(29) A.M. Sayied: The Many-Body Problem in Accelerators Due to High Beam Intensity, Brookhaven Report AADD-73, (1964, unpublished).
(30) L. D. Landau: J. Phys. (USSR) *10*, 25 (1946).
(31) R. L. Pease: Particle Accelerator Conference, Washington, 1965; IEEE Trans. on Nuclear Science *NS-12*, 561 (1965).
(32) H. G. Hereward: The elementary Theory of Landau Damping, CERN Report 65/20, (1965, unpublished).
(33) L. D. Landau and E. M. Lifshitz: Electrodynamics of Continuous Media, (Addison-Wesley, 1960), p. 186.
(34) E. Keil: SLAC-49, (1965) (see Ref. 15), p. 71; M. Hine: ibid., p. 74.
(35) C. Bernardini et al.: Phys. Rev. Letters *10*, 407 (1963).
(36) G. R. Lambertson: Int. Conf. on High Energy Particle Accelerators, Dubna, 1963, (Atomizdat, Moscow, 1964), p. 153.
(37) M. Q. Barton: ibid., p. 157.
(38) I. M. Samoilov and A. A. Sokolov: Soviet Phys.-JETP *12*, 185 (1961).
(39) H. Bruck et al.: Int. Conf. on High Energy Accelerators, Brookhaven, 1961, (U. S. Government Printing Office, Washington, D.C., 1961), p. 175.
(40) M. Q. Barton and C. E. Nielsen: ibid., p. 163.
(41) C. D. Curtis et al.: Int. Conf. on High Energy Particle Accelerators, Dubna, 1963, (Atomizdat, Moscow, 1964), p. 620.
(42) C. Pruett and R. Otte: Beam Instabilities in the MURA 50 MeV Accelerator, MURA Tech. Note TN-407, (1963); D. A. Swenson: On the Threshold for the Coherent Vertical Instability, MURA Tech. Note TN-421, (1963); R. A. Otte: Measurements of the Frequency Spread and Growth Time of the Coherent Beam Instability in the MURA 50 MeV Accelerator, MURA Tech. Note TN-532 A, (1965); C. H. Pruett and R. A. Otte: An Experimental Study of Coupling of the Vertical Resistive Wall Instability Between Two Adjacent Beams, MURA Tech. Note TN-533, (1965); and R. A. Otte, C. Pruett, and H. Kamei: Propagation of the Coherent Beam Instability in a Stacked Beam, MURA Tech. Note TN-538, (1965, all unpublished).
(43) R. A. Otte: private communication.
(44) L. J. Laslett: private communication.
(45) M. Q. Barton, J. G. Cottingham, and A. Tranis: Rev. Sci. Instr. *35*, 624 (1964).
(46) D. Ritson and J. Rees: Limitations on Storage Ring Reaction Rates, Stanford Report, SLAC-TN-65-39, (1965, unpublished.
(47) A. M. Sessler: SLAC-49, (1965) (see Ref. 15), p. 8.
(48) R. J. Briggs and V. K. Neil: Stabilization of Intense Coasting Beams in Particle Accelerators by Means of Inductive Walls, UCRL-14407, (1965, unpublished).

BEAM INSTABILITIES IN THE PRINCETON-STANFORD STORAGE RINGS *

W. C. Barber

High Energy Physics Laboratory, Stanford University, Stanford, California (USA)

B. Gittelman, G. K. O'Neill

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey (USA)

B. Richter

Stanford Linear Accelerator Center, Stanford University, Stanford, California (USA)

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.

