The dependence of the strength of this instability on beam energy and bunch length has been investigated. The threshold current I_{th} at which the instability could just be observed was measured for different accelerating rf voltages (see Fig. 2). The parameter that

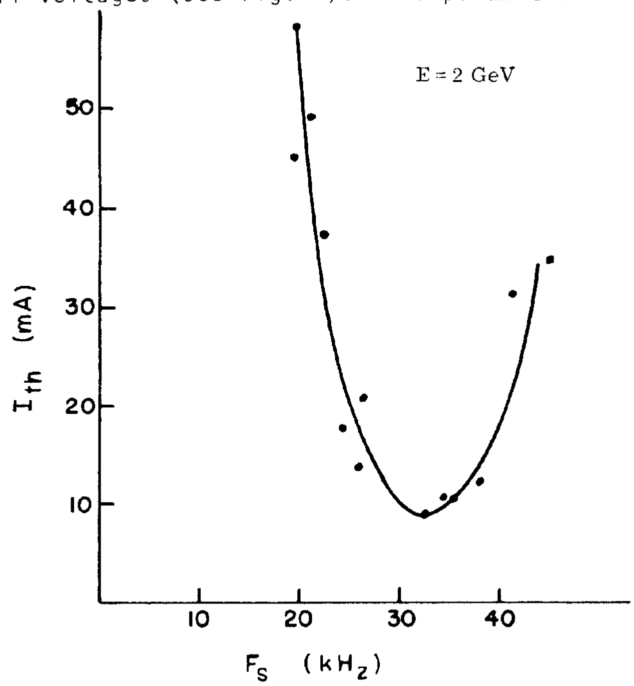

Figure 2

Threshold Current vs Synchrotron Oscillation Frequency

was measured was the synchrotron oscillation frequency, F_s, which is related[4] to peak rf voltage, V_o ($F_s \propto \sqrt{V_o}$). From the synchrotron frequency, the bunch length, ϕ, expressed in rf phase angle (radians) was calculated, assuming that at the threshold conventional theory applies and that there is as yet no significant effect of the instability on bunch length:

$$\phi = \frac{F\alpha_M}{F_s}\left(\frac{\Delta E}{E}\right) \qquad \text{(Ref. 4)}$$

where $\pm(\Delta E/E) = .00027 \times E(\text{GeV})$ is the 1/e energy spread calculated from the measured beamwidth; $\alpha_M = .0327$ is the momentum compaction factor, and $F = 475.7$ MHz is the accelerating frequency. For the CEA:

$$\phi = \frac{4150}{F_s\ (\text{Hz})} E(\text{GeV}) = 1/e \text{ bunch half length}$$

In Figure 3 the threshold current is plotted vs bunch length.

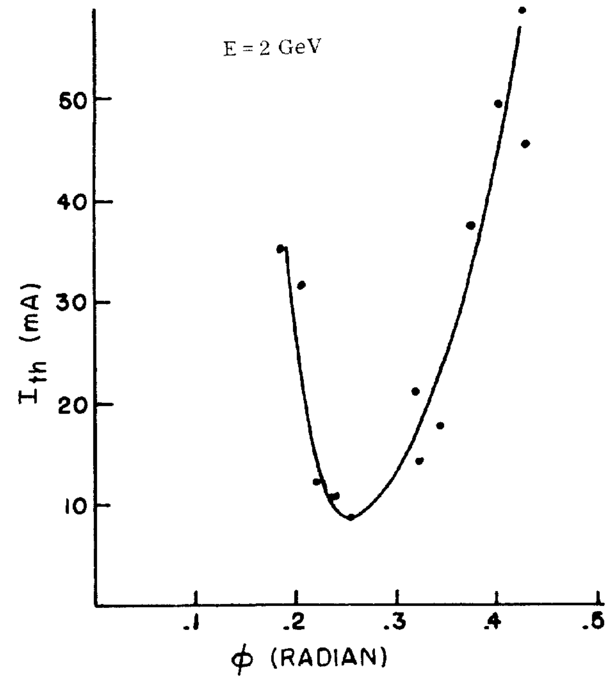

Figure 3

Threshold Current vs Bunch Length

At the threshold the growth rate of the phase instability must be approximately equal to the sum of the radiation and Landau damping rates ($\alpha = \alpha_R + \alpha_L$). The latter can be estimated from the bunch length and the nonlinearity of the rf voltage:

