

LNF - 69/12
28 Febbraio 1969

F. Amman: ELECTRON POSITRON STORAGE RINGS: STATUS
AND PRESENT LIMITATIONS. -

Laboratori Nazionali di Frascati del CNEN
Servizio Documentazione

LNF-69/12

Nota interna : n. 434
28 Febbraio 1969.

F. Amman: ELECTRON POSITRON STORAGE RINGS : STATUS AND
PRESENT LIMITATIONS.

(Invited paper at the 1969 National Particle Accelerator Conference,
Washington, 5-7 March 1969)

ELECTRON POSITRON STORAGE RINGS: STATUS AND PRESENT LIMITATIONS.

Fernando Amman

Laboratori Nazionali di Frascati del CNEN - Italy.

Summary

A review of the current status of electron and positron storage rings is presented. The experimental results on beam instabilities, their consequences on the design of a high current storage ring and the technological problems involved are discussed.

Introduction

The e^+e^- collisions at very high energy are of extreme interest for the elementary particle physicist, as the information that can be gathered with this instrument is in most cases unique, and, in other cases, of much easier interpretation and more precise than that obtained with other types of accelerators, as it has been demonstrated by the first results achieved with VEPP-II (Novosibirsk, URSS) and ACO (Orsay, France).

In this respect it is instructive to read the various proposals for e^+e^- storage rings that have been built, but are not operating, or that have not yet been built: the justification for their construction can be repeated more or less exactly as it was laid down five to eight years ago.

The first electron beam was successfully stored in ADA, the Frascati 250 MeV e^+e^- ring in the spring of 1961¹; in the years 1962-64 the Princeton-Stanford 550 MeV e^-e^- ring and VEP-I, a 130 MeV, e^-e^- ring, in Novosibirsk, came into operation; the second Novosibirsk ring, VEPP-II, 700 MeV, e^+e^- , began to produce high-energy physics data in 1966, and shortly afterwards was followed by ACO, a 500 MeV e^+e^- ring built at Orsay. ADONE, the 1.5 GeV e^+e^- ring in Frascati, is not yet running for high energy physics: the first beam was stored in December 1967. The modification of the CEA electron synchrotron as a 3 GeV e^+e^- ring is well along and it is supposed to be ready for tests with the two beams during 1969; VEPP-III, a 3.5 GeV e^+e^- ring, will be in operation in Novosibirsk probably next year.

The new generation is coming: at DESY, Hamburg, it has been recently approved the construction of a 3 GeV, ultra-high luminosity, e^+e^- ring.

ACO and VEPP-II, after the first experiments on the ρ , ω and φ resonances, are undergoing a few modifications to improve their characteristics (luminosity and interaction region size); ADONE, after the first year of trouble-

-shooting (talking of a storage ring it would be better to say instability-shooting), should start high energy physics experiments during 1969.

It may seem strange that eight years after the initial operation of a storage ring, only one e^-e^- (the Princeton-Stanford 550 MeV) and two e^+e^- rings, VEPP-II and ACO, have produced high energy physics results, and these are limited to experiments with very high cross section. I would like to remark that the first beam instabilities observed on the Princeton-Stanford e^-e^- ring, and interpreted as being due to the resistance of the walls², opened a new era in the accelerator field: it has been realized for the first time that the interaction of the beam with its environment makes a circular accelerator an essentially unstable system, that can become stable, in virtue of the Landau damping, when the beam density is not too high and the non linearities in the focusing forces give a frequency distribution of the particles large enough to compete with the instabilities.

While a conventional accelerator operates usually at very low particle density, in an electron storage ring the radiation damping brings the density to very high values, also when the current is in the range of the mA; a whole new set of theoretical and technical problems had to be solved.

The progress in the knowledge of the beam behaviour in a ring, achieved in the last few years, is quite impressive; the more so when one takes into account how difficult and time consuming are the experiments in a ultra-high vacuum system.

In the following, after a short review of general principles underlying the design of a storage ring, I shall summarize the present knowledge, in the light of the experimental results, on four main issues: single beam behaviour; two beam behaviour; positron injection; vacuum system. It should be understood that the interpretation of the experimental results is far from being complete, so that in many cases I shall refer to work in progress; when no other explicit indication is given, reference is made to results obtained with ADONE.

Considerations on the general requirements

The quality of a storage ring depends on few conditions that must be satisfied:

- 1) the luminosity, defined as the interaction rate for an event having unitary cross section, has to be such to give reasonable counting rates for the events of interest (whose cross section in the GeV range is of the order of $10^{-32} + 10^{-34} \text{ cm}^2$);
- 2) the signal to noise ratio in the experimental apparatus must be high enough: the background must therefore be low (which means low residual gas pressure and long beam lifetime) and the interaction region small;
- 3) the dead times due to the storage process must be reduced to a minimum: the positron injection rate has to be accordingly high.

The luminosity L due to the interaction of two beams of total current I_W and I_S ($I_W \ll I_S$), having an equivalent transverse cross section A is given by the following formula:

$$L = \frac{1}{k f_0 e^2} \frac{I_W I_S}{A} \quad (1)$$

Where k is the number of bunches per beam, f_0 the rotation frequency and e the electron charge.

