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BEAM-BEAM EFFECT AND LUMINOSITY IN SPEAR*)

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1. INTRODUCTION

Many measurements on the beam-beam limit in SPEAR have been performed over the past eight years since colliding beam operation began. The goal for these measurements was to find the proper parameterization of the beam-beam effect. Earlier measurements$^{1,2)}$ in SPEAR, however, were limited in their validity by two circumstances. First, until 1978 we had no control over the so-called flip-flop phenomenon.$^{3)}$ We did not even know about this effect because it seemed natural that due to the beam-beam interaction one of the beams — the "weaker" one — got vertically blown up when high current beams were brought into collision. In 1978 we found, however, that we could choose which beam gets blown up or, what is more important, we could manage to make the particle distribution in both beams the same. This can be done by adjusting the relative phase of the two rf systems located symmetrically on either side of the interaction points. As yet we do not understand this effect, but control of the flip-flop effect resulted in an increase in luminosity by a factor 1.5 to 2 (Fig. 1). All measurements in this report were done with both beams equally blown up. The second shortcoming of the earlier measurements was the limited energy variation possible in SPEAR. This led to erroneous energy scalings of the beam-beam incoherent tune shift parameter$^{2)}$ ξ. In 1979 the magnet power supplies were modified such that operation at energies as low as 400 MeV was possible. We have made colliding beam measurements at energies as low as 600 MeV and together with earlier measurements we can now present the scaling of some relevant storage ring parameters from 600 MeV up to almost 4 GeV. All measurements have been done with a natural beam emittance of $\varepsilon_x(\text{rad m}) = 5.0\times10^{-8}\,E^2\,(\text{GeV}^2)$, the wiggler magnets off, and with the following beam dynamic parameters at the interaction point

$\nu_x \simeq 5.28$ $\qquad$ $\nu_y = 5.17$

$\beta_x^* = 120$ cm $\qquad$ $\beta_y^* = 10$ cm

$\eta_x^* = 0$

The damping time for transverse betatron oscillations is given by $\tau_{x,y}(\text{sec}) = 0.226/E^3\,(\text{GeV}^3)$. In all measurements the beam currents were equal to better than 10% and there is only one bunch per beam in SPEAR.

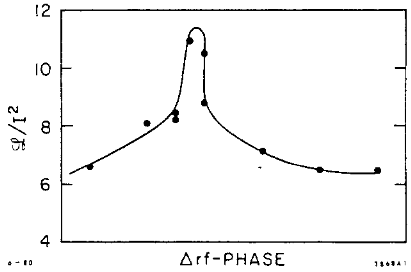

Fig. 1. Effect of the beam beam flip-flop on the specific luminosity.

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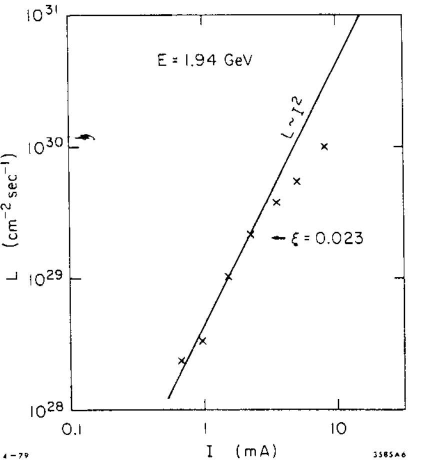

Fig. 2. Typical variation of luminosity with beam current.

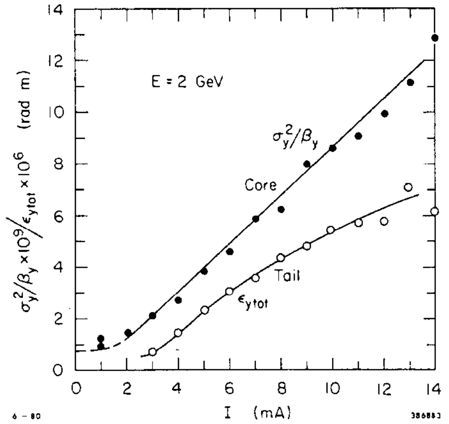

Fig. 3. Beam height as a function of colliding beam current.

