SYNCHROTRON AND BETATRON INSTABILITIES OF STORED BEAMS IN THE CEA

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Abstract

Betatron and synchrotron oscillation instabilities have been observed with stored electron and positron beams in the CEA. Both types of instabilities seem to depend on the peak circulating current and to be independent of the circumferential fill factor. Both types of instabilities are observed as coherent displacement signals on beam displacement monitors. A short range bunch-bunch-interaction is observed for betatron as well as synchrotron oscillation instabilities. Betatron instabilities, which are of the head-tail-type, have been eliminated up to peak currents of 150 mA with a system of distributed sextupoles. The effects of synchrotron oscillation instabilities have been reduced by operating the CEA during multicycle filling at the lowest possible rf-accelerating voltage.

Introduction

This paper discusses only the observed beam instabilities and their effect on the present performance of the CEA as an electron-positron storage ring. Detailed information on design and operation of the system is given in References 1, 2, 3.

During accumulation of positron and electron beams, and during storage at constant energies, various beam instabilities have been observed: betatron oscillation instabilities in the horizontal and to some lesser degree in the vertical plane, phase oscillation instabilities and, at large average currents, instabilities due to beam-cavity interaction.

Instabilities manifest themselves in many ways. They can be observed with the help of our beam displacement monitors as coherent oscillation signals, they can lead to sudden loss of current in some parts of the circumferential filling thereby producing large intensity structures, and they can increase the incoherent width of the beam up to the point where the lifetime becomes very short.

Betatron Instabilities

a. Observations

In the CEA betatron instabilities were first observed during multicycle accumulation of electrons and positrons: as the accumulated current increases an intensity structure in the circumferential filling develops, indicating a certain amount of bunch-bunch interaction (Fig. 1). Large current bunches are observed to cause short lifetime in the following bunches. Sometimes a whole group of 10 to 20 consecutive bunches disappears suddenly. At the same time pick-up coils show coherent betatron

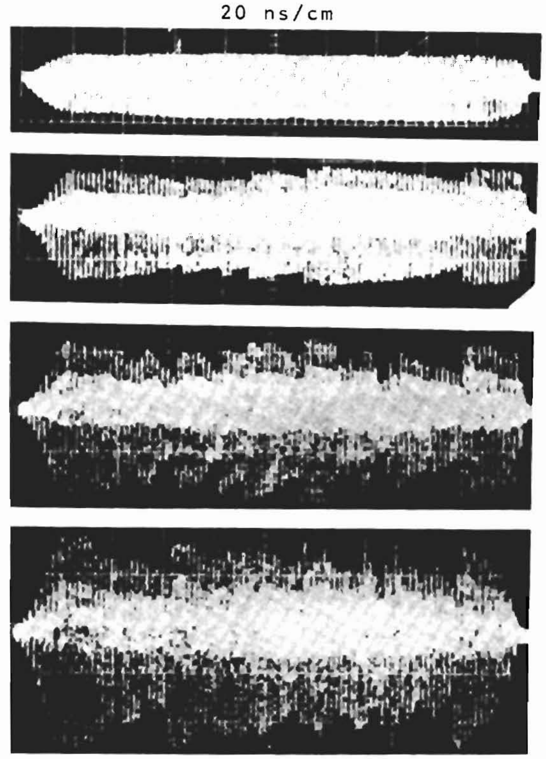

Fig. 1. Progressive changes in structure of sausage of positron beam during multicycle injection. Photographs were taken at 15-second intervals. Beam peak current increased from 2 to 3 to 4 to 5 mA in a), b), c), d).

oscillations. Through continuous losses of bunches or groups of bunches during beam accumulation a saturation current is reached (typically of the order of 30 mA for electrons and 10 mA for positrons) which is well below the design current of 100 mA for each beam. This beam instability depends only on the peak circulating current and is independent of the circumferential filling factor. The force which causes the obvious bunch-bunch interaction can therefore only have short ranges. This bunch-bunch interaction has been simulated on a computer by Morton et al.[5] The model used gives a good qualitative description of the observed phenomena.

Analysis of beam instabilities during the multicycle filling process is complicated by the fact that the beam energy varies rapidly between 120 MeV and 2 GeV and with it the beam size; furthermore during the top part of this cycle the beam is moved into the damping magnets[4], elements with large sextupole and octupole contents. Due to the strong Landau damping provided by these damping magnets, coherent betatron signals generally disappear when beams are brought into the damping system, but begin to develop again at the bottom part of the cycle.

