ELECTRON AND POSITRON STORAGE RINGS: PRESENT SITUATION AND FUTURE PROSPECTS

F. Amman

Laboratori Nazionali di Frascati del CNEN, Frascati, Italy

Abstract

Ten years have passed since the first electrons have been stored in a colliding beam ring; e^+e^- rings have produced high energy physics results for about five years and a new generation of ultra-high luminosity rings is being built. The progress in the field and the experimental observations on the beam behaviour in storage rings, gathered in many laboratories all over the world, are outlined in this paper. The possible improvements in the performances are briefly discussed.

1 - Introduction

The development of the colliding beam accelerators can be traced to its beginning in the Proceedings of the High Energy Accelerator Conferences; preliminary proposals for proton-proton beams were discussed at the first Conference, in 1956, and developed at the second one, in 1959, when also the design of the 500 MeV e^-e^- rings, under construction at Stanford, was described. The interest in the study of the high energy electron positron annihilation, pointed out in 1960, gave a new impulse to storage rings, and at the III Conference, 1961, we find a session devoted to them (they are not any more "New ideas"), and, what is more important, we find also the first experimental results on electron (or positron) storage, for times of the order of one minute, in the small ring AdA 1).

In the last ten years the progress in the field has been impressive: the Stanford-Princeton 500 MeV e^-e^- rings and three e^+e^- rings (VEPP-2, ACO and ADONE with energies ranging from 500 to 1.500 MeV) have produced high energy physics results; two higher energy (3 ÷ 3.5 GeV) e^+e^- rings are in the pre-operation stage (CEA-Bypass and VEPP-3); three other e^+e^- rings are being built (SPEAR, DORIS and ACO-II) and this list falls short for sure of some new born of the VEPP family. The proton-proton rings have experienced a similar progress, leading to the CERN-ISR operation: they will be the subject of other papers in this Conference.

The problems encountered and solved in the electron storage ring operation are related to the very high beam density and to the long lifetimes required; the fundamental instability of a circular accelerator (due to the beam interaction with its environment) becomes fully evident at the currents and densities achieved in the present rings ($10^{10} \div 10^{11}$ particles/cm^3) and it requires, to be mastered, an accurate knowledge of the forces and beam dynamics, and the use of complicated methods to control the instabilities and to reduce the forces.

The work done so far to understand and cure the instabilities in the storage rings is becoming very valuable also for conventional accelerators, as greater and greater currents are required.

In the following the most relevant experimental observations on the beam behaviour in electron positron storage rings and, when available, their interpretation are discussed; the two beam effects are presented first, with an analysis of the parameters that affect the storage ring performances; the single beam effects follow, including a brief discussion of the vacuum problems.

2 - Two beam behaviour

The performance of an electron positron storage ring can be summarized by giving the energy (the energy per beam is here consistently used) and the luminosity, defined as the interaction rate for an event having unitary cross section; in the simple case of head-on collision of two beams of total currents I_W and I_S, uniformly distributed in k bunches per beam, with overlapping transverse gaussian distributions, whose r.m.s. dimensions σ_x and σ_z are equal for the two beams, the luminosity L per interaction region is given by:

$$L = \frac{1}{k f_o e^2} \frac{I_W I_S}{4\pi \sigma_x \sigma_z} \qquad (1)$$

where f_o is the revolution frequency and e the electronic charge.

The Coulomb interaction between the two beams at the crossing changes the focusing forces acting on them; since the early days of the storage rings it has been realized that the beam transverse density at the crossing should not exceed some limit value to preserve the beam stability 2),3),4),5). The parameter used to express this assumption is the linear betatron tune shift per crossing, δQ, or, more commonly, a quantity, here called ζ, proportional to the central beam density, which, in some cases, is a good approximation for δQ; they are given by:

$$\zeta_{x,z} = \frac{r_e N_s}{2\pi\sigma_x\sigma_z\gamma\left(\frac{1}{\sigma_x}+\frac{1}{\sigma_z}\right)}\left(\frac{\beta}{\sigma}\right)_{x,z} \qquad (2)$$