2. OBSERVATIONS ON THE BEAM-BEAM EFFECT

When two beams at not too low an intensity are brought into collision usually one beam is blown up much more than the other one. By adjusting the flip-flop effect we can make both beams equal and achieve maximum luminosity. A typical luminosity curve versus beam current I is shown in Fig. 2. At very low currents there is no beam blowup and the luminosity scales as expected, like I^2. As the current is increased we reach a threshold above which the vertical beam size increases due to the beam-beam effect. The horizontal beam size is not affected within the errors of observation. In Fig. 3, the increase of the vertical beam emittance is shown as a function of the colliding current. One curve represents the vertical emittance of the core of the beam as calculated from the luminosity. The other curve shows the vertical emittance of the total beam (tails) as determined by lifetime measurements with scrapers. The core emittance increases linear with beam current while the emittance of the tail increases somewhat differently. The limit is reached as soon as the tail emittance reaches the acceptance of the storage ring. We have reduced the acceptance of the storage ring by scrapers and measured the maximum beam-beam tune shift as a function of the aperture in SPEAR (Fig. 4). It is clear from these measurements that the beam-beam effect generates a vertical blow up which is stopped by some effect — probably damping. The absolute limit on the beam-beam effect, and, therefore, the maximum luminosity, then is reached when the vertical beam size reaches the aperture limit. Later in this note we will have to come back to this point. In Fig. 5, data at or near maximum luminosity as

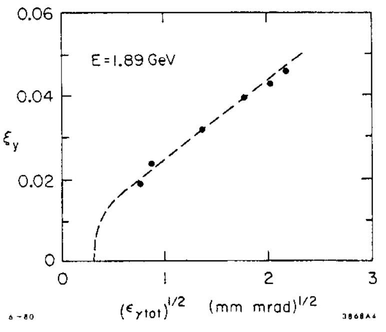

Fig. 4. Maximum tune shift parameter as a function of the ring acceptance.

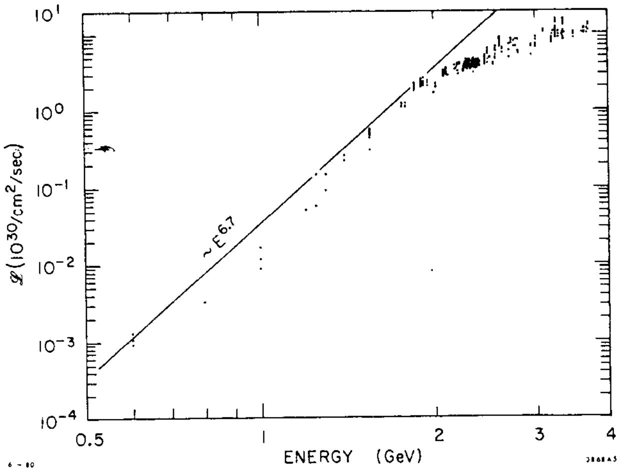

Fig. 5. Maximum luminosity in SPEAR.

achieved in normal runs for high energy physics, as well as in accelerator studies runs, are collected. The maximum luminosity scales like $E^{6.7}$ up to an energy of about 2 GeV. This is in agreement with the $\mathscr{L} \sim E^7$ scaling reported from Adone.$^{4)}$ Note that for lack of time the measurements at 0.8 and 1.0 GeV do not yet represent the maximum achievable luminosities. The associated beam currents are shown in Fig. 6 and the linear tune shift parameter ξ_y in Fig. 7. This tune shift parameter ξ_y was calculated from the luminosity by

$$\xi_y = \left(2r_e mc^2 e\right)\, \beta^*_y \; \frac{\mathscr{L}/I}{E\left(1+\sigma^*_y\ \sigma^*_x\right)} \quad . \qquad (1)$$

This equation is derived by combining the definition of the luminosity $\mathscr{L} = (4\pi e^2 f)^{-1} \cdot I^2/(\sigma^*_x \sigma^*_y)$ and the linear tune shift parameter

$$\xi_y = \left(r_e mc^2/2\pi e f\right)\, I\beta^*_y/E/\sigma^*_x\sigma^*_y/\left(1+\sigma^*_y/\sigma^*_x\right) \quad . \qquad (2)$$

