BEAM INSTABILITIES IN THE PRINCETON-STANFORD STORAGE RINGS *

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During the past two years the Princeton-Stanford storage ring group has spent a lot of time investigating a number of beam instabilities associated with operating the rings at currents above 5 mA. The purpose of this report is to summarize the most salient features of the instabilities which might be of some interest to other storage ring groups. We can classify the phenomena into three groups:

1. Vertical instabilities of a single beam.
2. Vertical instabilities associated with the interaction between two beams.
3. Changes in radial and azimuthal size of a single beam.

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The machine design and its general operation have been described in several places (1). Here we list only the properties which are pertinent:

1. Energy. Almost all of our systematic studies have been made at 300 MeV. This paper will describe these only.

2. R.f. Frequency. 25.4 Mc. We can vary this by approximately ±150 Kc.

3. Beam Length. We have calculated the beam length from quantum fluctuations to be approximately 30 cm. We have measured the beam length to be from 50 to 70 cm for what appears to be a stable beam. The length varies with r.f. frequency. At the present time this is a mystery for us and will be described under radial instabilities.

4. Beam Width. The width of the stable beam has been measured to be 3 mm.

5. Beam Height. In much of the discussion on vertical beam instabilities the beam height varies. We observe changes in beam height induced by space charge effects. Furthermore, we have installed a quadrupole magnet on each ring which allows us to vary the height by coupling radial and vertical motion. We have tried to measure the natural size of a weak beam and found it to be less than our resolution of 0.3 mm. We estimate the size to be between 0.05 and 0.1 mm.

6. The Betatron Frequencies. The machine as originally built and \( Q = 0.88 \) and \( Q_k = 0.77 \) for both rings. We have added another quadrupole magnet on each ring to enable us to vary the \( Q \) values. \( Q \) may now be varied independently on each ring from 0.82 to 0.94. The relation between \( Q \) and \( Q_k \) is given by

\[
(Q - 0.88) + (Q_k - 0.77) = 0
\]

7. Machine Non-Linearities. By measuring the vertical oscillation frequency as a function of r.f. frequency we have determined the variation in \( Q \) value as a function of radius. For the guide fields without quadrupoles, this is given by

\[
Q = 0.88 - (9.3 \times 10^{-4}) x + \epsilon x^2
\]

where \( x \) is in mm and \( \epsilon < (2 \times 10^{-4}) \text{ mm}^{-1} \). The linear term agrees well with the measurements of \( N \) value that were made when the magnets were constructed. We have not tried to understand the quadratic term.

We have installed an 8-pole magnet to enable us to increase the quadratic term. When it is fully energized \( Q \) is given by:

\[
Q = 0.88 - (9.3 \times 10^{-4}) x + (2.4 \times 10^{-4}) x^2 - (0.8 \times 10^{-7}) z^2
\]

where \( x \) and \( z \) are in mm.

8. The Vacuum Chamber. The cross section of the vacuum chamber inside the guide field is shown in Fig. 1.

The four straight sections comprise 26% of the orbit. Two of the straight sections have electrodes for clearing ions away from the beam. One of the remaining sections has r.f. fields which will move the ions.

**SINGLE BEAM VERTICAL INSTABILITY**

With voltage on the clearing field electrodes so that ions are removed from the beam, and with the 8-pole magnets turned off, we have found that with a circulating beam current greater than some critical value (between 5 and 50 mA), small perturbations of the beam result in coherent growth of vertical betatron motion until a large fraction of the beam is lost (typically between 50 and 100 percent). We have not understood all the important parameters in determining the critical current. It seems to be highly dependent on the density of ions in the beam. By permitting ions to remain in the beam along 25% of the orbit, we raise the critical current to several hundred milliamperes, and with the clearing electrodes off, we can stably stack up to 500 or 600 mA.

We have looked at the r.f. signal on the clearing field electrodes. These have enabled us to identify coherent motion at the betatron frequency. With ions removed from the beam, the signal grows more or less exponentially (see Fig. 2). Starting the growth at three different current levels (60, 45, and 25 mA), we have found the growth rate to be \( = 2.5 \text{ sec}^{-1} \text{ mA}^{-1} \).