$$\zeta_{x,z} = \frac{\sin(2\pi\delta Q_{x,z})}{2\pi}\left\{1+\mathrm{tg}(\pi\,\delta Q_{x,z})\,\mathrm{ctg}\,\mu_{x,z}\right\} \simeq \qquad (3)$$

$$\simeq \delta Q_{x,z}\left\{1+\pi\delta Q_{x,z}\,\mathrm{ctg}\,\mu_{x,z}\right\}$$

where: N_s is the charge per bunch of the more intense beam; $\beta_{x,z}$ the reduced local betatron wavelength at the crossing; r_e the classical electron radius: γ the beam energy in rest mass units; $\sigma_{x,z}$ the r.m.s. transverse dimension; $\mu_{x,z}$ the betatron phase angle between successive crossings. Unless otherwise specified, in the following the quantities ζ and δQ will always be referred to one crossing; the total linear tune shift over the ring is $p\delta Q$, if there are p crossings. Eq. 3 shows that, as long as $|\pi\delta Q\ \mathrm{ctg}\mu| \ll 1$, $\zeta \simeq \delta Q$; what in the current literature is referred to as the approximate tune shift (often indicated with $\Delta\nu$) is the quantity ζ (or sometimes $p\zeta$).

ζ can be expressed as a function of the luminosity L and the total current of the weaker beam I_w (eqs. 1 and 2):

$$\zeta_{x,z} = \frac{2\,e\,r_e}{\gamma}\,\frac{L}{I_w}\left(\frac{1}{\sigma_x}+\frac{1}{\sigma_z}\right)^{-1}\left(\frac{\beta}{\sigma}\right)_{x,z} \qquad (4)$$

The ratio L/I_w will be referred to, in the following, as the specific luminosity; eq. 4 gives a convenient way to obtain the value of ζ from a measurement of specific luminosity, as the only other machine parameters entering in the formula are the beam energy, γ , the β at the crossing and the beam aspect ratio.

Assuming that there is indeed a limit value ζ_m (or δQ_m) that cannot be exceeded, from eqs. 1 and 2 one can obtain, for $I_w = I_s$:

$$L_m = \frac{\pi k f_o}{r_e^2}\,\zeta_m^2\,\gamma^2\,\sigma_x\sigma_z\left(\frac{1}{\sigma_x}+\frac{1}{\sigma_z}\right)^2\left(\frac{\sigma}{\beta}\right)^2_{x,z} \qquad (5)$$

where, for the ratio $(\beta/\sigma)_{x,z}$, the greater of the two must be used.

This parametrization is significative only if ζ_m or δQ_m do not depend on the other parameters entering in eqs. 1 and 2 (I, γ, σ, β): if this is the case, eq. 5 shows that the maximum luminosity is achieved for equal beam currents, is proportional to β^{-2} and can be increased proportionally to the beam cross section (with a corresponding increase of the beam currents). If the beam dimensions are the natural ones, $\sigma_x\sigma_z \propto \gamma^2$, the maximum luminosity scales with γ^4. If the limit is on δQ, and not on ζ, eq. 3 shows that it is convenient to make the term $\mathrm{ctg}\,\mu$ positive and very large (μ close to, but greater than, a multiple of π for e^+e^- rings): for a given δQ_m a greater value of ζ_m will be obtained for $\mu \rightarrow \pi$, and therefore a greater luminosity.

In the storage ring design it has always been made the assumption of an "optical" limit (a linear or nonlinear lens effect due to the beam-beam interaction); in this assumption ζ_m or δQ_m should not depend on I, β , γ , while they might depend on the beam aspect ratio, or on the ring focusing structure. Table I summarizes the most relevant data of the operating e^+e^- storage rings, together with the expected performances of those in the pre-operation stage or in construction.

