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AN INVESTIGATION OF THE 'FLIP-FLOP' BEAM-BEAM EFFECT IN SPEAR*

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Abstract

When colliding electron and positron bunches in SPEAR at high values of the beam-beam tune shift parameter $\Delta\nu$, it had been observed that sometimes one of the equal intensity beams would blow up in the vertical plane more than the other beam. It was subsequently found that a small adjustment to the phase difference between the RF accelerating cavities would make the beam 'flip' the other way. The results of the investigation of this phenomenon are presented in this paper.

Introduction

The flip-flop has been known at SPEAR for some time but it is only recently that it has had an impact on routine operation. The operating luminosity of SPEAR has been gradually improved by control of the orbits, dispersion functions, betatron coupling and synchro-betatron resonances. This routine operation at high values of the beam-beam tune shift has led to the flip-flop effect becoming more noticeable and more troublesome. One can balance the beam sizes and thereby optimize the luminosity using RF phasing. However this phenomenon exhibits considerable hysteresis and close to the beam-beam limit it can limit the peak luminosity attainable. A further undesirable effect, which prompted this investigation, is that when the Bunch Lengthening Cavity (BLC) is powered the flip-flop condition is usually very much worse.

It is important to get some understanding of the phenomenon in order to: (a) use the proven good effects of the BLC, (b) be able to predict the effects in PEP and larger e^+- e^- storage rings, and (c) perhaps gain some more understanding of the beam-beam effect in general. So far we have made some interesting measurements but have no theory to explain them. We hope that further measurements will give us some more clues to the nature of the effect.

We shall group the evidence under three headings: (1) 'hard' effects, which are very noticeable and reproducible, (2) 'soft' effects, which are less sharp or less reproducible, and (3) 'null' effects, in which parameter changes have no discernable effect on the flip-flop.

We mention first some of the easily calculated effects of changing the intercavity phase. The biggest of these effects is the separation of the electron and positron orbits which cause the bunches to collide not quite head-on. Orbit measurements are in fairly good agreement with calculations and for 30^o of intercavity phase shift we find an orbit separation at one of the interaction points of $\Delta x \approx 2 \times 10^{-3}$ m $\approx 0.4\sigma_x$. Another easily calculated effect is the difference in synchronous energy of the beams at the interaction points. At the East interaction point the energy difference is $\Delta E \approx 0.3 \times 10^{-3} \approx 0.6\sigma_E/E$ for the same phase difference.

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The Measurements

The position of the RF cavities in SPEAR are shown in Fig. 1.

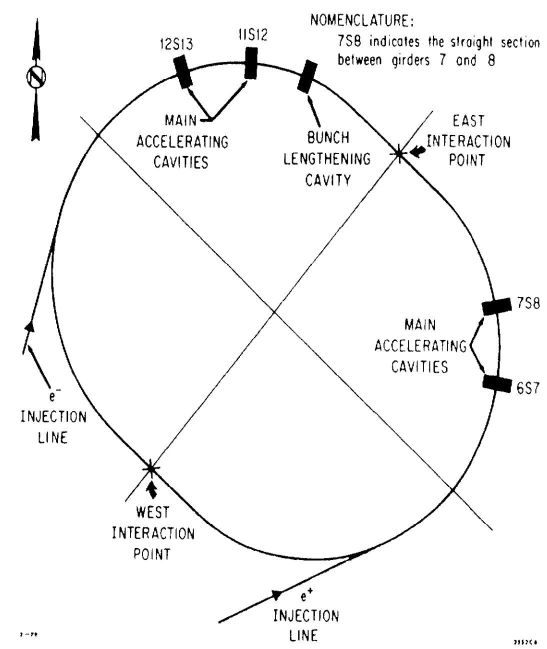

Fig. 1. Layout of RF cavities in SPEAR.

The experiments were usually done with cavities 7S8 and 11S12 powered but the cavity pair 6S7 and 12S13 has also been used. When the phase control to cavity 7S8 is varied we observe changes to the heights of the e^+ and e^- bunches. We observe the height of the bunches by means of a vertical profile scan of the synchrotron light emitted by the particles.[1] The light is scanned across a narrow slit in front of a phototube detector by means of a mirror vibrating about its suspension at 100 Hz. To produce profile scans the X plates of an oscilloscope are driven from a signal proportional to the mirror deflection.

To obtain plots of relative beam height as a function of intercavity phase the signal from the phototube is passed through a peak detector and fed to the Y terminals of a chart recorder, the X terminals being driven by a signal proportional to the intercavity phase.