$$\alpha_L\ (\text{sec}^{-1}) = \frac{\phi^2 F_s\ (\text{Hz})}{16} \qquad \text{(Ref. 5)}$$

and $\alpha_R\ (\text{sec}^{-1}) = 4.4\ [E(\text{GeV})]^3$ for the CEA.[6]

α_L dominates. The quantity (α/I_{th}) is then a measure of the strength of the instability and is plotted in Fig. 4. The strength (α/I_{th}) at first increases with increasing bunch length but then becomes smaller again for very long bunches. This is consistent with instabilities

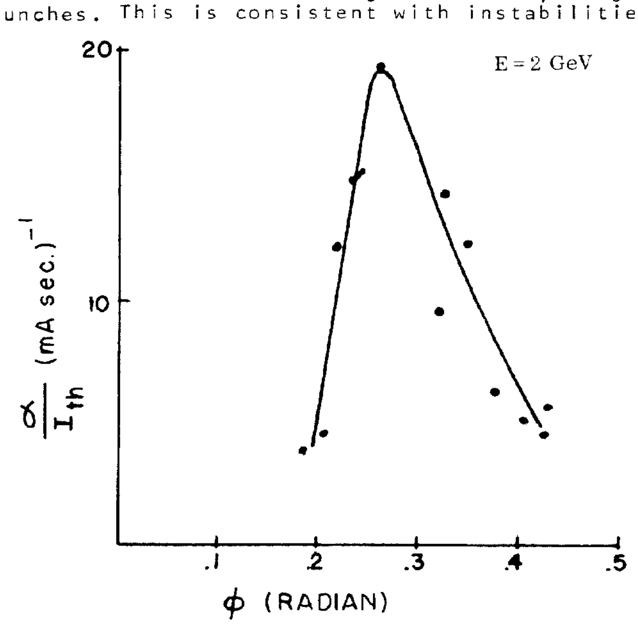

Figure 4

Growth Rate vs Bunch Length

resulting from a short-range force of the beam induced fields. Similar results at different beam energies show that the instability threshold is approximately proportional to the third power of energy, as has been previously reported.[2]

We can estimate what field strength is necessary to produce the measured growth rate. A longitudinal electric field with a radial dependence such that the field strength changes a few hundred volts/turn if the bunch energy changes by 1%, would be sufficient.

Beam-Induced Fields

The interaction of the beam with the ceramic vacuum chamber wall seems to be particularly large in the CEA. The image currents in the ceramic chamber wall produce a defocusing effect in the vertical plane (Fig. 5), which depends only on the peak circulating current (i.e. independent of the number of bunches), and is of a strength consistent with the assumption that only electric fields (no compensating magnetic fields!) act. These fields are so strong that it is easy to imagine the existence of the much smaller radially-dependent longitudinal field necessary to drive the phase instability (especially considering that half of the CEA vacuum chambers have radially-dependent gap height).

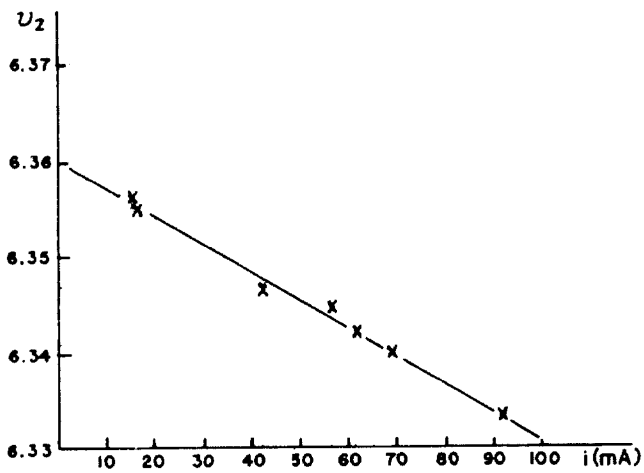

Figure 5

Vertical Betatron Frequency vs Beam Current. Particle energy is 240 MeV.