Here $r_e = 2.84 \times 10^{-15}$m, $mc^2 = 0.511$ MeV, e the electron charge, f the revolution frequency and σ^*_x, σ^*_y the beam width and height at the interaction point. The effective beam height $\dot{\sigma}^*_y$ is calculated from the luminosity assuming the theoretical beam width σ^*_y which is precise enough for the correction factor $(1+\sigma^*_y/\sigma^*_x)$. We find in Fig. 7 the vertical linear beam-beam tune shift parameter to scale like

$$\xi_y \sim E^{2.4}$$

up to about 2 GeV. Above that energy the tune shift parameter is constant

The limitation seems to be distinctively different for energies below and above 2 GeV. Below 2 GeV, the limit is consistent with the aperture of SPEAR. Above 2 GeV we cannot make a

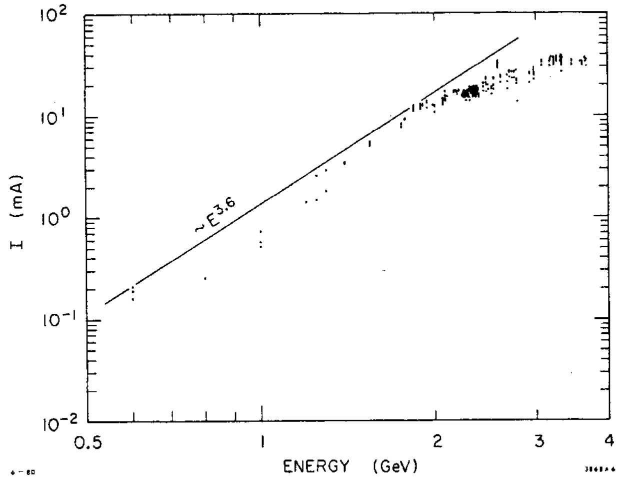

Fig. 6 Maximum colliding beam currents in SPEAR.

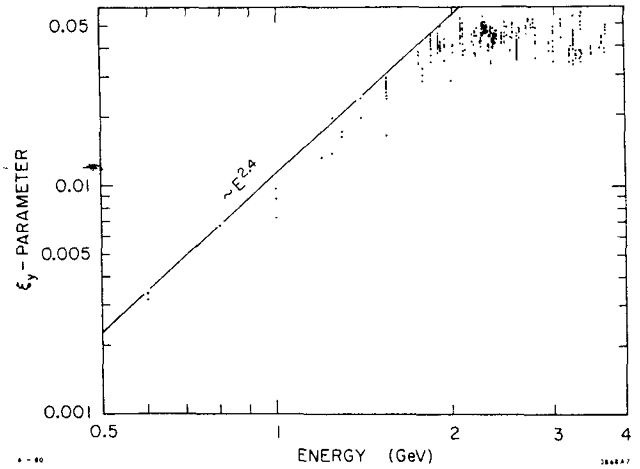

Fig. 7. Maximum tune shift parameter in SPEAR.

similar statement since not enough detailed measurements have been performed. The different behavior is further illustrated in two other measurements. In Fig. 8 the linear tune shift parameter ξ_y is shown as a function of energy for a constant beam current $I^+ + I^-$ = const and a vertical betatron function at the interaction point of $\beta_y^* = 20$ cm. Above 3 GeV the tune shift parameter drops as expected $\xi_y \sim E^{-3}$. At 3 GeV and lower energies the tune shift stays constant and only the vertical beam size increases till the limit is reached. In another experiment (Fig. 9) the current and the energy was kept constant but the value of β_y^* was varied. Here again we experience a saturation of values of $\xi_y \simeq .06$.

For the design of new storage rings it would be extremely interesting to know what separates the two regimes in order to determine where the new storage ring will operate. Since a similar limit at about the same value for ξ_y has been observed also in Adone[4)] it may very well be a fundamental limitation due to the mere magnitude of the nonlinear perturbation. In this case a proper theory is needed to be able to scale the transition point from one storage ring to another.

So far we have not addressed the horizontal linear tune shift parameter ξ_x. Since we do not observe any significant horizontal beam blow up we conclude that the horizontal tune shift parameter does not take part in the beam-beam limit. In particular, we observed that ξ_x can be much larger than ξ_y. At the beam-beam limit for the

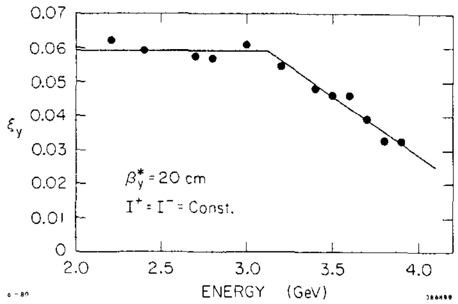

Fig. 8. Tune shift parameter vs. energy for constant beam currents.