The experimental results on the beam-beam limit obtained on ACO can be summarized as follows[6]:

1) the maximum luminosity (on a coupling resonance with natural beam dimensions) scales with γ^5 and the current at the beam-beam limit with $\gamma^{3.5}$; the beam cross section at the limit scales therefore with γ^2 and ζ_m with $\gamma^{0.5}$: δQ_m scales approximately with γ (the $\mathrm{ctg}\mu$ term in eq. 3 is negative for the case of one bunch mode in ACO);
2) the ζ_m and the δQ_m are higher with one bunch per beam (two interaction points per turn) than with two bunches per beam: there is a factor of ~ 1.5 on ζ_m and ~ 1.8 on δQ_m;
3) the maximum measured value of ζ_m is 0.04 at 510 MeV, in the one bunch mode, and the corresponding δQ_m is 0.06.

The results obtained on ADONE are[7]:

1) the maximum luminosity (on a coupling resonance with natural beam dimensions) scales with γ^7 in the region where there is not a limitation in the current that can be stored: the specific luminosity (L/I_w) scales with $\gamma^{2.5}$: the beam cross section at the maximum luminosity scales therefore with γ^2, ζ_m with $\gamma^{1.5}$ and δQ_m with γ ;
2) δQ_m remains approximately constant changing the μ per crossing in the range $(\pi + 4^o) \div (\pi + 12^o)$;
3) in the one bunch mode the δQ_m is greater than in the three bunch mode: the factor is intermediate between 1 and 3;

TABLE I - Electron electron and electron positron storage rings

a) in operation or discontinued (measured values). -

	Max Energy (GeV)	Max Luminosity ($cm^{-2}s^{-1}$)	Currents mA	N° of crossings	ζ_m	δQ_m/crossing
e^-e^- Stanford-Princeton	0.55	5×10^{28}	60 + 60	1	$\sim 10^{-2}$	$\sim 10^{-2}$
e^+e^- VEPP-2	0.70	$(1 \div 2) \times 10^{28}$	40 + 70	2	$\sim (0.5 \div 1) \times 10^{-2}$	$\sim (0.5 \div 1) \times 10^{-2}$
e^+e^- ACO	0.5	6×10^{28}	25 + 25	2	~ 0.04	~ 0.06
e^+e^- ADONE	1.5	3×10^{29}	50 + 50	6	~ 0.08	~ 0.03

b) in pre-operation stage or construction (design values). -

	Max Energy (GeV)	Max Luminosity ($cm^{-2}s^{-1}$)	Remarks
e^+e^- CEA-By pass	3 (3.5)	10^{31}	low β
e^+e^- VEPP-3	3.5	10^{31}	low β
e^+e^- DORIS	3 (4.5)	10^{33}	low β
e^+e^- SPEAR	3 (4.5)	10^{32}	low β
e^+e^- ACO-II	1.8	10^{32}	space charge compensation

4) in the case of a very weak beam against an intense one the δQ_m is greater than in the case of equal currents, and does not seem to depend on energy;
5) operation out of the coupling resonance seems to give a δQ_m somewhat greater than on the coupling resonance (10 ÷ 20%);
6) measurements of luminosity as a function of beam current indicate a current dependence of the beam cross section different from what expected taking into account the corrections due to the lens effect of the crossing (which in ADONE are considerable, as the operating point is close to an integer);
7) the maximum measured values of ζ_m (on the coupling resonance) is about 0.08 at 1.050 MeV and the corresponding δQ_m is about 0.03.

The exponents of γ in the scaling laws for the various quantities have to be taken with some care; the γ dependence of the maximum luminosity and of the current at the beam-beam limit (or of the specific luminosity) is approximated with a power law over the whole operation range, while the beam behaviour at the beam-beam limit at low energy seems to be different from that at high energy, both in ACO and ADONE.

Preliminary results on the two beam operation with different values of the β at the crossing have been obtained at ACO[6]: they seem to show that the beam current at the beam-beam limit is approximately constant, whichever is the β (lower or higher then the normal value; the total range explored is about a factor of four in β).

This point needs however more experimental work to be confirmed: in the next future also on ADONE there will be the possibility of changing the β at the crossing, and more data will therefore be available from ACO, ADONE and the CEA-Bypass.