Damping Technique

Ways to improve the current limit as given by the phase instability have been explored. To increase the Landau damping due to the nonlinearity of the accelerating rf voltage, we operate at the lowest possible rf voltage so that the bunch is very long.

In addition, the Landau damping has been increased by adding a special cavity operating at a 3rd harmonic (1427 MHz) of the accelerating rf, thus further increasing the nonlinearity of the voltage seen by the bunch.

This cavity is composed of a series of six cylindrical chambers coupled so that successive resonators have a pi-mode voltage relationship at the operating frequency. The individual resonators operate in the TM_{010} mode. The cavity has a large aperture (3½ in.) and a remotely-controlled inductive slug which tunes the two central resonators. The shunt impedance is 3.4 megohms and the loaded Q is about 10,000. The cavity is excited to several hundred watts, phaseable and synchronous with respect to the accelerating rf.

The effect of this cavity on the threshold current was measured and is shown in Fig. 6.

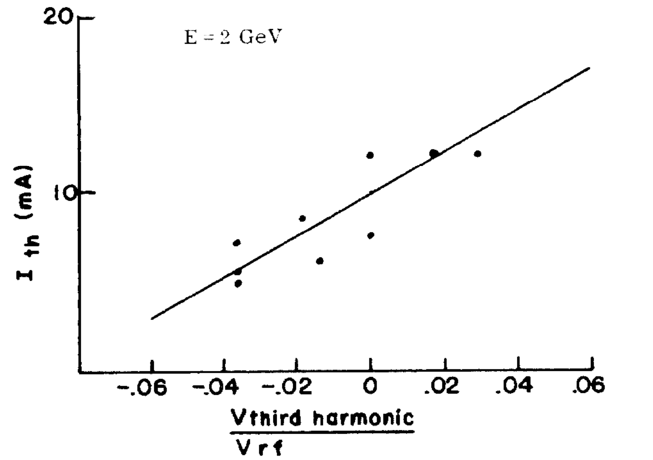

Figure 6

Threshold Current of the Phase Instability vs Voltage of the Third Harmonic Cavity.

The optimum phasing of the Landau voltage (i.e. the phasing that increased the instability threshold) was such as to add to the main accelerating voltage. By adjusting Landau cavity voltage phase 180° from optimum so that nonlinearity of total rf voltage is reduced, the threshold was decreased. The magnitude of the Landau voltage was determined from the measured change in synchrotron oscillation frequency as the Landau cavity was powered either in or out of phase. Lack of adequate power source limited the improvement from the Landau cavity to ∿ 30%.

Acknowledgement

The authors wish to thank K. W. Robinson for many helpful discussions.

References

*Work supported by the U.S. Atomic Energy Commission under Contract No. AT(11-1)-3063.

†Now at CERN.
‡Now at SLAC.
§Now at DESY.

[1] R. Averill *et al.*, "Synchrotron and Betatron Instabilities of Stored Beams in the CEA", Proceedings 8th International Conference on High Energy Accelerators, Geneva, Switzerland, 1971, p. 301.
[2] R. Averill *et al.*, "Colliding Electron and Positron Beams in the CEA Bypass", Proceedings 8th International Conference on High Energy Accelerators, Geneva, Switzerland, 1971, p. 140.
[3] A. Hofmann *et al.*, "Observation of the Head-Tail Instability at the Cambridge Electron Accelerator", Proceedings 8th International Conference on High Energy Accelerators, Geneva, Switzerland, 1971, p. 306.
[4] M. Sands, "The Physics of Electron Storage Rings", SLAC-121, 1970, p. 85.
[5] K. W. Robinson - private communication.
[6] K. W. Robinson, "Radiation Effects in Circular Electron Accelerators", Phys. Rev. 111, 373 (1958).