Hard Effects

Dependence on $\Delta\nu$

The effect is strongly dependent on the beam-beam tune shift parameter appearing when $\Delta\nu$ > .025 per interaction region.

Horizontal Dispersion Function

SPEAR usually operates with the nominal value of the horizontal dispersion function η_x^* set equal to zero at the interaction points. With this condition the flip-flop is relatively easy to control and its polari-

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ty (direction of phase change needed to blow up a particular beam) depends on the configuration used and the closed orbit errors. If however the nominal value of η_x^* is set outside the range $-2\text{cm} < \eta_x^* < 2\text{cm}$, then a very strong hysteresis effect is evident and the flip-flop becomes uncontrollable. Typical hysteresis loops for a range of η_x^* are shown in Fig. 2.

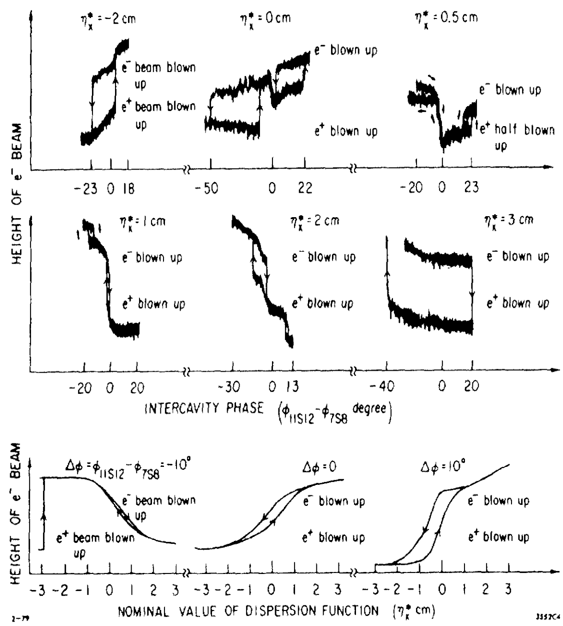

Fig. 2. Hysteresis Loops. Beam height vs intercavity phase and dispersion function.

It is unfortunately not possible to measure η_x^* to a precision better than 1cm but averaged data indicate that differences from the nominal value are approximately 0.5-1cm and that the dispersion function is different at the two interaction points.

Keeping the intercavity phase at a constant value we have scanned the value of η_x^* from -3cm to +3cm obtaining the flip-flop condition. The hysteresis loops obtained by this method are much more smooth than those obtained by varying the intercavity phase at constant η_x^*. We also observed a reversal of the polarity close to the condition of zero misphasing.

Beam Separation

Recently we have used the stripline monitor plates to make a small horizontal separation of the two beams at the interaction points. We have found that when separating voltages are applied the hysteresis loops shift along the phase axis with very little change otherwise. The orbit separation due to such a shift in intercavity phase corresponds to the orbit separation due to the separation voltage. Measurements will be continued using combinations of separating voltage and cavity phasing to separate the beams at the two interaction points independently.

Energy Dependence

The experiments described here have been done at energies of 1.88 GeV and at 2.4 GeV, most of the quantitative work being done at the former energy. In the absence of detailed quantitative data for comparison we can only report our findings at these two energies and quote operational experience at other energies.

The flip-flop is only apparent close to the beam-beam limit at any energy. At low energies (1.5-1.9 GeV) the onset is sudden and the flip-flop is very hard to control and appears to be sensitive to very small changes in conditions. In the medium energy range (2.0-2.5 GeV) the onset is more gradual and the phenomenon is much more reproducible. At energies higher than 3 GeV the flip-flop disappears.

Bunch Lengthening Cavity

A bunch lengthening cavity (BLC) was installed in SPEAR in order to improve performance.[2] The BLC is a powered cavity operating at 860 MHz at the 672^{th} harmonic of the revolution frequency. This cavity modifies the potential well of the synchrotron phase oscillations (this potential well is provided by the main RF cavities operating at the 280^{th} harmonic). The flattened potential well thus produced can lengthen the bunches so as to avoid single bunch instabilities that cause energy broadening. The lengthened bunches also produce less higher mode RF heating and cure the problem of synchro-betatron resonances.

On one occasion only, powering the BLC made the flip-flop better, but on every other occasion it made the flip-flop uncontrollable.