The beam-beam interaction causes a betatron frequency shift, $\delta\nu$, which depends on A , among other parameters; theoretical investigation and the experimental results obtained at Stanford, Novosibirsk and Orsay show that the highest allowable value of the betatron frequency shift per crossing, $(\delta\nu)_M$, is approximately independent of other machine parameters (except, probably, the number of beam crossings in the ring, when it becomes much bigger than two) and its value can be taken between 0.02 and 0.04.

Combining eq. (1) and the equation which expresses the $\delta\nu$, we can write a new equation for the luminosity at the space charge limit:

$$L \approx \frac{\gamma}{2 e r_e} \frac{I_W}{\beta} (\delta\nu)_M = \quad (2)$$

$$= 1.1 \times 10^{31} (\text{A} \cdot \text{cm} \cdot \text{sec})^{-1} \gamma \frac{I_W}{\beta} (\delta\nu)_M$$

provided that the following condition holds:

$$4\pi \epsilon_x \epsilon_z \approx \frac{2 r_e}{e} \frac{\beta}{f_0 k \gamma} \frac{I_S}{(\delta\nu)_M} \quad (3)$$

The beams are supposed to have gaussian distribution, with r. m. s. transverse dimensions ϵ_x and ϵ_z equal for the two beams; β is the usual focusing parameter, that can be considered as the local betatron reduced wavelength, r_e the classical electron radius and γ the beam energy in rest mass units. When the two beams are crossing at an angle, the transverse equivalent dimensions ϵ_x and ϵ_z are defined on the projection of the beams on a plane orthogonal to the bisector of

the beam orbits. Of the two β 's, for radial and vertical motion, one has to take that for which the ratio $(\beta/\epsilon)_{x,z}$ is larger.

From eqs. (2) and (3) it is easily seen that:

- 1) the maximum luminosity, for a given machine, is achieved with equal beam currents $I_W = I_S$;
- 2) the luminosity can be increased increasing the beam current; but, at the same time, the beam equivalent cross section must be made proportionally larger;
- 3) the luminosity is proportional to $1/\beta$: the low-beta insertions³ allow therefore a higher luminosity;
- 4) the number of bunches in the beam and the rotation frequency do not affect the luminosity, as long as eq. (3) is satisfied and the number of crossings in the ring is not much bigger than two.

The values of luminosity so far achieved in e^+e^- rings (Novosibirsk and Orsay) range from 2×10^{27} to $2 \times 10^{28} \text{ cm}^{-2} \text{ sec}^{-1}$; somewhat higher values have been obtained in the e^-e^- Stanford rings ($\sim 5 \times 10^{28} \text{ cm}^{-2} \text{ sec}^{-1}$).

For a more interesting exploitation of the storage ring capabilities a higher luminosity is required; in the GeV region values between 10^{29} and $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, which correspond to $I/\beta \approx 2 \times 10^{-4} + 2 \times 10^{-1} \text{ A/cm}$, are aimed at. The high side of this range can be practically achieved only with very small β (typical example: $I=2\text{A}, \beta = 10 \text{ cm}$), while the lower side is accessible with ADONE ($\beta = 300 \text{ cm}, I = 0.1 \text{ A}$).

These considerations outline the main characteristics of the e^+e^- storage ring design: the beam intensity and the beam size required are such that the particle density is a few orders of magnitude higher than in conventional accelerators, with the consequence that the system, if not properly designed, is well into the region of instability; the beam lifetime has to be of the order of hours, to reduce background and dead time, which implies a residual gas pressure in the ntorr (10^{-9} mm Hg) range; positron currents of $0.1 + 1 \text{ A}$ must be stored in a time short as compared to the lifetime.

Single beam behaviour.

a) Phase instabilities

Coherent phase oscillations have been observed on VEPP-II⁴ and, later, on ACO and ADO NE. The single bunch beam-RF cavity interaction^{4, 5, 6, 7} can be easily interpreted as follows: the bunch rotating with frequency ω_0 interacts with an RF cavity whose real part of the impedance $R(\omega)$ has a maximum for $\omega_c < \omega_0$ (see fig. 1): if a coherent synchrotron oscillation is excited, the bunch frequency will be lower for higher

beam energy, and higher for lower beam energy. The energy given by the beam to the cavity in the situation considered ($\omega_c \ll \omega_0$), has an increment of the same sign as the beam energy, and this gives damping. The opposite happens when $\omega_c > \omega_0$, and in this situation one has antidamping for the coherent synchrotron oscillations.

The same argument applies also to higher harmonics of the rotation frequency, up to frequencies comparable with the inverse of the bunch length: the synchrotron motion will be stable only if the following condition is satisfied⁴:

$$\sum_n n (R_n^- - R_n^+) > 0 \quad (4)$$

where R_n^\pm are the real impedances of the RF cavity and of other possible structures present in the vacuum chamber at the frequencies $\omega_n = n\omega_0 \pm \Omega_s$, Ω_s being the synchrotron frequency, and ω_0 the rotation frequency of the synchrotron particle.