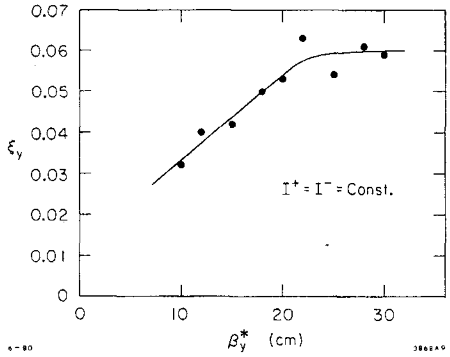

Fig. 9. Tune shift parameter vs. β_y^* for constant beam currents.

following two energies we have:

Energy	600 MeV	2.0 GeV
ξ_x	.016	.040
ξ_y	.0034	.045

This may or may not be a peculiarity of SPEAR since in all cases the beam at the interaction point is rather flat.

3. SCALING OF BEAM-BEAM RELATED PARAMETERS

In the rest of this note we will discuss only the measurements up to 2 GeV, that is in the regime where the maximum linear tune shift parameter changes with energy. From the measurements we obtain the following scaling laws:

$$\mathcal{L}_{\max} \sim E^{6.7 \pm 0.1}$$

$$I_{\max} \sim E^{3.6 \pm 0.1}$$

$$\xi_{y\,\max} \sim E^{2.4 \pm 0.1}$$

We also observe a threshold current above which the vertical beam size becomes blown up. If we plot $\mathcal{L}/E^{6.7}$ versus $I/E^{3.6}$ in the regime between threshold and beam-beam limit for different energies we find a common behavior (Fig. 10):

$$\frac{\mathcal{L}}{E^{6.7}} = \text{const} \cdot \left(\frac{I}{E^{3.6}}\right)^{1.5\pm0.1} \qquad (5)$$

From this we can derive a scaling law for the vertical beam size. Using the definition equation of the luminosity, we get

$$\frac{\mathcal{L}}{E^{6.7}} \sim \frac{I^{\frac{1}{2}}}{\sigma_x^* \sigma_y^* E^{1.3}} \left(\frac{I}{E^{3.6}}\right)^{1.5\pm0.1.} \qquad (6)$$

Since $\sigma_y^* \sim E$ we get

$$\sigma_y^* \sim \frac{I^{\frac{1}{2}}}{E^{2.3\pm0.4}} \qquad (7)$$

Eq. (7) is in agreement with the observation at PETRA$^{5)}$ where $\sigma_y^* \sim I^{\frac{1}{2}}/E^2$ was measured. If we now use the measured scaling for the maximum current from Eq. (4),

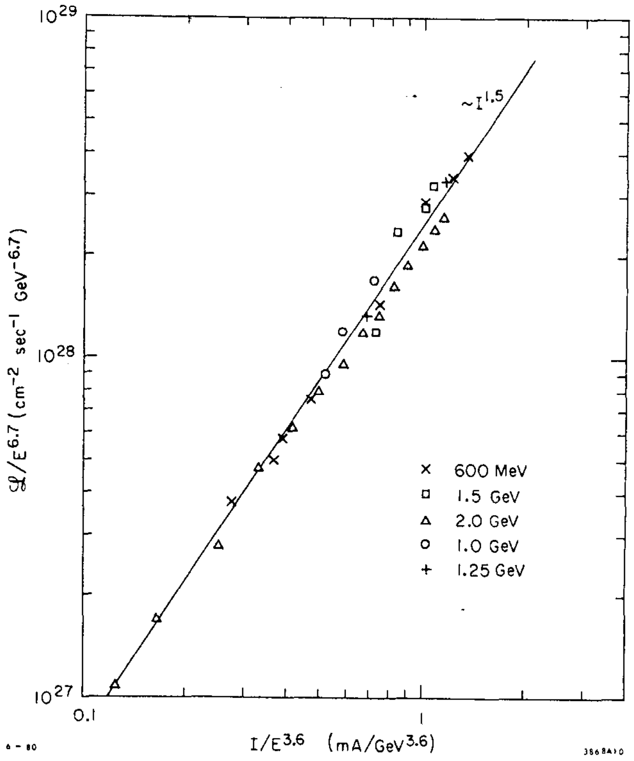

Fig. 10. Normalized luminosity vs. normalized current SPEAR.