Risetime Measurements

We have measured the risetime of the flip-flop beam growth by applying a square wave modulation to the intercavity phase. To obtain a measure of the height of the beams we took an output from the profile monitor scan and displayed this on an oscilloscope, the oscilloscope being triggered from the pulse generator used in the phase switch. The height of the pulses from the profile monitor system is inversely proportional to the beam height. Measurements suggest that the risetime is independent of energy and is about 80-100 msec which is long compared to the transverse damping time.

Soft Effects

Rotated Quadrupole

A detailed study of these effects has not yet been done but measurements and operational experience indicate that increasing the linear coupling by means of the rotated quadrupoles makes the flip-flop less sensitive. This is probably due to an increase in the non beam-beam contribution to the height of both beams resulting in a decrease in beam-beam tune shift. The increased strength of the rotated quadrupoles might also be expected to change the flip-flop by coupling residual horizontal dispersion to the vertical plane.

Chromaticity and Sextupoles

SPEAR normally operates with horizontal and vertical chromaticities $\xi_x = \xi_y = +3.2$. The natural chromaticities for normal operation with $\beta_y^* = 10\text{cm}$ are $\xi_x = -10$ and $\xi_y = -20$, the correction being accomplished by two families of sextupoles.

Increasing the chromaticity substantially (25% increase in sextupole strength) made the flip-flop worse but not disasterously so. Decreasing the horizontal chromaticity towards zero had an effect on the hysteresis print of the flip-flop. This effect was not however reproducible between experiments and no dramatic effect was observed close to the value $\xi_x = 0$. Decreasing the vertical chromaticity alone had no effect. The most probable explanation for this behaviour is the effect that the sextupoles have on orbits and dispersion functions at the interaction points.

Horizontal Beam Size

Measurements indicate that, when the beam heights are flipped and flopped, the widths also change. We might expect that if the effect were due to coupling, then an increase in beam height should be accompanied by a reduction in beam width. We in fact noticed an increase in width of the beam that was blown up vertically. For moderate values of beam-beam tune shift the change in beam width was about 5% but at the higher currents the change was about 10%. The effect is most easily seen by applying a square wave phase modulation at a frequency of about 1 Hz.

Null Effects

Vertical Orbit and Dispersion Function

No correlation could be found between the flip-flop and measured vertical orbits and dispersion functions.

Coherent Motion

We have not detected any coherent motion associated with the flip-flop. Since the beam cross section is small compared to the distance between the beam and the monitors, it is only possible to detect the barycentric (dipole) mode of oscillation by using these monitors. We have however also viewed samples of the beam profile by using the synchrotron light monitoring system. This technique should be sensitive to higher modes of oscillation.

Longitudinal Motion

We have looked for changes in bunch shape or bunch length associated with the flip-flop. Both by direct observation of the synchrotron light using a fast photodiode and by observing the spectrum of signals from the beam monitors, we have been unable to detect any such changes when the beams undergo a change in state.

Conclusions

For a small intercavity misphasing all calculated effects are extremely small except for the beam separation, beam crossing angle and energy separation. By keeping the cavities phased and varying the dispersion function η_x^* we can also make the beams flip and flop. This observation combined with the evidence from the horizontal separation experiment leads us to believe that the energy separation is not necessary to the phenomenon. We believe that a beam separation (or possibly crossing angle) at a finite value of η_x^* is the combination necessary to drive the flip-flop. We think that coherent motion is unlikely because (a) the rise-time is long compared to the transverse damping time, (b) we have not observed any coherent motion, and (c) the dependence on chromaticity is not very strong. Single resonance effects are also unlikely since the effect is independent of machine tune and because the bunch lengthening cavity cures the individual synchro-betatron resonances by creating a continuum of synchrotron tunes.

The calculated changes in amplitude function β and dispersion function η as a function of orbit difference and energy difference are very small and are unlikely to play a part in deciding which beam should blow up.

Because of the sensitivity to horizontal dispersion function it is possible that synchro-betatron resonances are excited by the beam-beam force as in Ref. 3 but that these resonances are of high order and are associated with the nonlinearity of the beam-beam force.

Acknowledgements

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References

1. A. P. Sabersky, "Monitoring the Beams in SPEAR with Synchrotron Light," IEEE Trans. on Nucl. Sci. (June 1973), vol. NS-20, no. 3, p. 638.

2. W. R. Fowkes and P. B. Wilson, "Predicted Bunch Shapes in SPEAR using Active Bunch Lengthener (ABLE)," SPEAR-209, (January 1977), unpublished.

3. A. Piwinski, "Satellite Resonances Due to Beam-Beam Interaction," IEEE Trans. on Nucl. Sci. (June 1977), vol. NS-24, no. 3, p. 1408.