After positron and electron currents have been accumulated in a multicycle injection mode, the ac component of the synchrotron magnet current is turned off and beams are stored at a constant dc energy. Then stored beams are switched into the bypass. During these operations betatron instabilities have been observed which cause horizontal or vertical beam blow-up and associated beam loss (Fig. 2).

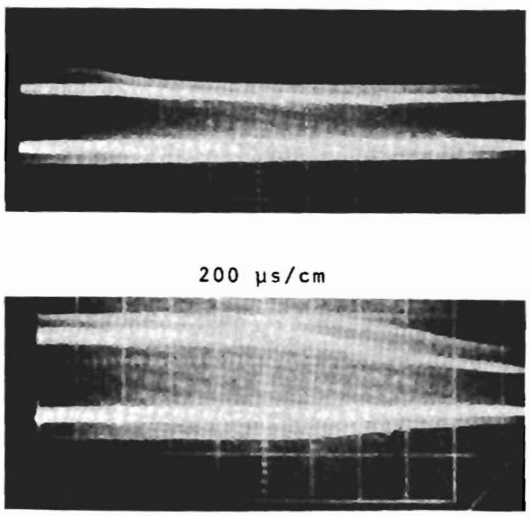

Fig. 2. CRO traces showing the delay in onset of instability of a 2-GeV electron beam (after beam is switched into the bypass) as a function of beam current. a) 7.5-mA peak beam, for which the delay was 3.5 ms, and b) 18-mA peak beam, with 1.2 ms delay. (The scales are different in the two photographs.)

b. Attempts to Solve the Betatron Instability Problem

A feedback system to stabilize betatron instabilities would have been very difficult to build in view of the very large band-width requirements. No serious attempt to design such a system has been made. Octupole magnets which increase the Landau damping of coherent betatron oscillations and thereby raise the threshold for betatron instabilities have been tried, but it was found that octupole magnets strong enough to significantly raise the betatron instability limit were incompatible with off-axis injection. Octupole magnets have been used to stabilize beams in the dc storage mode but since not enough space is available to ensure an adequate distribution of these magnets, they produce octupole resonances and are undesirable.

Bunch-bunch interaction as evidenced by the developing structure in the filling suggests that an improvement of the betatron instability problem should be possible by giving different bunches different betatron frequencies. A radiofrequency quadrupole operating on the 24th harmonic of the circumferential frequency was installed. This quadrupole provides a maximum $\Delta\nu$ variation between neighboring bunches of .011 at 120 MeV, when powered with 1 kW at 31.7 MHz. It was found that such a radiofrequency quadrupole lens indeed allows accumulation of larger currents and prevents bunch-bunch interaction. However the improvement in maximum stored current levels was limited to a factor of roughly 2, and powering of the rf quadrupole to higher levels made no further improvements.

The solution of the betatron instability problem came with the installation of a distributed system of 30 sextupole magnets. These magnets are mounted in the small available space in the centers of the focusing and defocusing magnets in the CEA ring and allow, because of the difference in betatron amplitude functions, independent adjustment of the chromaticities $\xi = \Delta\nu/(\Delta p/p)$ in both planes. Betatron instabilities in the CEA are apparently of the head-tail type[6] and by making chromaticities in both planes close to zero, thresholds for these instabilities are greatly increased. Six of the sextupole magnets are powered in series with the synchrotron magnets such as to provide zero or slightly positive chromaticity throughout the cycle. The other 24 magnets are dc-powered during dc storage to correct the large negative chromaticities which are present when the beams go through the bypass. After installation of this sextupole system no more betatron instabilities have been observed, even with peak currents as large as 150 mA. At the same time the circumferential intensity structure due to bunch-bunch interaction has disappeared and operation of the rf quadrupole lens is no longer necessary. From these observations we conclude that a head-tail type betatron instability is the principal mechanism for betatron instabilities in the CEA but that the fields associated with this instability have some range beyond the single bunch which creates them, causing a certain amount of bunch-bunch interaction.

Phase Oscillation Instabilities

a. Observations

Instabilities of synchrotron oscillations are observed during multicycle injection and beam storage at constant energy.