A firm conclusion that can be drawn from the experimental results is that the beam-beam limit is not purely "optical"; in other words the δQ_m(or the ζ_m) depends on γ (at least over certain energy ranges) and, possibly, on β.

It was suggested [8] that a possible interpretation of the results could have been a current limitation; however this model is not consistent with the observation made on ADONE that, when the beam-beam limit is reached on a coupling resonance, a slight change of one of the betatron frequencies drives one of the beams unstable: this would suggest that the limitation is related to the beam density, and not only to the beam current[9].

No model has been proposed, so far, that explains the beam-beam results; an hypothesis that can be advanced[10] is that the beam-beam limit, at least in a certain energy range, is due to a "random" excitation in competition with the radiation damping (which scales like γ^3); the excitation should be an increasing function of the δQ's (or the ζ's) seen by the two beams: this hypothesis is connected to a remark made years ago and checked with numerical computations[5], namely that the localized interaction between two intense beams introduces strong fluctuations in the particle spatial distribution. The evidence that in the weak-strong beam collision the δQ_m is higher than in the strong-strong beam case, and, possibly, independent from energy, supports the hypothesis; in the weak-strong beam collision the δQ_m should give the "optical" limit.

Another result that has not been understood refers to the beam crossing at an angle. It is known that a way of increasing the equivalent transverse cross section of the beams at the crossing is to have them to cross at an angle; this method has been successfully used on the Stanford-Princeton e⁻e⁻ rings and has been tried, afterwards, on ADONE, where however it has been found that the current could not be increased above the values that were stable in the head-on collision, while the luminosity decreased[11]. The limitation did not seem to be due to the longitudinal beam-beam effect [12], [13], consisting in the change of the longitudinal restoring force due to the beam-beam interaction when the beams cross at an angle, as the currents were quite below the values that give appreciable changes in the synchrotron frequency; no coherent synchrotron oscillation was observed and the beam loss, when the currents were too high, was relatively slow (order of tenths of seconds). The significance of this tests may be questionable as the crossing angle was obtained by a localized electric field, and the closed orbit had therefore a very strong harmonic component close to the betatron frequency.

The experimental data on the beam-beam limit are not sufficient nor accurate enough to draw a definite conclusion on its dependence on the various parameters; in particular more experiments are needed on the two beam behaviour as a function of the β at the crossing. As the "optical" model of the beam-beam limit seems to be in disagreement with the experimental data, a new model of the phenomenon has to be developed in order to provide new ways to improve the storage rings performances, if those already proposed (low β [14], space charge compensation[15]) should turn out to be less effective than foreseen.

3 - Single beam behaviour

3.1. - Trasverse instabilities

The forces due to the interaction of the beam with its environment induce a shift on the frequency of the collective motion which has, in general, a real and an imaginary part; depending on the sign of the imaginary shift the collective motion will be either damped or antidamped. The external forces will therefore make some of the oscillation modes stable and others unstable, unless there is a sufficiently strong damping mechanism.

It has to be pointed out that usually the Landau damping turns out to be more effective than the radiation damping, at least for the transverse modes. The betatron frequency spread (due to octupolar terms of the focusing fields or to the presence of positive ions in an e⁻ beam) are typically of the order of $10^2 \div 10^4$ sec^{-1}, to be compared with the radiation damping whose range can be from 1 to 10^2 sec^{-1}.

The frequency distribution is normally an exponential starting at Q_o and extending on one side or the other of this value; it has been pointed out[16] that this particular type of distribution, whose tails do not extend on both sides of the average value, has a peculiar consequence on the thresholds, that, for a given absolute value of the betatron frequency spread, can be quite different depending on the sign of the frequency distribution parameter (i.e. of the octupolar term): this effect has been observed on ACO[17], ADONE[18] and the CEA-Bypass[19][20].

To make full use of the Landau damping one should therefore keep the possibility of changing the sign of the octupolar terms in the focusing fields, by introducing in the magnetic structure suitable octupoles.