The situation with many bunches is more complicated, as the number of oscillation modes is increased. Sustained phase oscillations of electron or positron beam have been observed at ACO (two bunches) and ADONE (three bunches), without beam loss, usually; tuning of the RF cavity acts on the barycentric mode of oscillation, but not on the relative motion of the bunches. The current threshold for these oscillation is very low; in ADONE a fraction of a mA at 300 MeV.

The interpretation of the phase instability with many bunches has been given by a number of authors⁸: all the modes with frequency close to $(nk+p)\omega_0$, where k is the number of bunches and p an integer from 0 to $k-1$, contribute to the instability.

The more general condition for stability in the simple case of k equal bunches is given by a set of k equations (one for each value of p):

$$\sum_n \left\{ (nk-p)R_{nk-p}^- - (nk+p)R_{nk+p}^+ \right\} > 0 \quad (5)$$

A spurious mode (present in the RF cavity or in other structures in the vacuum chamber) at a frequency $nk+p$ will give damping to one oscillation mode and antidamping to another one: the modes with $p=0$ (interacting with the barycentric oscillation mode) and $p=k/2$ (when k is even) are special in the sense that they contribute to a single oscillation mode.

In our case ($k=3$) the addition of a passive cavity with $p=1$ has been sufficient to stabilize currents up to 30 mA (our cavity had a strong spurious mode with $p=2$), but the operation is critical. A more convenient solution⁸ has been to introduce a synchrotron frequency shift between the different bunches, obtained with a small RF cavity operating on a frequency harmonic of the

revolution frequency, but not of the RF frequency ($p \neq 0$).

This type of stabilization must be used with some precaution: the stable phases of the different bunches must not have a large spread (which results either in a spread of the collision region or in a decrease of the luminosity, when the beams cross at an angle); it is therefore convenient to use high harmonics. Also there is probably a practical intensity limit.

In our case 0.6 KV at 71 Mc ($n=8, p=1$) are sufficient to stabilize 150 mA at 300 MeV, in three bunches.

Recently it has been observed, at ACO, that operation without clearing electrodes, or with clearing electrodes grounded inside the vacuum chamber, has removed the phase instability: a possible interpretation is that the electrode structure (terminated in the middle) had some mode, interacting with the synchrotron motion, that was responsible for the instability.

The phase instability renders more complicated the design of storage rings with RF systems at very high harmonic; active feedback systems are probably required to take care of at least some of the possible oscillation modes.

b) Bunch length

It has been observed, on ACO and ADONE, that the bunch length is longer than expected, and has a current dependence that cannot be explained by the multiple scattering in the bunch; the energy and current dependence is quite similar in the two rings.

When more than one bunch is present in the machine, with different charge per bunch, their length depends on the charge per bunch; at Orsay it has been observed that also in the case of two colliding beams the bunch length depends only on the charge per bunch. These observations exclude as a possible explanation a beam-cavity interaction.

It has been suggested, by Pellegrini and Sessler, that the clearing electrodes might be responsible for the bunch lengthening; however the measurements done at ACO and ADONE after the clearing electrodes have been taken out show that the bunch length is not changed.

The bunch length l (FWHM) in ACO varies with energy E (in GeV) and current per bunch i (mA) as follows⁹:

$$l^2 = l_{\text{rad}}^2 \left(1 + 2 \times 10^{-3} \frac{i \text{ mA}}{E^4 \text{ GeV}^4} \right) \quad (6)$$

where l_{rad} is the bunch length due to radiation, and the lengths are expressed in nsec.

In ADONE it has been found that, up to a certain critical value of current, the bunch length is determined by radiation; for higher currents the bunch length is given by:

$$\frac{1}{l_{\text{rad}}} = 0.31 \quad i^{1/3} \quad E^{-5/3} \quad \text{for } l > l_{\text{rad}} \quad (7)$$

The experimental results cover the following ranges: $0.2 < i < 70$ mA; $0.3 < E < 0.9$ GeV; RF voltage between 20 and 40 kV.

The two formulas agree quite well, apart from a constant, in the region $l \gg l_{\text{rad}}$:

$$\text{ACO} : \frac{1}{l_{\text{rad}}} \approx 0.13 \quad i^{1/3} \quad E^{-4/3} \quad (8)$$

$$\text{ADONE} : \frac{1}{l_{\text{rad}}} \approx 0.46 \quad i^{1/3} \quad E^{-7/6} \left(\frac{30}{V_{\text{rf}}}\right)^{1/6}$$

where V_{rf} is the RF voltage in kV. The dependence on RF voltage in ADONE might be still weaker than indicated.

The multiple scattering in the bunch, in the high current limit, should give $i^{1/7}$ dependence which is certainly much weaker than that observed.

The bunch length can be affected by a change either in the momentum spread in the beam or in the restoring force of the synchrotron oscillations. A measurement of the ratio of the bunch length to bunch radial width (which depends only on focusing parameters and longitudinal restoring force) can tell us whether the bunch lengthening depends on an increase of the momentum spread or on a decrease of the restoring forces. The measurements so far done on ADONE of the bunch radial width are not accurate enough to allow a satisfactory analysis.

c) Transverse instabilities.