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 $\simeq 30$ 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 $Q_v = 0.88$ and $Q_R = 0.77$ for both rings. We have added another quadrupole magnet on each ring to enable us to vary the Q values. Q_v may now be varied independently on each ring from 0.82 to 0.94. The relation between Q_v and Q_R is gixen by

$$(Q_v - 0.88) + (Q_R - 0.77) = 0$$

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

$$Q_v = 0.88 - (9.3 \times 10^{-4}) x + \varepsilon x^2$$

where x is in mm and $\varepsilon < (2 \times 10^{-6})$ mm^{-2}. 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_v is given by:

$$Q_v = 0.88 - (9.3 \times 10^{-4}) x + (2.4 \times 10^{-5}) x^2 - (0.8 \times 10^{-5}) z^2$$

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 milliamps, 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 $\simeq 2.5$ sec^{-1} 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 3×10^{-4} 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 hawe 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 intersting to note that these curves are not changed by turning the eight-pole magnet 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 unneces
sary 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 func-
tion of beam current. With clearing electrodes
on we get $\dfrac{dQ_v}{dI_{beam}} = - 8 \times 10^{-6}\,mA^{-1}$ for beam currents
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 che-
ked this. Our measured number is three times
too large compared to the frequency shift of
incoherent betatron oscillations which one cal-
culates 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 $\dfrac{dQ_v}{dI_{beam}} =$
$= + 50 \times 10^{-6}\,mA^{-1}$. 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 $\dfrac{dQ_v}{dI_{beam}}$ 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 measu-
red 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
$\delta Q_v \simeq 0.4 \times 10^{-4}$. Then LNS theory predicts a
threshold of $\simeq 4$ mA.

STAINLESS STEEL
WALLS

$1\frac{13}{16}$"

ELECTRODE FOR
CLEARING IONS
(STAINLESS STEEL)

$5\frac{5}{8}$"
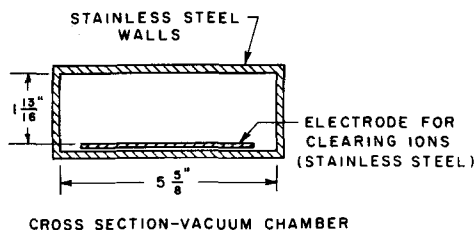
CROSS SECTION-VACUUM CHAMBER

Fig. 1 - Cross section of vacuum chamber inside the guide
field.

HORIZONTAL SCALE - 50 m sec / cm
BEAM CURRENT - 25 mA
CLEARING FIELD ON (NO IONS)
BEAM IN ONE RING ONLY

Fig. 2 - Signal on clearing field electrode when beam lea-
ves the vacuum chamber.

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 experi-
ments the effect of a strong beam of 10 mA to 200
mA on a weak beam of less than 1 mA is consi-
dered. 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 2.5×10^8 (1 mA) down to 400 without
noticing signicant changes in its behavior.

2. *Strong Beam-Strong Beam.* In these experi-
ments 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
~ 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
vs current in the strong beam for various oper-
ating 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 dif-
ferent sets of measurements. The dotted curve
through the points should not be taken too se-
riously. 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) $\approx Q_v$ (strong).

We have loocked for coherent motion of the
weak beam with a phototube viewing the synchro-
tron 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,
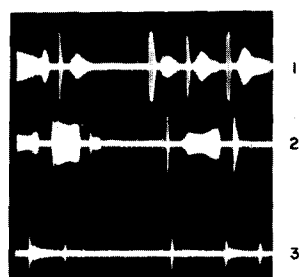
in units of $\delta Q = \dfrac{2\, r_e\, R_M N}{\pi Q b\,(a + b)\,\gamma}$, is 0.2, where $r_e =$ classical electron radius, $R_M =$ mean radius of the machine, $Q =$ betatron frequency divided by the r. f. frequency, a = beam width (standard deviation on a gaussian distribution), b = the beam height (standard deviation on a gaussian distribution), $\gamma =$ 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 $\delta Q \simeq 0.1$. We have concluded that Courant's explanation is correct and $\delta Q \simeq 0.1$ 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 elestrode at the betatron frequency. Early experiments on thresholds were done with beams whose vertical di-

BEAM IN RING I ONLY

VERTICAL BETATRON OSCILLATION FREQ. = 0.92

Fig. 4 - Height of single beam as a function of current.