With ions left in the beam the signal on the clearing field electrodes at currents of 10 mA to 100 mA consist of bursts of the type shown in Fig. 3. The fast signal of 2 to 3 \( \times 10^{-4} \text{ sec} \) duration followed by the slow wave is characteristic of all the bursts. The bursts seem to come at random intervals but the average rate increases sharply with beam currents above 20 mA.

By turning on the 8-pole field we make the beam stable against loss from the vacuum chamber up to the beam currents we have investigated of 500 mA. We have measured the height of a single beam as a function of beam current. Figure 4 shows typical curves with and without ions. It is interesting to note that these curves are not changed by turning the eight-pole magnets on or off.

We have installed a beam stabilizing servo system. The r.f. signal on one clearing field plate is put into an amplifier and fed back onto a second plate with a phase appropriate to damp betatron motion. The servo renders the beam
stable against perturbations, making it unnecessary to use the 8-pole field. The curve of beam height vs current with ions in the beam is the same with and without the servo. However, with ions removed, we see no increase in beam height of a single beam with the servo operating.

We have also measured the change in coherent vertical betatron oscillation frequency as a function of beam current. With clearing electrodes

\[
dQ = -8 \times 10^{-6} \text{mA}^{-1}
\]
of 48 mA to 130 mA. This number should be calculable from the Lasslett, Neill, Sessler (2) paper on resistive wall instabilities which takes into account the effect of image charges on the walls of the vacuum chamber. We have not checked this. Our measured number is three times too large compared to the frequency shift of incoherent betatron oscillations which one calculates from the paper on space charge effect by J. Lasslett (3) in the 1963 Brookhaven summer study report.

With ions left in the beam we measured

\[
dI_{\text{beam}} = +50 \times 10^{-6} \text{mA}^{-1}
\]

An early theory on the effect of ions in beam size pictured the ions as shifting the vertical betatron frequency up until \( Q_v = 1 \), at which point beam growth took place to reduce the ion density. The small value of \( dI_{\text{beam}} \) has eliminated this model. We do not understand the beam properties in the presence of ions.

We have tentatively interpreted the single beam instability in terms of the LNS model (2). Our growth rates are consistent with those predicted by LNS modified appropriately for bunched beams. The lowest «threshold» we have measured was 5 mA. If one assumes a completely linear machine then the frequency spread in the beam comes from the radiation damping and has a \( 8Q_v = 0.4 \times 10^{-6} \). Then LNS theory predicts a threshold of \( 4 \) mA.

**TWO BEAM VERTICAL INSTABILITIES**

Our investigation of the behavior of the beam-beam interaction can be described in terms of two classes of experiments:

1. **Weak Beam - Strong Beam.** In these experiments the effect of a strong beam of 10 mA to 200 mA on a weak beam of less than 1 mA is considered. The weak beam is considered to have the same properties as a single circulating electron. We have varied the number of particles in the weak beam from \( 2.5 \times 10^8 \) (1 mA) down to 400 without noticing significant changes in its behavior.

2. **Strong Beam - Strong Beam.** In these experiments the strength of both beams are comparable and are in the range of 5 mA to 100 mA. Typically, above some current level when the beams are made to pass through each other one beam is lost (or partially lost) from the vacuum chamber.

**Weak Beam - Strong Beam Regime**

When the beams are brought into interaction vertically, the weak beam suddenly grows in size to several millimeters. The growth takes place when the two beam centers are separated by \( \sim 1/2 \) mm. Figure 5 shows the curve for height of the weak beam as a function of the distance between centers. We have made a large number of measurements of the height of the weak beam versus current in the strong beam for various operating conditions. Figure 6 is a height vs current curve for different values of \( Q_v \) of the weak beam. Figure 7 shows how threshold current varies with \( Q_v \). The points shown come from two different sets of measurements. The dotted curve through the points should not be taken too seriously. It represents our qualitative impression of the behavior of threshold. The data does emphasize the strong dependence on \( Q_v \) of the weak beam for \( Q_v \) (weak) \( \sim Q_v \) (strong).