The forces due to the interaction of the beam with its environment induce not only a real frequency shift on the collective frequency, but also an imaginary shift, which corresponds, depending on its sign, to a damping or antidamping term. Moreover the beam cannot be considered a rigid body; it will have a certain number of (relevant) degrees of freedom, and a corresponding number of oscillation modes. The external forces, in general, will give damping to part of the modes and antidamping to the other modes and the beam will be unstable, unless there is a sufficiently strong damping mechanism.

The Landau damping turns out to be the dominant stabilizing effect, not only in proton machines, but also in electron rings, in spite of the radiation damping. As a first approximation one can say that the width of the betatron frequency

distribution is equivalent to a damping term for the collective motion; as an example in ADONE, at the injection energy, the width of the radial betatron frequency distribution, due to the octupolar terms of the focusing field alone, is of the order of 100 sec^{-1} , to be compared with the radiation damping equal to 1 sec^{-1} . Other non-linear fields, as those due to the positive ions trapped in an electron beam, give a still wider frequency distribution, and, for this reason, a different behaviour of the positron and electron beams has to be expected.

At higher energies the radiation damping (increasing like γ^3) tends to overcome the Landau damping (for constant nonlinearities the betatron frequency distribution is proportional to γ^2 in the region where the energy distribution in the beam is determined by quantum fluctuations): but this does not happen in the ADONE energy range.

In ACO and ADONE transverse betatron instabilities have been observed, with a threshold much lower than expected. In both rings many different experiments have been performed to understand the instability and to find ways to cure it; recently, during December 1968, all the clearing electrodes (used to sweep out the ions and to displace the beam orbits in order to obtain the crossing at an angle) have been taken out of ACO and ADONE.

With the clearing electrodes in the rings, the common features of the instability are:

- 1) it occurs with positron beam, or with electron beam without positive ions (clearing fields on); the electron beam with ions trapped is stable up to very high currents (more than 150 mA in one bunch, at 300 MeV, have been stored in ADONE without any transverse instability);
- 2) the threshold current is very low: in ADONE, at 300 MeV, the injection energy, with the natural beam dimensions, the threshold positron current is about $150 \mu\text{A}$ per bunch;
- 3) the threshold of the instability is a function of the longitudinal charge density in the bunch; the influence of the total current is small, if any;
- 4) the dependence of the threshold longitudinal density on machine parameters is compatible with a force independent of energy, and with the Landau damping as a stabilizing mechanism (the threshold density is proportional to energy times the betatron frequency spread; the threshold increases making the beam larger and is proportional to the octupolar terms present in the machine);
- 5) the threshold does not depend on the betatron wave number (over a range from 3.2 to 3.8 for ADONE, with single bunch operation).

The main difference observed between ACO and ADONE is that in the first one the center

of mass of the bunch does not move appreciably during the instability, while in the second the center of mass displacement is of the same order of magnitude as the maximum amplitude. This is an important difference, that allowed the use of a feedback on the center of mass of the bunch to stabilize the positron beam in ADONE.

After the clearing electrodes have been taken out, the picture has not changed in ACO, except for an increase in the thresholds (about a factor of 2 for the vertical instability). In ADONE, on the contrary, we had a major change, namely the threshold of the instability depends on the total charge per bunch, not on the longitudinal density; the threshold current is now, at the injection energy, about 15 times higher than before.

The theory of the coherent beam instability^{2, 10} developed in the years 1963-1966 for coasting and bunched beams, but neglecting the synchrotron oscillations, considered the interaction of a particle in the beam with the fields due to all the preceding particles, in the assumption that the relative azimuthal position remained the same.

In the case of a bunched beam, the regenerative action can exist only if the different bunches are coupled together, that is if the decay of the fields is of the order of the distance between bunches, or longer. The threshold for instability will therefore depend on the total charge in the ring, and the stability or instability of a certain mode of oscillation will be influenced by the betatron wave number.

The experimental results obtained at ACO and ADONE are therefore in complete disagreement with the theory of the "slow effects" ("slow" in the sense that the decay of the fields must be long enough to couple the different bunches, or a bunch with itself in the single bunch operation).

A plausible explanation of the instability has been proposed in Frascati, by Pellegrini, Sands and Touschek; the theory is being developed independently by C. Pellegrini, H. G. Hereward and P. Morton. It takes into account the synchrotron oscillations, and can be understood with the following simple model: let us imagine a bunch made of two particles, A and B: A is ahead, and is perturbed. B sees the fields due to A, and starts a forced oscillation, with growing amplitude, as its frequency is very close to that of A. If the relative position of A and B remains the same, and the coupling force does not exceed a certain critical value, nothing dramatic will happen, as A will eventually damp down, and so would B. But the phase motion interchanges their positions: B would then force A in its oscillation increasing its amplitude. This "head-tail" process can be

clearly regenerative and is sustained by fields whose decay length is of the order of the bunch length or longer.

A completely new class of forces, very rapidly decaying, can therefore cause transverse instability in bunched beams; in the design of the beam environment one must reduce as much as possible the intensity of these forces, which means that all the elements in the vacuum chamber interacting with the beam should be suitably terminated for frequencies comparable with those corresponding to the bunch length (typically in the range of the GHz).

The dependence of the threshold on bunch length in the "head-tail" theory is related to the type of interaction force; the results obtained after the clearing electrodes have been taken out of ADONE are therefore still compatible with the theory.