Single beam transverse instabilities have been observed and studied on positron beams or on electron beams without trapped ions. The first model, that explained the coherent instabilities observed on the Stanford-Princeton rings, considered the interaction of a rigid bunch with the fields induced in the environment by itself (in the preceding passages) or by other bunches of the beam[21]. The instability considered in this model is commonly known as the "slow" or "multi-turn" effect, with reference to the decay time assumed for the induced fields; the synchrotron motion within the bunch was not taken into account.

The transverse instabilities observed later on ACO and ADONE could not be explained with the afore mentioned model; the instability developed without showing any sign of coupling between bunches, or between successive passages of the same bunch (in the single bunch mode of operation), and, in the ACO case, with negligible amplitude of the bunch center of mass.

The new model proposed[22][23], known as the "head-tail" effect, takes into account the synchrotron motion, which turns out to be responsible for the regenerative action, allowing the transmission of the information on the particle motion to the same particle, with a phase delay, after a fraction of synchrotron oscillation. In this model fields decaying in a time comparable with the bunch length (typically 0.1 ÷ 5 nsec) can be cause of instability, and modes of oscillation without appreciable motion of the bunch center of mass are possible.

A peculiarity of the "head-tail" instability provides a cure and explains why it had not been observed in weak focusing rings: the rise time of the instability is proportional to $(1-C/\alpha)^{-1}$, where C is the chromatism of the ring (defined as the relative change of the betatron frequency divided by the relative change of the particle energy), and α is the momentum compaction. In a strong focusing structure without sextupoles C/α is of the order of $-10 \div -50$, while in a weak focusing its absolute value is usually smaller than unity. When $C = \alpha$ the instability rise time should tend to ∞; a compensation of the chromatism with sextupoles should therefore avoid the "head-tail" instability.

Tests with sectupoles have been done on ADONE, and, more recently with very positive results, on ACO24) and on the CEA-Bypass20)25); on ACO it has also been found that, in agreement with the model, reversing the sign of the chromatism the instability changes qualitatively, becoming coherent over the bunch length (the center of mass amplitude is comparable with the particle amplitudes)17).

On the basis of the present knowledge, the design of an electron positron storage ring should therefore incorporate sextupoles, to control the chromatism, and octupoles, to control the betatron frequency distribution; a fast feedback, transferring the position information from one bunch to the same bunch after one or more revolutions, should take care of the "multiturn" effects; all the elements in the vacuum chamber should be properly terminated for frequencies comparable with those corresponding to the bunch length (typically in the GHz range) to reduce the forces that cause instability.

Operation with many bunches per beam makes more difficult the fast feedback; the use of an RF quadrupole, that separates the betatron frequencies of the different bunches and reduces the coupling between bunches, has improved the instability thresholds on the CEA-Bypass19) 25), and might turn out to be a sufficient cure, together with controllable nonlinearities, for the transverse instabilities.

3.2. - Longitudinal instabilities.

Sustained coherent synchrotron oscillations or longitudinal instabilities have been observed on all the operating rings; their interpretation in the single bunch26), 27), 28) and in the multiple bunch operation29), 30) is in good agreement with the experimental results.

They are due to the interaction of the beam with axial fields induced by the beam itself in the surrounding structures; in the single bunch case the cure is quite simple, and consists in a proper adjustment of the impedance of an RF cavity (that can be either the main cavity or an additional one); an active feedback can also be considered and does not present particular problems (the bandwidth of the system should possibly be larger than the synchrotron oscillation frequency: this fact may suggest the use of an additional cavity).

In the multiple bunch operation the situation is much more complex, as each non RF harmonic frequency (multiple of the revolution frequency, but not of the RF frequency) interacts with two relative modes, damping one of them and antidamping the other. While the zeroth order mode (and a second mode, when the number of bunches is even) can be controlled as in the single bunch case (and it is actually done on ADONE11), 31)), the other relative modes require a different approach.

On ADONE11) and CEA-Bypass25) the separation of the synchrotron frequencies of the different bunches by a small, non RF harmonic, cavity has greatly improved the thresholds: the drawback of this solution is the introduction of a stable phase spread between the different bunches, resulting in a spread of the collision regions, that should be kept within a fraction of the source size to avoid problems in experimental apparatus acceptance and event identification.

