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INSTABILITY THRESHOLD CURRENTS VS. ENERGY IN CESR*

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Abstract

CESR has been observed to have two coupled bunch instabilities, one horizontal and the other longitudinal, which can limit the total beam current when operating with trains of bunches. Feedback has been employed for some time to counter these instabilities. This paper reports on the threshold current for the onset of the longitudinal instability when feedback is turned off vs. beam energy over a range from 1.9 GeV to 5.2 GeV and compares the change in threshold current with that expected from the change in radiation damping. Operating performance with feedback in use will also be reported for both longitudinal and horizontal instabilities.*

INTRODUCTION

CESR is an electron-positron storage ring collider, generating luminosity at 4.7 to 5.5 GeV beam energies and operating with both beams circulating in the same vacuum chamber throughout the entire ring. In 1983 CESR began operating with multiple bunches in the ring with head on collisions; in 1994 it progressed to 9 trains of from 1 to 5 bunches with a crossing angle in the interaction region. In 1983 a horizontal, coupled bunch dipole instability was observed for the positron beam only[1]. This instability was countered with feedback and the cause ultimately determined to be due to the action of the distributed ion pumps in use in CESR[2]. The mechanism is believed to be photo-electrons trapped inside the beam chamber by weak electric fields, which have “leaked” through the pumping slots[3]. In 1996 a coupled bunch longitudinal dipole instability was first observed when CESR was operating at higher beam currents with 9 trains of 2 bunches. The threshold current for this instability initially had a strong dependence on the number and spacing of bunches in each train. Subsequent studies had identified the dominant source of the offending impedance as the 20 cells of the normal-conducting RF accelerator cavities. Simulations of the growth rates used results from beam induced signals on field probes in each cell, and predicted the variation of instability threshold currents for all of the various filling patterns of bunches in 9 trains[4].

Over the course of several years the four 5-cell normal conducting RF cavity structures have been replaced with four single cell, superconducting RF cavities, having very low loaded Q’s for all higher order modes. As the superconducting RF cavities began replacing the normal conducting cavities, the instability threshold currents increased on the average and the large variation of these currents due to changes in the filling pattern lessened substantially[4]. Now the dominant impedance causing the longitudinal dipole coupled bunch instability is suspected to be due to the 4 horizontal and 2 vertical separators in use in CESR for beam separation.

Shortly after this instability was observed, longitudinal feedback was added to stabilize the beams. The latest implementation of this feedback uses a very low-Q RF cavity as the longitudinal feedback system kicker[5]. In the range of 4.7 to 5.5 GeV the feedback system is able to stabilize the beams at all operating currents and in all desired filling patterns of 9 trains of bunches.

During the next several years CESR will be operating part of the time at lower beam energies (1.5-2.5 GeV) to produce luminosity in the charm physics energy range[6]. The plan is to operate with approximately 20 m of superconducting wiggler magnets to increase the emittance and the radiation damping rate. During the summer of 2002 a single 1.6 m superconducting wiggler was installed in CESR for studies at or near 1.88 GeV beam energy. This allowed for measurements to test the beam stability at low energies with and without the wiggler being powered. Also at lower energies the pumping from the distributed ion pumps, which use the lower dipole magnetic fields, will be ineffective and these will be turned off for operations. As a result the horizontal dipole coupled bunch instability for positrons should not be important, however the longitudinal stability will not be affected by turning off the distributed vacuum pumps and, therefore, will continue to be a concern for operations.

THEORY

As the beam energy in a storage ring is lowered, the longitudinal or transverse deflection, felt by the beam, from the vacuum chamber’s impedance or from a feedback kicker increases inversely proportional to the beam energy. Also if no additional source of radiation loss is added to the ring (such as the wiggler magnets), the radiation damping rate should decrease proportional to the beam energy to the third power. The time evolution of an oscillation amplitude, A(t), for any particular mode in CESR will have the general form,

$$\frac{dA}{dt} = \left[\alpha_Z' \ I + \alpha_{FB}' \ I + \alpha_R\right] A(t) + e(t) \qquad (1)$$

where I is the total beam current, α_Z’I is the growth rate due to the vacuum system impedance, α_{FB}’I < 0 is the damping rate due to feedback, $\alpha_R < 0$ is the radiation damping rate and e(t) is any excitation applied to the beam. Notice particularly that the damping rate from feedback in CESR grows proportional to beam current (by design) over a fairly large range in current per bunch. As was stated above, also note that beam energy, E_b, dependence is