What has not yet been understood is where the forces come from; calculations are under way to see whether the vacuum chamber discontinuities could explain the rise time observed for the instability.

It should be underlined that the "head-tail" type of instability does not seem to be present in weak focusing ring, at least with such low thresholds: this could be due either to much stronger Landau damping, as the beam dimensions are typically ten times bigger, or to the focusing structure difference.

A peculiar behaviour of the "head-tail" instability theory¹¹ has been tested on ADONE: the rise time turns out to be approximately proportional to $(1 - C/\alpha)$, where C is the chromatism of the ring, defined as the relative change of the betatron wave number divided by the relative change of the particle energy, and α is the momentum compaction. In a strong focusing ring without sextupoles C/α is typically of the order of $-10 \div -50$, while in a weak focusing the absolute value of C/α is usually smaller than 1. According to the theory a strong focusing ring should therefore have much lower thresholds for the "head-tail" instability than a weak focusing ring, assuming the same fields due to the beam-environment interaction.

Tests with different values of the chromatism have been done on ADONE using a very crude sextupole; the results are in qualitative agreement with the theory. With a beam current higher than the threshold by a factor of about 2.5, the stabilizing feedback gain can be decreased by a factor of about 5 when the chromatism is compensated within about $10 \div 20\%$ of the original value, and must be increased accordingly when the chromatism is increased. The threshold current decrea

ses when the chromatism is increased, but it does not change appreciably when the chromatism is compensated.

This last result seems strange; it has been interpreted by C. Pellegrini, and this interpretation can explain also another result obtained at ACO and ADONE which was not understood before. When an octupolar field is added, to compensate the octupolar terms present in the machine, the threshold current varies with octupole current as shown in fig. 2; the minimum of the curve corresponds to the cancellation of the relevant term contributing to the betatron frequency spread (the case of the fig. 2 refers to the radial instability in ADONE: the minimum corresponds to the cancellation of the term depending on the radial dimensions). The strange effect, which has been observed, though less pronounced, also at ACO, is that the slope of the threshold curve is different on the two sides of the minimum.

It can be shown¹² that, when the betatron frequency distribution is not symmetric around some central value ν_0 (as it is the case with bunched beams, where the frequency distribution is an exponential in the amplitudes squared), and the real part of the coupling force is larger than the imaginary part, two different regimes of the Landau damping are possible, depending on the relative sign of the real part of the coupling force and of the parameter defining the asymmetry of the frequency distribution. For one sign the threshold is determined by the imaginary part of the force, for the other by the real part; in the second case the thresholds are lower than in the first case.

The compensation of the chromatism affects mainly the imaginary part of the force, and the decrease of the feedback gain necessary to stabilize the beam proves that this actually happens; the fact that the threshold does not increase seems to prove that it is determined by the real part of the coupling force.

The result with the octupole indicates the same thing: reversing the sign of the non linear terms the thresholds become higher. We should therefore obtain a substantial increase of the threshold current changing the sign of the octupole terms of the focusing field, and the same should happen at ACO: the gain in ADONE should be of about a factor of 10, as it can be deduced from the slopes of the two sides of the curve in fig. 2.

An active feedback to stabilize the transverse motion of a beam has been used with success in ADONE: the most intense positron current so far stored in the ring, 60 mA in one bunch, has been kept stable with two feedbacks, one for

the radial and one for the vertical motion, operating on the frequency $(\nu - m)f_0$, where $\nu = 3.2$, $m = 3$ and f_0 , the revolution frequency, is 2.86 Mc/sec.

The feedback system becomes more complicated with more than one bunch, as the number of oscillation modes increases: we shall use a fast feedback, with pulsed operation on the different bunches. But, apart from the technical problems of a feedback system with very short pulses (order of 10 nsec) and high repetition rate (about 20 Mc/sec), it is important to remark that the result obtained with the resonant feedback assures us that, in ADONE, the active feedback can stabilize a beam up to currents at least 30 times the threshold value. A measurement of the feedback gain required for stable operation versus intensity gave a result in reasonable agreement with the simple-minded theory, i. e. $G \approx G_0 (1 - i_{th}/i)$, where G is the gain at the current i , G_0 a constant, i_{th} the threshold current.

Two beam behaviour

The experimental results obtained so far at Stanford, Novosibirsk and Orsay for the maximum allowable value for the betatron frequency shift per crossing range, as it has been already said, between 0.02 and 0.04; some results at ACO at low intensity tend to indicate somewhat higher values.

It is not as yet clear how much the maximum $\delta\nu$ per crossing depends on the total number of crossings; in other words, whether the limiting parameter is the total $\delta\nu$ over the whole ring or the $\delta\nu$ per crossing. Results at ACO¹³ tend to indicate that with four crossings the total $\delta\nu$ allowable is higher than with two crossings, but only by a factor of about 1.5.