CHANGE IN HEIGHT OF A WEAK BEAM AS IT PASSED THROUGH A STRONG BEAM

Fig. 5. - Height of a weak beam induced by passing through a strong beam.

SWEEP SPEED 10 msec/cm
CLEARING VOLTAGE - OFF
TRACE:
1 = 169 mA; 2 = 130 mA; 3 = 68 mA.

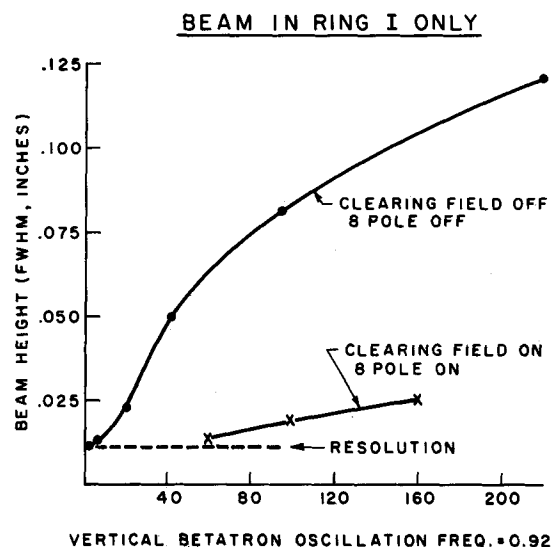Fi. 3 - Signals on clearing field electrode with ions in the beam.
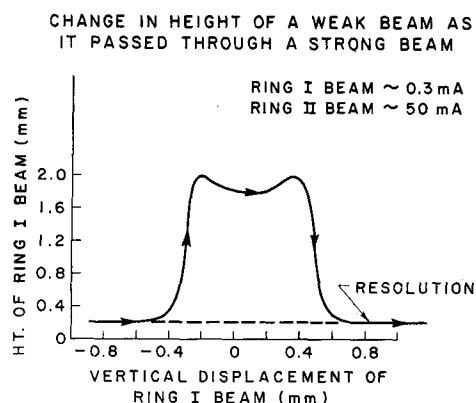
HEIGHT OF RING I BEAM (~ImA) vs RING II BEAM CURRENT FOR SEVERAL VALUES OF Q_{VI}
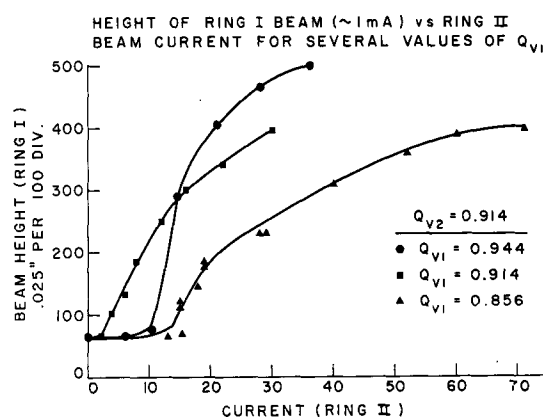

Fig. 6 - Height of a weak beam vs current in the strong beam.

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 $Q_{v1} - Q_{v2} = 0.05$) 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

$$\left(\frac{L}{I_1 I_2} \simeq 2 \times 10^{-25} cm^{-2} mA^{-2} sec^{-1} \right).$$

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. slowy decreases to 0.75×10^{-25} cm^{-2} mA^{-2} 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 sing 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.