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$$\alpha_Z' \text{ and } \alpha_{FB}' \propto \frac{1}{E_b} \quad \text{while} \quad \alpha_R \propto E_b^3$$

assuming (for the last proportionality) fixed bending radii for all of the dipole magnets. During the entire machine studies CESR has operated with two permanent magnet wigglers closed to increase the damping at low energy. The field in these magnets did not scale with energy, but instead remained constant. An approximate fit to the total radiation growth (damping) rate calculated from the design of the optics vs. energy yields a dependence which scales as $E_b^{2.7}$. Unstable motion will occur when the term in brackets in equation 1 is greater than zero, so the instability threshold current, I_{thresh}, will then be given by

$$I_{thresh} = -\frac{\alpha_R}{\alpha_Z' + \alpha_{FB}'} \qquad (2)$$

With Feedback

For modes of oscillation that are damped by feedback, i.e. $\alpha_{FB}'I < 0$, if the feedback damping exceeds the instability growth rate, $-\alpha_{FB}'I > \alpha_Z'I$, then the bracket in equation 1 will always be negative and the amplitude of oscillation will damp. This is true independent of energy since both the instability growth rate and the feedback damping rate have the same beam energy dependence.

Without Feedback

For the case when the mode of oscillation is not damped by feedback ($\alpha_{FB}' = 0$), from equation 2 the threshold current will be proportional to $-\alpha_R / \alpha_Z'$, which in turn for CESR is proportional to $E_b^{3.7}$. (For storage rings, which have magnets with fields that scale with energy, this dependence would be E_b^4.) Therefore, instabilities from modes without any feedback will become much more important at low energy.

OBSERVATIONS

Measurements of the longitudinal dipole coupled bunch instability thresholds were made at several different energies. For longitudinal dipole oscillations, the onset of the instability was determined by observing the amplitudes of the synchrotron sidebands of the rotation harmonics from a phase detected, beam position monitor signal. (Because of the unequal spacing of the trains of bunches in CESR, it is only necessary to observe the lowest 10 sidebands.) At the instability threshold some of the sideband frequency amplitudes increase, indicating larger displacements of the bunches. Generally the oscillation amplitude will increase several orders of magnitude before it reaches a limiting value, thought to be caused by the motion becoming non-linear due to the non-linearities of the RF restoring force. The threshold current is defined as the current at which this growth of the oscillation amplitude first begins. Generally it has been observed that there is some variation over time with a measured threshold current for a particular filling pattern for the bunches. This is thought to be caused by changes in the dimensions of the vacuum chamber structures in the ring adjusting the frequencies of parasitic modes in the structures. If more than one set of measurements has been performed, the data presented here will always use the highest threshold current that has been measured for a given set of conditions.

Figure 1 shows the dependence of the instability threshold current vs. beam energy when the longitudinal feedback and the superconducting wiggler magnet were turned off. Data was taken at different energies with different numbers of bunches in the 9 trains. The spacing between the bunches within the train is always 14 nsec. The data was limited to RF settings, which gave design bunch lengths between 12.5 and 16.5 mm at zero current. Figure 1 also contains a solid curve proportional to the expected dependence for CESR of the instability threshold current on beam energy to the 3.7 power as a reference to guide the eyes. A second, dotted curve is plotted, which is the least squares fit of the log of the threshold current to the beam energy raised to a power. This fit gives the beam energy to the 3.36 power in reasonable agreement with the expected 3.7 power dependence. The figure shows that there are some variations in the threshold currents for different filling patterns at the same energy, however this variation is fairly small compared to the almost factor of 30 which is expected for the range of beam energy. When the longitudinal feedback system is turned on and the wiggler was not powered, no instability was observed up to total single beam current of 160mA.

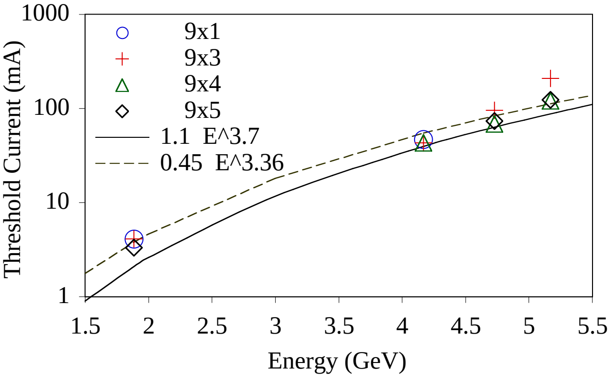

Figure 1. Instability threshold currents for different filling patterns vs. energy. The filling pattern 9xN designates 9 trains of N bunches.

The effect of turning on and off the superconducting wiggler on the instability threshold may be seen in table 1. These measurements were taken at 1.88 GeV with the longitudinal feedback off and at two RF voltages for several different filling patterns. For the conditions used, the bunch length at zero current is computed and displayed as part of table 1. The ratio of the instability thresholds for the wiggler being on and off is also given in table 1. Notice that although there is some variation from fill pattern to fill pattern, the average increase in the instability threshold current was a factor of 2.2-2.3. From the optics and the measured synchrotron oscillation frequency, the calculated increase in damping rate is expected to be a factor of 1.6. The measured values give a result that is about 40% larger than expected.