We have looked for coherent motion of the weak beam with a phototube viewing the synchrotron light through a slit and by trying to pick up a signal on a radio receiver directly from the clear-
ing field plates. A null result shows the coherent motion to be less than 0.2 mm.

E. Courant (4) has suggested that a single electron on passing through the nonlinear potential of the strong beam will pick up large betatron motion. In a series of computer calculations he has shown the critical beams strength,

\[ \delta Q = \frac{2 \pi r_e \gamma}{2 \pi b (a + b)} \]

in units of \( \delta Q = \frac{2 \pi r_e (a + b)}{\gamma} \), is 0.2, where \( r_e \) is classical electron radius, \( R_m \) is the mean radius of the machine, \( Q \) is betatron frequency divided by the r. f. frequency, \( a \) is beam width (standard deviation on a gaussian distribution), \( b \) is the beam height (standard deviation on a gaussian distribution), \( \gamma \) is electron energy divided by its rest mass and \( N \) is the number of particles in the strong beam.

We had taken a number of measurements of the height of the weak beam vs current in the strong beam for different heights of the strong beam. Measurements were made for values of \( b = 0.11, 0.22, \) and 0.44 mm. To check Courant's \( \delta Q = 0.20 \) against our measurements we have defined the threshold current to be the value at which the weak beam has grown in size to that of the strong beam. For each case the threshold occurred at \( \delta Q = 0.1 \). We have concluded that Courant's explanation is correct and \( \delta Q = 0.1 \) is probably a good criteria when considering space charge limits for storage rings.

**Strong Beam - Strong Beam Regime**

Our information on the strong beam-strong beam interaction is of a qualitative nature. We have found that the beam loss in accompanied by a signal on the clearing field electrode at the betatron frequency. Early experiments on thresholds were done with beams whose vertical di-
mension was smaller than we could measure. Under those conditions we saw beam loss for currents as low as 5 mA. Last spring we found that by increasing the beam height to ~ 1 mm and by splitting the betatron Q values (we have been using \( Q_v - Q_\alpha = 0.05 \)) we were able to maintain interacting beams at currents up to 40 or 50 mA. Above this level we lose one of the beams.

From a series of runs devoted to measuring the wide angle electron-electron scattering angular distribution we have obtained the luminosity as a function of beam current. The luminosity per unit mA\(^2\) is roughly constant for values of \( I_1 \times I_2 \) up to 400 to 600 mA\(^2\).

\[
\frac{L}{I_1 I_2} = 2 \times 10^{-25} \text{cm}^{-2} \text{mA}^{-2} \text{sec}^{-1}
\]

This number is about half of what we calculate it should be from measurements of beam size. At higher currents the luminosity per unit mA\(^2\) slowly decreases to \( 0.75 \times 10^{-25} \text{cm}^{-2} \text{mA}^{-2} \text{sec} \) at 1600 mA\(^2\).

From this we have concluded that probably there are instabilities present at beam currents of 20 to 25 mA but they do not lead to beam loss.

We have been interpreting the strong beam-strong beam phenomena in terms of the two beam resistive will instability (5). A report was given at the Washington Accelerator Conference (1) summarizing the stability limits for our machine. They are still pertinent.

**RADIAL INSTABILITIES**

Radial stability of a single circulating beam in our machine is strongly dependent on the frequency of the r. f. system. By viewing the synchrotron light of the bunched beam with a fast photodiode we have been able to monitor the effect on the beam. The following description is typical.

The beam current is ~20 mA. Starting at 25,250 mc we slowly raise the frequency. The beam has large synchrotron oscillations. At 25,290 mc the synchrotron oscillations disappear and the beam is bunched tightly into a 60 cm length. Above 25,310 cm the beam length increases to 120 cm. There is no sign of coherent synchrotron oscillation. At 25,335 mc the beam again begins to narrow to the 60 cm length at 25,370 mc. Above 25,370 mc synchrotron oscillations reappear.