Similar to betatron instabilities the instabilities of phase oscillations seem to be independent of the circumferential filling of the synchrotron ring and dependent only on the peak circulating current. Although phase oscillation instabilities have very small threshold currents (typically 5 mA peak current during the cycling operation), their main effect is only an increase in equilibrium momentum spread. They become bothersome only when this increase in momentum spread and the associated increase in beam width is too large for the acceptance of the synchrotron.

In the CEA phase oscillation instabilities - like betatron instabilities - can be observed as coherent displacement signals with our pick-up coil system. The signals appear as sidebands to the harmonics of the circumferential frequency of 1.3 MHz. Synchrotron oscillation signals caused by instabilities can be observed at the proper sideband frequencies throughout the whole frequency spectrum up to 475 MHz, which is the accelerating radio frequency. Within this frequency spectrum there are no strong dominant signals. Instead the instability signals seem to have constant amplitudes within a factor of three throughout the whole frequency spectrum. This could be interpreted as independent motion of all bunches. However any dominant signals due to bunch-bunch interaction would be spread out over a number of harmonics because of the non-uniform circumferential filling of the ring. If there were a large number of such dominant frequencies, their observation would be difficult.

Indeed a certain amount of bunch-bunch interaction seems to be present in the case of phase oscillation instabilities. This can be observed in the following way: due to the increased momentum spread the instabilities increase the bunch width of the individual bunches. When horizontal scrapers are moved in to decrease the lifetime of the beam, the first bunches in the circumferential filling decay slower than the rest of the sausage, indicating a smaller width of these first few bunches (Fig. 3). On the other hand even the very first bunch in the circumferential filling decays much faster at large currents than at small currents. This may indicate that phase oscillation instabilities like betatron instabilities are single bunch effects with a certain amount of short range bunch-bunch coupling.

The increase in beam width due to synchrotron oscillation instabilities has been measured at two different energy values of stored beams (Fig. 4). In order to extract from these width measurements the increase in momentum spread, one must know the equilibrium amplitudes of betatron and synchrotron oscillations at small currents. The ratio of these two amplitudes is supposed to be 1.4 under our operating conditions,

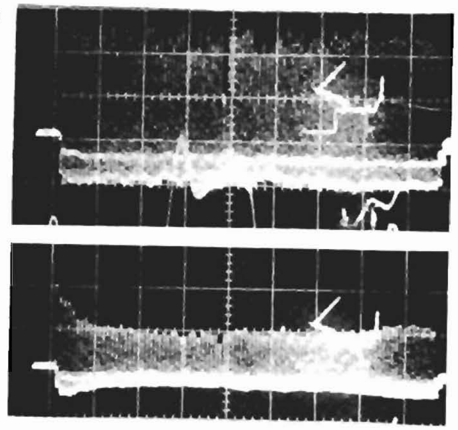

Fig. 3. Change of circumferential filling during horizontal scraping. Pictures (a) and (b) were taken at an interval of 1 min while the horizontal scraper was at a position which would result in a lifetime of 20 minutes at small currents. Note that the first bunches, although decaying by much more than 5% between (a) and (b), decay less than the rest of the sausage.

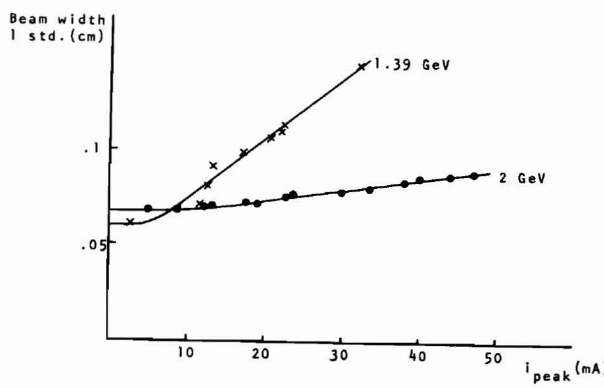

Fig. 4. Bunch widening as function of peak circulating current.

but may depend to some extent on the way our damping system is operated[4]. If we assume that the ratio of 1.4 is the correct one at small currents, the indicated width increase of 1.29 would correspond to a momentum width increase by a factor of 1.73 when going from small currents to peak currents of 44 mA at 2 GeV. This number is in surprisingly good agreement with a measurement of the bunch length at 2 GeV, which we will now describe. As the bunch length varies, the harmonic frequency content of the bunches varies. We measure the harmonic frequency content at 2856 MHz and 1428 MHz with our pick-up coils. A calibration is obtained using small bunch currents and varying the accelerating rf-voltage and thereby varying the bunch length by a known amount. The results of the relative measurement of bunch length vs. current are shown in Fig. 5. The bunch lengthening at 2 GeV with 44 mA peak current is observed to be 1.63, in good agreement with the observed increase in beam width.