It is most probable that for a very high number of crossings the total $\delta\nu$ would limit the luminosity; taking into account the fact that the beam-beam interaction is a long range interaction, that gives a betatron frequency shift also when the bunches are separated, in the very high energy and intensity rings with a large number of bunches, it is more convenient to separate completely the path of the two beams, except of course for the interaction regions, using two interlaced rings¹⁴. ADONE, with three bunches per beam, is an intermediate case: the contribution to the ν -shift of the four crossings where the beams are separated by distances of the order of 5 to 10 mm, can be evaluated to be about 20 ÷ 50% (depending on bunch length and crossing angle).

The use of transverse electric field to separate the orbits of the two beams circulating

in the same ring is more difficult than expected for three reasons: the very strict requirements on the termination of the electrodes present in the vacuum chamber, the single beam behaviour in presence of an electric field, which is not as yet fully understood, and the vacuum problems when a high voltage is applied to the electrodes in presence of the beam⁹.

The luminosity linear dependence on beam current, when the transverse density is kept constant increasing the beam size with current, has been checked experimentally on the Princeton-Stanford ring, where the increase of the equivalent transverse size was obtained with a crossing angle; at ACO the beam size can be changed acting on the ring operating point (on the coupling resonance the beam is approximately round) and with a kicker that gives very frequent small coherent perturbations and, in average, an incoherent spread of the oscillation amplitudes. The luminosity increases with current, as predicted, when the beam size is adjusted with the operating point; the use of the kicker, however, does not give the expected results⁹: it has been observed that the allowable δy decreases, and, in some instance, that the beam lifetime becomes much shorter.

The increase of the Landau damping, observed at ACO and ADONE using a kicker with a single beam, is a check that the effect on the beam size is primarily incoherent; the result on the luminosity is qualitatively interpreted as due to the recurrent small coherent excitation that can cause a diffusion of the particles, due to non linear terms of the interaction field¹⁵. Similar tests on ADONE are now under way.

Positron injection

The absolute value of positron injection rate in ADONE has proved to be very good: without an accurate optimization of the positron beam in the linac and in the transport system from the linac to the ring, we have obtained a maximum storage rate of 200 μ A per pulse, injecting at 300 MeV on one bunch out of three, and a normal rate of about 100 μ A per pulse.

The injection rate in three bunches at 350 MeV (2.5 pulses per second) is expected to be, in normal operating conditions, about 50 mA/minute; we think that a careful optimization of the positron beam will allow to obtain normally this value of injection rate, extrapolated from the best values we have achieved so far.

These results show that the positron current that can be delivered by a linac with the appropriate focusing system¹⁶ is sufficiently high

so that it does not represent a technical problem in the operation of an electron-positron storage ring, at least up to stored currents of the order of fraction of an Ampere.

For higher current rings one must use higher injection repetition rate, and therefore higher injection energy; an extrapolation to the Ampere range, which means about $5 \div 10 \times 10^3$ injection pulses, requires an accurate evaluation of the stored beam losses for each new injection pulse.

In ADONE we have indications that a saturation might occur at the level of a few thousand pulses, but no careful analysis has been done on the subject, so that the indication we have can be taken only as a lower limit for the storage efficiency.

Vacuum system and pressure rise with the beam

The typical value of the residual gas pressure that must be maintained in the vacuum chamber, to reduce the background to acceptable levels and to obtain a lifetime in the range of 10 + 20 hours, is 1 ntorr.

A much lower gas pressure in the crossing region can be very useful in reducing the background. However for zero angle events (beam-beam single and double bremsstrahlung and annihilation in two γ 's) which are very convenient as a luminosity measurement, what matters when one evaluates the background at these small angles is the gas pressure over the whole length of the straight beam path on the two sides of the crossing region¹⁷.

While it is not difficult, with the present technology, to achieve a static residual pressure of a few tenths of a ntorr, it becomes a problem to keep that pressure when a beam radiating kilowatts, and even megawatts, is present.

The pressure rise with beam has been first observed on the Princeton-Stanford ring and on ADA, and it has been interpreted by Garwin¹⁸ as being due to a double process induced by the radiated electromagnetic radiation: photons extract electrons from the walls (when their energy is sufficiently high), which, hitting back the wall, desorb gas molecules. Experimental measurements of the probability of desorption by electrons have been performed in Frascati¹⁹ and at CEA²⁰. The results are that the desorption probabilities are a very weak function of the electron energy; as a first crude approximation one can consider that the probability of desorbing a gas molecule is proportional to the photon number, and independent of the photon energy, as long as it is higher than the work function of the vacuum

chamber surface.

In this approximation the quantity of gas desorbed per second, Q , if the work function is \mathcal{E}_0 , is given by:

$$Q = 1.45 \times 10^7 \gamma I D \left\{ 1 - \left(\frac{\mathcal{E}_0}{\mathcal{E}_c} \right)^{1/3} \right\} \quad (\text{ntorr lt/sec}) \quad (9)$$

where $\mathcal{E}_c = \frac{3}{2} \frac{\hbar c}{\mathcal{S}} \gamma^3$ is the cut off energy of the approximate synchrotron radiation spectrum, \mathcal{S} the magnetic radius of the ring, I the total circulating current (in A), γ the beam energy and D the probability of desorbing one gas molecule per photon with energy higher than \mathcal{E}_0 , averaged over the photon energy spectrum. Typical values of D , as measured in small systems, are in the low 10^{-7} range^{19, 20}.