RING II BEAM CURRENT AT WHICH RING I
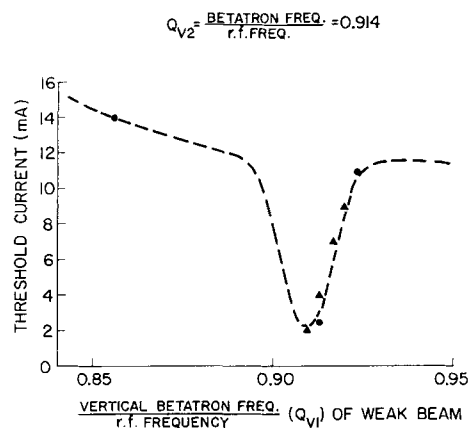BEAM BECOMES UNSTABLE VS BETATRON
FREQUENCY OF RING I BEAM

$$Q_{v2} = \frac{BETATRON\ FREQ.}{r.f.FREQ.} = 0.914$$

$\frac{VERTICAL\ BETATRON\ FREQ.}{r.f.\ FREQUENCY}$ (Q_{vI}) OF WEAK BEAM

Fig. 7 - Current in the strong beam to blow up a weak beam vs Q_v of the weak beam.

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 one has stability if $\frac{d|z|}{d\omega} < 0.$). Our cavities are operating with $\frac{d|z|}{d\omega} > 0$. 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.

REFERENCES

(1) G. K. O'Neill and J. A. Ball: An experiment on the structure of the electron, pt. 1, USAEC-NYO-8015 (1957); P. D. Federbush, pt. 2. USAEC-NYO-8136 (1957).

G. K. O'Neill: Design of a quantum electrodynamics limit experiment, Bull. Am. Phys. Soc. 3, 170 (1958).
W. C. Barber, G. K. O'Neill, W. K. H. Panofsky and B. Richter: A proposed experiment on the limits of quantum electrodynamics, pt. I, HEPL, Stanford (1958); W. C. Barber, B. Gittelman, G. K. O'Neill, W. K. H. Panofsky and B. Richter, pt. II, HELP Report 170 (1959).
G. K. O'Neill: Storage rings for electrons and protons, Int. Conf. on High Energy Accelerators, CERN, 1959, p. 125.
G. K. O'Neill: Design and initial testing of the Princeton-Stanford 500 MeV colliding beam experiment, Int. Conf. on High Energy Accelerators, Brookhaven, 1961;
B. Gittelman: Recent developments on the Stanford 500 MeV electron storage rings; Particle Accelerator Conf. Washington, 1965; Also available as HELP, report 336;
Cf. Progress Reports, HELP, Stanford, 1958-1965.

(2) L. J. Laslett, V. K. Neill, A. M. Sessler: Transverse Resistive Instabilities of Intense Coasting Beams in Particle Accelerators, UCRL-11090 (1963).

(3) L. J. Laslett: 1963 Summer Study on Storage Rings, Accelerators and Experimentation at Super High Energies (Brookhaven National Laboratories) p. 324.

(4) E. Courant: Particle Accelerator Conf., Washington, 1965; IEEE Trans. on Nuclear Science NS-12 n. 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).

(6) W. E. Henry: J. Appl. Phys., 31 (1960); Barishev and Heifetz: Soviet Phys. JETP 33 (1963); K. Robinson: CEA Report.

EXPERIMENTAL RESULTS ON BEAM-BEAM INTERACTION

V. L. Auslander, G. N. Kulipanov, G. I. Mishnev, A. A. Naumov, S. G. Popov, A. N. Skrynsky and G. M. Tumaikin

Institute of Nuclear Physics, Siberian Division of the USSR Academy of Sciences, Novosibirsk, (USSR)

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 $\partial v/\partial R = 1,5.10^{-2}$ I/cm and a cubic $\partial^2 v/\partial R^2 = 4.10^{-1}$ 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 ambigously 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 $v_z = 3/4$ to $v_z = 4/5$ (Fig. 1). It turned out that when beam passes through the nonlinear resonances $v_z = 3/4; 4/5; v_r = 2/3; 3/5$ 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 $v_r = 0,792$ 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 $v_z = 4/5$ by Ω/ω_o were ω_o is the revolution frequency and Ω is the frequency of synchrotron oscilla-