Another cure has been tested on the CEA-Bypass25), with positive results, and consists in the increase of the synchrotron frequency spread within each bunch through the use of a small RF cavity on a frequency harmonic of the main RF system (it is the analogue of the octupoles for the transverse instabilities).

A third type of cure is an active feedback that turns out to be very complicated32) and has not yet been tested.

Multi-bunch operation is therefore more difficult than the single bunch mode also with respect to the longitudinal instabilities; as this type of instability has been recently observed also in conventional accelerators, when operating at high intensity, a convenient solution to the problem has to be found without reducing the number of bunches.

3.3. - Beam dimension.

At low current the beam dimensions have been found to be in agreement with those expected on the basis of the synchrotron radiation effects. As at least two of the e^+e^- rings presently in operation are working close to or on a difference coupling resonance ($Q_x - Q_z$ = integer), it is worthwhile to remark that in two recent papers33), 34) a very useful approximate calculation of the transverse dimensions in the case of weak coupling force (which is generally the case of interest) is pre sented. The transverse betatron invariants W_x and W_z as a function of the radial betatron invariant W_o, computed without coupling, are given, in the case of equal damping for the two modes, by34):

$$W_x \cong \frac{W_o}{2} \frac{2+F^2}{1+F^2} \; ; \; W_z \cong \frac{W_o}{2} \frac{F^2}{1+F^2} \qquad (6)$$

where F is a function of the coupling force (expressed through the minimum wavenumber separation η that can be obtained on the coupling resonance $\eta = Q'_x - Q'_z$) and of the unperturbed wavenumbers Q_x and Q_z:

$$F^2 \simeq (\pi\eta)^2 \left[\frac{1}{\mathrm{Sin}^2(\pi\left[Q_x - Q_z\right])} - \frac{1}{\mathrm{Sin}^2(\pi\left[Q_x + Q_z\right])} \right] \qquad (7)$$

The experimental values on the coupling resonance observed on ACO agree with eq. 6 for the vertical dimension, while for the radial ones it seems that the agreement is poorer 33); on ADONE they seem to agree, within the accuracy of the dimension monitor calibration.

Of the current effects on beam dimensions, one was expected, and this is the transverse growth in e^- beam, due to the focusing effect of the trapped ions.

The unexpected effect, which has not yet been satisfactorily interpreted, is the bunch lengthening observed on ACO35) and ADONE11), which depends on the charge per bunch, energy and RF voltage; the fit of the experimental results is given by the following formulas:

$$\text{ACO} \qquad (L/L_r)^2 = 1 + 2 \times 10^{-3} \frac{I}{E^4 L}$$

$$\text{ADONE} \qquad (L/L_r)^2 = 1 + (2 \pm 0.2) \times 10^{-2} \cdot \frac{V^{0.3 \pm 0.05} \, I^{1.05 \pm 0.05}}{E^{4 \pm 0.2} \, L} \qquad (8)$$

where L is the FWHH experimental bunch length and L_r the FWHH bunch length due to radiation, in nsec; I is the current per bunch in mA; V is the RF voltage in kV and E the beam energy in GeV.

A very similar fit is reported as being obtained by the Kharkov group on a small e^- ring35).

A correlation between bunch lengthening and increase in radial dimensions has been measured on ADONE11): the results indicate that the bunch lengthening is due to an increase of the momentum spread in the beam, but are not accurate enough to determine whether there is a corresponding increase of the betatron invariant; on ACO, where the radial dimensions observed are dominated by the betatron contribution, there seem to be no increase in radial dimensions correlated with the bunch lengthening: the two observations are consistent with an increase of the momentum spread without any increase of the betatron invariant.