we get

$$\sigma_{y\ \max} \sim \frac{I^{\frac{1}{2}}_{\max}}{E^{2.3 \pm 0.4}} \sim E^{-0.5 \pm 0.45} \simeq \text{const.} \qquad (8)$$

This again is a confirmation that the maximum beam-beam limit in SPEAR is reached at all energies below 2 GeV as soon as the vertical beam size approaches a certain value which is consistent with the SPEAR aperture limit. The total vertical beam size at the beam-beam limit has been measured for a few different energies and configurations and agrees within the errors of the measurement with the acceptance of the SPEAR storage ring.

The scaling of luminosity curves at different energies in SPEAR (Fig. 10) encouraged the author to try for a common scaling for all storage rings. In Fig. 11 the results of such a tryout is plotted. Over many orders of magnitudes the luminosities scale the same way in all storage rings if we normalize the luminosity on the damping and use the number of particles per bunch rather than the beam current. There are certainly more subtle differences between different storage rings as beta functions, tunes, etc. These differences, however, account only for factors two to maybe five in the luminosity. On the scale of Fig. 11, these small factors, however, do not show up.

Three storage rings (ACO, ADONE and DCI) seem to behave differently. This might be due to the fact that these storage rings have no beta section and run at the coupling resonance, whereas all the other storage rings have small vertical betatron functions at the interaction point and run at minimum coupling.

The common scaling suggests the same process to be responsible for the beam-beam effect in all storage rings. From Fig. 11 we get

$$\frac{\mathscr{L}\tau}{E^{3.7}} \sim \left(\frac{N_B}{E^{3.6}}\right)^{3/2} \qquad (9)$$

where τ is the transverse damping time and N_B the number of particles per bunch.

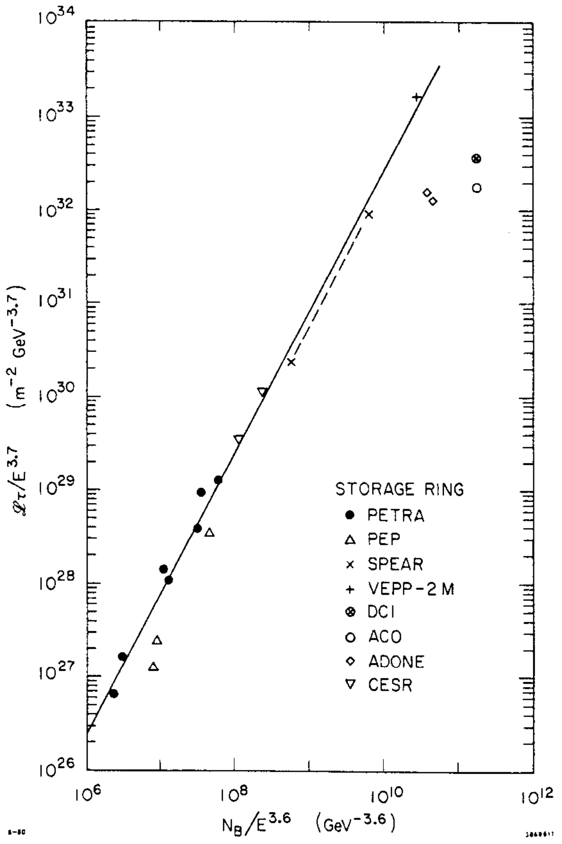

Fig. 11. Luminosity scaling in different storage rings.

CONCLUSION

Measurements performed at SPEAR have been discussed and scaling laws for the maximum luminosity and the maximum linear tune shift parameter with energy are shown. We made the following observation: there are two distinct regimes, one below 2 GeV where the linear tune shift parameter scales like $\xi_y \sim E^{2.4}$ and the other regime where this parameter is constant $\xi_y \simeq 0.05$ to 0.06. In the lower energy regime the limit is reached when the vertical beam size is blown up to the acceptance of the storage ring. We do not observe a significant (< 10%) horizontal beam blow up and the value of the horizontal linear tune shift parameter ξ_x does not seem to be related to the beam-beam limit.

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