The r. f. cavities are servoed to hold the phase of the cavity voltage with respect to the master oscillator constant so that the tune of the cavity is constant over the frequency range. A number of papers have been written (6) about beam-cavity instabilities and the tune of the cavity. The general conclusion is that the beam cavity system will be stable if the cavity is tuned capacitively (i.e., if \( z \) is the cavity impedance, then \( \frac{dz}{d\omega} < 0 \)). Our cavities are operating with \( \frac{dz}{d\omega} > 0 \). We have not been able to operate on the other side of resonance because the cavity alone is unstable there. We are presently fixing this. Operating the cavities on the wrong side of resonance could explain the coherent synchrotron oscillation of the beam, however, we do not understand the increase in beam length around 25,320 Mc. At present the only hypothesis we can make is the presence of several hundred volts of r. f. at some high harmonic of the r. f. This could reduce the derivative of the voltage with respect to phase at the equilibrium phase angle and the quantum noise would increase the beam length.

The machine is presently disassembled to make some changes in the vacuum system. We expect to be operating again by January 1966, and plan on continuing our studies of beam stability.

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B. Gittelman: Recent developments on the Stanford 500 MeV electron storage rings; Particle Accelerator Conf. Washington, 1965; Also available as HELP, report 316;
(4) E. Courant: Particle Accelerator Conf., Washington, 1965; IEEE Trans. on Nuclear Science NS-12 n. 5, 550 (1965). The idea of a strong beam detuning the vertical betatron oscillations has been raised by many people. A Sessler and K. Robinson have also done some calculations on this.
(5) The original idea for this came from A. Sessler. E. Courant has helped our understanding of the problem. A number of reports have been written on the subject at the SLAC summer study on Storage Rings (these will be available soon).

EXPERIMENTAL RESULTS ON BEAM-BEAM INTERACTION

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Effects of electromagnetic interaction between colliding beams ("Beam-beam phenomena") seem to place rather principles restriction on the achievable luminosity. Therefore, the experimental study of these effects appears to be of importance in the accelerating program of the storage ring investigation. In this connection, this report gives a survey of the preliminary results on beam-beam phenomena study obtained with the electron storage ring VEP-1. Beside this, are described the first notices about the behaviour on the positron beam in presence of the electrons in the storage ring VEPP-2. The description of the machine and the main beam parameters (stored current intensity, life time and beam dimensions) are given in (1).

Experiments at the storage ring VEP-1 were carried out mainly with beam energy of 43 MeV. For practical reasons the study of beam-beam phenomena was carried out by observing the beam behaviour in the upper ring, which will be called in what follows the first ring. Also, the magnetic field on this ring has the following nonlinearities, such as a quadratic $\frac{\partial v}{\partial R} = 1.5 \times 10^{-2}$ l/cm and a cubic $\frac{\partial^2 v}{\partial R^2} = 4 \times 10^{-1}$ cm$^{-2}$. In the storage of each beam the equilibrium orbit are separated at the collision point. After the storage of the current required, beams are matched by means of special arrangements (2). Beam-beam phenomena ambiguously depend on the dimensionless frequency of betatron oscillations $v$. Therefore beam behaviour in each ring depending on the $v$ value have been studies. The working region in our storage ring is the region from $v_s = 3/4$ to $v_s = 4/5$ (Fig. 1). It turned out that when beam passes through the nonlinear resonances $v_s = 3/4; 4/5; v_s = 2/3; 3/5$ within times of 1 sec order (radiation damping time) its axial or radial dimensions highly increase, and the beam is lost. For other values for $v_s = 0.792$ the increase of beam transverse size resonantly depending on the resonator voltage amplitude was obtained. The maximal "blowing-up" corresponds to $v$ shifted from the resonant value $v_s = 4/5$ by $\Omega/\omega_0$. The increase of beam transverse size resonantly depending on the resonator voltage amplitude was obtained. The maximal "blowing-up" corresponds to $v$ shifted from the resonant value $v_s = 4/5$ by $\Omega/\omega_0$. $\omega_0$ is the revolution frequency and $\Omega$ is the frequency of synchrotron oscillations.