The pressure rise with beam $\frac{\Delta P}{I}$ is obtained from eq. (9)

$$\frac{\Delta P}{I} = 1.45 \times 10^7 \gamma \frac{D}{S} \left\{ 1 - \left(\frac{\mathcal{E}_0}{\mathcal{E}_c} \right)^{1/3} \right\} \quad (\text{ntorr/A}) \quad (10)$$

where S is the total pumping speed in lt/sec.

The actual average values of D can be deduced from the experimental data of the pressure rise: in ACO, after the vacuum chamber bake-out and beam running, an average pressure rise of 0.13 ntorr/mA at 385 MeV has been observed²¹, which corresponds to $D \approx 10^{-5}$ (the pumping speed is about 10^3 lt/sec); the pressure rise is now lower by about a factor of two, giving $D \approx 5 \cdot 10^{-6}$ ²², the improvement being due, presumably, to the beam conditioning.

In ADONE before the vacuum chamber bake-out, it has been measured a pressure rise of 0.12 ntorr/mA at 500 MeV, which gives $D \approx 10^{-4}$ assuming a pumping speed of about 8.000 lt/sec. We expect a decrease in D of about one order of magnitude by the bake-out and the beam conditioning.

Very good results have been reported in 1967 by the CEA group, from which a value of $D \approx 5 \times 10^{-6}$ can be inferred.

It should be remarked that all these data on the value of D measured on a ring are at least one order of magnitude worse than what expected on the basis of measurements on small systems under controlled conditions.

Conclusion

The work done in the last years has provided new information on the high current e^+e^- storage rings: it turns out that, while no insuperable difficulties have come up, the operation

presents some problem that should be considered quite carefully in the design of new ultra-high intensity rings. I may list the following points:

- 1) longitudinal and transverse beam stabilization in the case of very high number of bunches; practical limitations of active feedback systems;
- 2) control of the nonlinearities in the ring (sextupole and octupole components);
- 3) suitable termination up to very high frequency of all the structures in the vacuum chamber;
- 4) automatic control of all the parameters that must be kept within tight tolerances;
- 5) ways to control the beam dimensions.

There are also aspects that have not yet been studied sufficiently to be fully understood, among which are the forces that cause the transverse instability, the bunch lengthening, the two beam behaviour when the beam cross section is enlarged and the high values of pressure rise with beam.

References

- 1 - C. Bernardini, U. Bizzarri, G. F. Corazza, G. Ghigo, R. Querzoli and B. Touschek, *Nuovo Cimento* **23**, 203 (1962).
- 2 - L. Jackson Laslett, V. K. Neil and A. Sessler, *Rev. Sci. Instr.* **36**, 436 (1965).
- 3 - K. Robinson and G. A. Voss, CEA-TM-149, 1965 (unpublished).
- 4 - V. L. Auslander, M. M. Karliner, A. A. Naumov, S. G. Popov, A. N. Skrinsky and I. A. Shekhtman, *Proc. V Int. Conf. on High Energy Accelerators*, Frascati (1965), pag. 339.
- 5 - I. G. Henry, *J. Appl. Phys.* **31**, 1338 (1960).
- 6 - K. Robinson, CEAL 1010, 1964 (unpublished).
- 7 - M. Bassetti, LNF-67/45, 1967 (unpublished).
- 8 - R. Littauer, C. Pellegrini, M. Sands and B. Touschek, *Adone Int. Mem.* 1968 (unpublished).
- 9 - R. Belbéoch et al, ACO Rapport Technique 10-68, 1968 (unpublished).
- 10 - The number of papers on the subject is very large: for references see: *Storage Ring Summer Study 1965*, SLAC-49, 1965; C. Pellegrini and A. Sessler, CERN 67-19, 1967 (unpublished).
- 11 - C. Pellegrini, Private communication.
- 12 - C. Pellegrini, *Adone Int. Mem.* 1969 (unpublished).
- 13 - R. Belbéoch et al, ACO Status Report, 1967 (unpublished).
- 14 - DESY Storage Ring Group, *Proc. VI High Energy Accel. Conf.* 1967, CEAL-2.000 (1967), pag. 104.
- 15 - E. D. Courant, BNL Int. Rep. AADD-69, 1965 (unpublished); B. V. Chirikov, Novosibirsk 1968.

- 16 - F. Amman, R. Andreani, J. Haimson and C. Nunan - Proc. 1966 Linear Accel. Conf. , Los Alamos (1966), pag. 435.
- 17 - S. Tazzari, LNF-67/23, 1967 (unpublished).
- 18 - E. L. Garwin, SLAC Mem. 1963 (unpublished).
- 19 - M. Bernardini and L. Malter, LNF-64/19, 1964 (unpublished).
- 20 - G. E. Fisher and R. A. Mack, CEAL-1013, 1964; CEAL-1017, 1965 (unpublished).
- 21 - Orsay Storage Ring Group, Proc. VI High Energy Accel. Conf. 1967, CEAL-2000 (1967), pag. 64.
- 22 - P. Marin, Private communication.