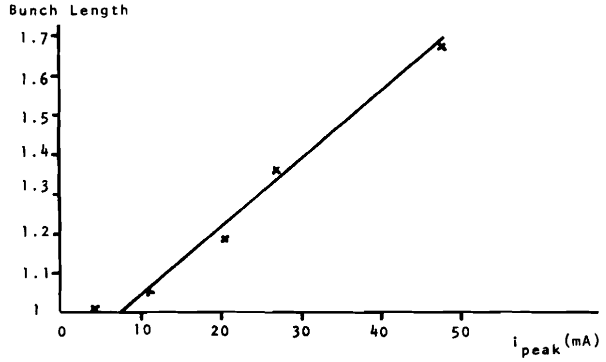

Fig. 5. Relative bunch length as function of peak current at 2 GeV (Theoretical value for small currents: 5.3 cm)

The threshold current for phase instabilities has been measured as a function of the energy (Fig. 6) by observing the onset of coherent phase oscillation amplitudes. Keeping in mind the relatively large systematic errors in this measurement, we estimate that the energy dependence is

$$i_{threshold} = \text{const (Energy)}^{3\pm.5}$$

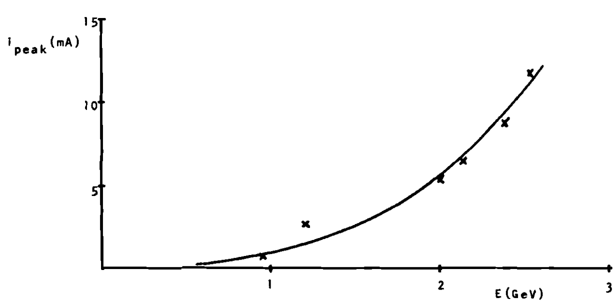

Fig. 6. Threshold current for observation of coherent synchrotron oscillations as function of energy.

b. Attempts to Solve the Phase Instability Problem

Landau damping together with radiation damping are the only forces which counteract phase instability growth of the equilibrium beam size as current increases. Under our operating conditions Landau damping due to the non-linearity of the accelerating field seems to be the determining element. The damping rate per phase oscillation is given roughly by $\phi^2/32$, where ϕ is the 1/e half-width of the equilibrium phase spread.[7] Increasing the phase spread by lowering the accelerating voltage is thus expected to increase the threshold for phase oscillation instabilities and to decrease the equilibrium momentum width once these instabilities have developed. This is indeed true: by lowering the accelerating voltage during multicycle injection it is possible to increase the amount of current which can be accumulated. But because of the large shunt impedance of the CEA accelerating system (about 100 MΩ) lowering of the accelerating voltage soon leads to beam-cavity instabilities. For this reason we lowered the shunt impedance of the rf-system to 10 MΩ by shortening out a number of accelerating cavities. This then allows us to run stably at an accelerating voltage of 450 kV/turn, which is about the minimum voltage in the cycling mode consistent with long lifetime. With this change in our accelerating system we were able to increase the electron current, which can be accumulated, by a factor of 3, and peak circulating currents as large as 150 mA have been observed.

Since a certain amount of bunch-bunch interaction is evident, as seen in Fig. 3, we also tried to increase the synchrotron oscillation frequency spread between bunches by powering one of the accelerating cavities at a different harmonic number (362) from the main accelerating system (360). This caused a maximum frequency spread of ± 5% in synchrotron frequency between bunches, a number which is large as compared to the frequency spread within a single bunch at small currents. We indeed observed an effect in the case of positron accumulation: the equilibrium beam size at injection, which is mostly determined by the momentum width, was somewhat decreased when the special cavity was powered.[8] There was no observable effect with the much larger currents during electron injection.

Another attempt to increase Landau damping was made by installation of a cavity operating at 1428 MHz, the third harmonic of the accelerating frequency. At constant bunch length the Landau damping produced by such a cavity can be shown to increase with the third power of the harmonic number - in this case 27 - multiplied by the voltage of this cavity divided by the main accelerating voltage. Lack of an adequate power source has prevented us so far from increasing threshold currents by more than a factor of 1.3.

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