An explanation for this enhanced damping rate may be that, as the wiggler was turned on, the bunch length also increased producing a longer, more stable bunch. The size of this effect may be estimated as follows. If the data in table 1 is compared for wiggler off conditions for filling patterns 9x1, 9x3 and 9x5, the average instability threshold increased by a factor of 1.4±0.5 as the bunch length changed from 6.4 mm to 8.3 mm (a factor of 1.38.) Similarly for the wiggler on conditions, the thresholds increased an average factor of 1.4±0.2 as the bunch length changed from 9.6 mm to 13.0 mm (a factor of 1.35.) These results suggest the instability threshold varies roughly inversely as the bunch length and when taken with the calculation of the change of the bunch length, as the wiggler turns on, yields a factor of 1.4 in agreement with the 40% larger threshold current seen above.

Fill Pattern	I_{thresh} (mA) Wiggler OFF σ_z = 8.8mm	I_{thresh} (mA) Wiggler ON σ_z = 13.0mm	Ratio
1 bunch	1.0 ± 0.2	2.2 ± 0.2	2.2 ± 0.5
9x1	4.1 ± 0.5	6.0 ± 0.5	1.5 ± 0.2
9x3	4.1 ± 0.6	10.5 ± 0.5	2.6 ± 0.4
9x4	3.2 ± 0.3	7.3 ± 0.3	2.3 ± 0.2
9x5	3.3 ± 0.7	8.0 ± 0.2	2.2 ± 0.5
Average			2.2 ± 0.4
Fill Pattern	I_{thresh} (mA) Wiggler OFF σ_z = 6.4mm	I_{thresh} (mA) Wiggler ON σ_z = 9.6mm	Ratio
9x1	2.6 ± 0.5	5.1 ± 0.5	2.0 ± 0.4
9x3	2.7 ± 0.5	6.4 ± 0.4	2.4 ± 0.5
9x5	3.0 ± 0.4	6.5 ± 0.5	2.2 ± 0.3
Average			2.3 ± 0.4

Table 1. Longitudinal instability threshold currents for different filling patterns, for the wiggler magnet on and off, and for two different zero current bunch lengths, σ_z. The filling pattern 9xN designates 9 trains of N bunches.

OPERATIONAL EXPERIENCE

CESR has operated at beam energies near 1.9 GeV with one 1.6 m superconducting wiggler and the two permanent magnet wigglers in use. In these conditions and with the distributed ion vacuum pumps in the normal bending magnets turned off, horizontal feedback was not needed to stabilize the positron beam, as expected. Generally horizontal and vertical feedback systems were used to damp the coherent oscillations caused by injection transients imparted to the beams. However, it was found necessary to limit the horizontal feedback gain setting to less than 15% of its value at 4.7-5.3 GeV. It was found that raising the feedback gain significantly for electrons, during injection reduced the accumulation rate into CESR. Although this effect has not been studied in depth, it is suspected that low level noise in the feedback system may be exciting beam motion at low per bunch currents, effectively reducing the injection aperture. It has been found that horizontal and vertical feedback loop gain settings in the range of 15-20% of their maximum levels are useful for stabilizing the beams especially during injection. The longitudinal feedback system is needed for operations with either one or two beams above the instability threshold currents presented above. There is no difficulty in operating this system at full gain during injection and HEP operation.

Lastly a vertical instability has been observed for 8 and 9 trains of electrons. This happens for electrons only. The instability threshold current can be raised first by using 8 trains of bunches rather than 9 and then further by using 7 trains of bunches. Vertical, dipole beam motion occurs at the onset of the instability, which is similar to some ion related events seen in the past. Operating with 7 trains has not been a problem thus far, but further study of this instability is needed.

FUTURE STUDIES

A number of machine studies of beam stability and feedback system operation are planned for the next several months. One question is why does the horizontal feedback gain need to be limited to approximately 15% of maximum gain during injection? If this is caused by low-level noise driving the beam at low current (where the loop gain and, hence, damping is lower), what modifications can be made to the feedback system to correct this effect? The electron transverse instability needs further study to determine the cause and whether it may be countered without needing to remove as many bunches from the ring. Another question is will the beam remain stable as the beam current is increased, especially when both beams are stored? Since CESR at low energy will operate with the current in both beams well above the maximum current achieved at 5.3 GeV scaled to low energy by E_b^4, quadrupole coupled bunch modes or other higher modes of oscillation may become unstable as the currents increase.

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