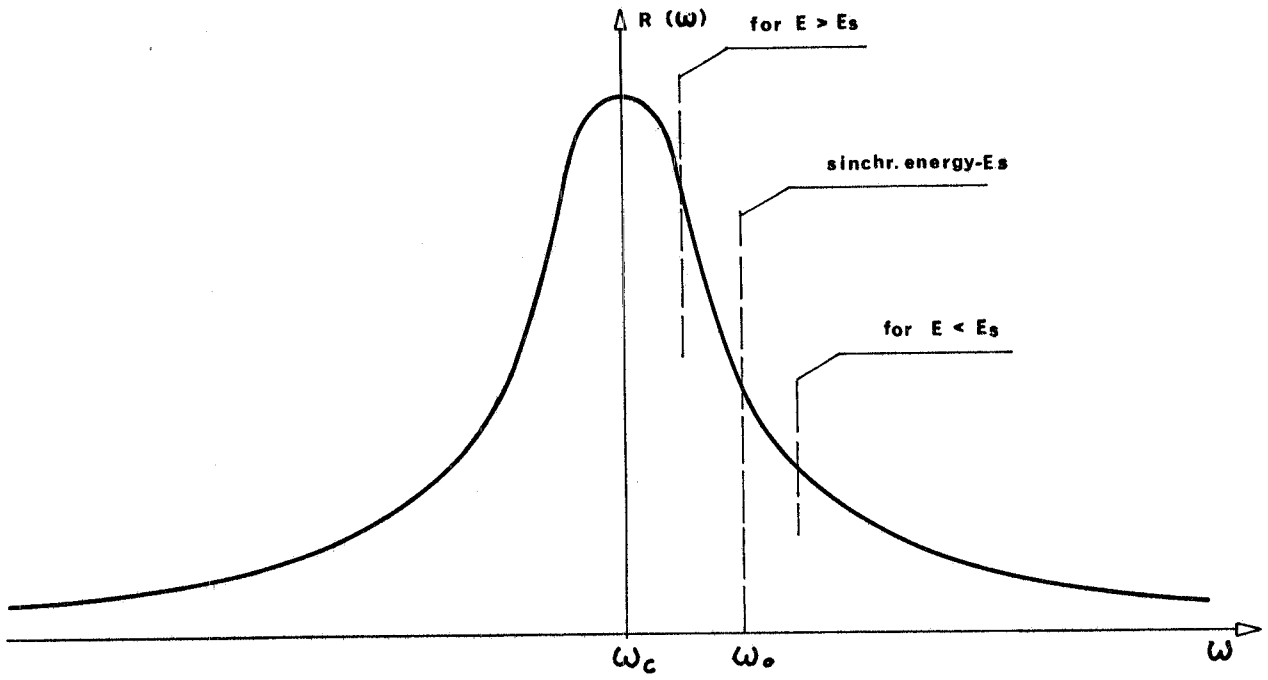


fig 1

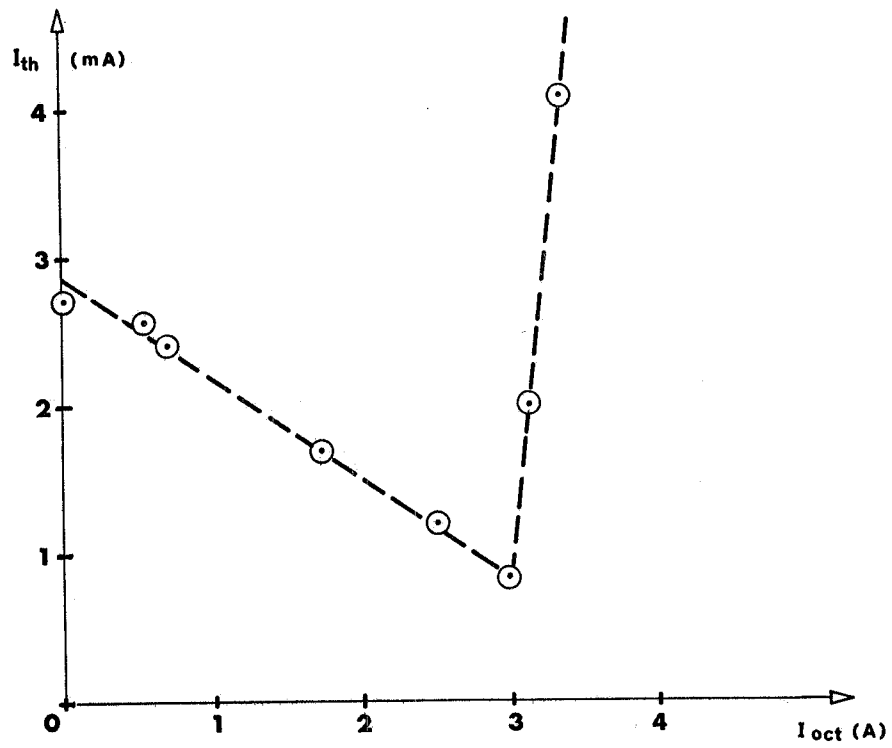


fig 2

LNF-69/12 (28/2/1969) - ERRATA CORRIGE

Page 5, 2nd column, 23rd line from the bottom should read

".... proportional to $(1 - C/\alpha)^{-1}$, where C is the chromatism"