Different models have been proposed to explain the bunch lengthening, but none of them fits all the experimental results. One model36), that takes into account a modification of the longitudinal restoring forces due to the beam interaction with elements in the vacuum chamber, gives a functional dependence of the bunch length very similar to that observed, but cannot explain the correlated increase in momentum spread. A second model37) assumes that the bunch lengthening is due to the equilibrium of high order longitudinal coherent oscillations and radiation damping: the momentum spread is therefore explained, but the functional dependence is not in agreement with the experiments; it has been however suggested by the author that the introduction of the Landau damping and a different excitation mechanism could change the functional dependence.

In the operating rings the bunch lengthening is a small effect at the currents normally used (typically 10 to 20%); nevertheless the interpretation of the effect would be very useful to decide the improvement in source size that could be obtained by going at higher RF frequencies.

An almost incoherent increase of transverse beam dimensions has been obtained by shock exciting small coherent oscillations, with a repetition frequency much higher than the inverse of the radiation damping time; the nonlinearities of the restoring forces dilute in phase space the particles after the excitation. This method is not useful when two beams, with the same betatron frequency, are colliding, as the residual coherent oscillations drive one of the two beams into a regime of large oscillations.

It has been observed (at Novosibirsk and Frascati) that when the betatron frequencies are splitted by means of an electric quadrupole the coherent growth is avoided.

The SPEAR group has proposed recently38) to use pulsed RF quadrupole excitation to increase the beam dimensions incoherently; a continuous RF quadrupole excitation, proposed by the same group time ago, has been tested on ADONE and found to cause rapid single beam loss; the pulsed operation has not been tested.

As shown by eq. 5, an incoherent increase of the beam transverse dimensions would allow to obtain higher luminosity with greater currents, and would therefore be an important improvement in the storage ring performances, as a way to extend to lower energies the useful range of operation of a given ring.

3.4. - Beam lifetime and residual gas pressure rise.

The beam lifetime is normally limited by gas bremsstrahlung; other effects give a negligible contribution to the loss rate in the normal operation. It is therefore of paramount importance to obtain a very low residual gas pressure possibly in the $0.1 \div 1$ nTorr range, to have long lifetime and low background on the experimental apparatus.

The gas load, in electron storage rings, is known to be primarily due to the gas desorption from the walls by photoelectrons produced by the synchrotron radiation. Measurements of electron desorption efficiencies have been done at Frascati time ago39): the results were typically an order of magnitude better then those that can be inferred from the pressure rise with beam measured in ACO and ADONE. There is however an interesting case in reference39): on one sample, that by mistake had been exposed to oil diffusion from a roughing pump, the desorption efficiency was at least one order of magnitude worse than usual, after a bake out at 300°C for 3 days. A treatment suggested by Garwin, consisting of one hour bake at 300°C in hydrogen at about 10^{-6} Torr followed by a similar procedure with oxygen, was found to be effective in the reduction of the desorption efficiency to normal values.

It thus appears that the pressure rises observed in ACO and ADONE are consistent with the desorption efficiency measured on an oil contaminated sample; moreover the bake out is known to be ineffective in reducing it to the values measured on clean surfaces.

The pressure rise as a function of energy in ADONE11) is in agreement with the assumption of approximate indipendence of the desorption probability from the photon energy, as long as it is higher than the work function of the wall material39).

The lowest pressure rise with beam current in ADONE, obtained after a month of operation subsequent to a vacuum chamber opening, is about 10^{-2} nTorr/mA at 1 GeV, with a total pumping speed at the vacuum gauges of about 7.000 lt/sec11); the static pressure (without beam) is $0.2 \div 0.3$ nTorr.

Improvements in the pressure rise could be obtained by lowering the electron desorption efficiency, or by lowering the photoelectron production efficiency (that depends on the angle of incidence of the synchrotron radiation on the walls), or by obtaining a greater pumping speed.

More experimental work is needed to understand the limits of the first two methods; as far as the greater pumping speed is concerned, a very simple solution has been suggested by the Novosibirsk group and is incorporated in the SPEAR design: a distributed titanium pump installed in the inner side of the vacuum chamber in the bending magnets. On a prototype built at SLAC a pumping speed of about 5 lt/s cm has been obtained40).

The gas composition in presence of the beam contains a large fraction of hydrogen; on ADONE it has been observed that the composition seems to change slightly with time. The $\langle Z^2 \rangle$ equivalent monoatomic is between 30 and 6011).

Anomalously short beam lifetime has been observed on many rings and interpreted as due to nonlinear resonances: operation of the CEA-Bypass at low β has shown that a better linearization of the field in the high β regions has improved the performances41). A similar effect, leading to short lifetimes, has been observed on ADONE when enlarging the beam to r.m.s. dimensions greater than about $3 \div 5$ mm. These results lead to the conclusion that the bending and focusing fields in a storage ring must be very accurately linearized; elements giving the required non linear fields (sextupoles and octupoles) should be added separately, be controllable and distributed along the ring with sufficiently high periodicity.

4 - Concluding remarks

The operation of the first generation of e^-e^- and e^+e^- storage rings has brought into light a number of problems that, at least in part, have been understood and solved; the single beam instabilities have been interpreted and different types of cures can be adopted, depending on the ring parameters.

Unfortunately the same cannot be said for the two beam behaviour, which is the most determining factor in the storage ring performance; it is not certainly the slight difference in the maximum betatron tune shift achieved in different rings that can cast some doubt on the parameters affecting the beam-beam limit, but the observed energy dependence and the possible dependence on β. It is not evident, at present, within which limits the scaling laws of the "optical" model are valid and which are therefore the possible improvements in the ring performances. The rings of the second generation, but one, have a new feature in common; the low β insertion, that should permit to achieve a much higher beam density at the crossing, and therefore a much higher luminosity. In one of them (ACO-II) a completely different approach is followed; the compensation of the beam-beam Coulomb interaction at the crossing through the use of four colliding beams, two of electrons and two of positrons.

It is difficult, at present, to assess the relative merits and difficulties; if, on one side, there is the complication of handling four beam, keeping all the conditions of an efficient space charge compensation, on the other side the CEA-Bypass operation has shown that a low β insertion has its problems.

Extentions in energy are being considered: very high energy rings, in the range of 10 ÷ 20 GeV, have been subject of preliminary study$^{42)}$; these proposals do not incorporate new ideas and the new technical problems involve essentially the RF systems. Some thought has been devoted to colliding beams of different types of particles, and they will be discussed at this Conference.

There has also been a proposal for a low energy (700 MeV) and very high luminosity ring, VEPP-2' at Novosibirsk. It is of some interest to remark that experience has shown that the useful energy range of a given ring is quite small, from about half to the maximum energy, and this makes very interesting, for high energy physics experiments, such a ring.

It is however important, in my opinion, to reach a better understanding of the fundamental storage ring limitation, before starting new huge projects, as it might suggest new approaches to improved performances; hopefully, at the next Accelerator Conference, the results coming from at least three more e^+e^- storage rings will help to make the whole matter completely clear.

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DISCUSSION

P. LAPOSTOLLE : Are the effects of possible outgassing which are cured by baking out the vacuum chamber well understood ?

F. AMMAN : As far as I know the basic process is known, but it is not possible to calculate the desorption efficiency for a real surface.

V.P. DZHELEPOV : What is the dependence on energy and beam currents of the size of the crossing region at the interaction point ?

F. AMMAN : The transverse cross section of a single beam scales with γ^2 (due to radiation effects) : when two beams collide, at the beam-beam limit, the scaling law for the cross section is again γ^2.

M. GOLDHABER : Is the increase of the cross section of the weaker beam true for both positron - electron rings, whichever beam is the stronger, and for electron - electron rings ?

F. AMMAN : In ADONE, to avoid spurious effects due to trapped ions, we operate always with more positrons than electrons. I should refer the question to the colleagues from Novosibirsk.

A.N. SKRINSKY : It was approximately the same situation for both electron - electron and electron - positron beams (but, in fact, much more complicated than just increase in size).

W.K.H. PANOFSKY : I might comment that usually storage rings are designed such that the upper energy limit is defined by RF power and the lower limit by orbit dynamics. Unless there is more flexibility in RF power than has been customary in the past, the useful energy band will remain narrow.