# STORAGE RINGS FOR ELECTRONS AND POSITRONS

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## Summary

Storage rings for electrons and positrons provide a powerful tool for investigation of a variety of high energy processes. The development of storage rings has relied heavily on advanced accelerator technology. Many problems such as beam instability have arisen but acceptable solutions to these problems appear to have been found. Presently contemplated storage ring projects include plans for storage rings for energies as high as 5 BeV.

## Introduction

The use of colliding beams as a tool for investigation of high energy physics processes is a technique which has grown rapidly in the past few years. Certainly not all the interesting physics that needs to be done can be done by this technique. On the other hand, as time progresses, more and more useful experiments appear which can be performed with storage rings and, in many cases, can be performed in no other way. As recently as ten or twelve years ago it appeared that colliding beams would be useful primarily for collisions of heavy particles, the argument being given that steps to energies higher than those currently available or contemplated would be too costly to undertake. Subsequent developments have shown that colliding beams with electrons, especially together with positrons, also provide a powerful tool for exploring interesting physics. The previous speaker has described one of the largest and most advanced colliding beam projects for heavy particles. I shall attempt to give a brief description of the evolution of storage rings for light particles and a discussion of some of the important problems that have been faced.

The first concrete plan for electron-electron collisions in this country came in the proposal by O'Neill, Panofsky, and others[1] to make a test of the theory of quantum electrodynamics by the construction of 500 MeV electron-electron storage rings in conjunction with the Stanford Mark III linac. These rings were constructed and results from their experiments were presented two hears ago at this conference.[2] A similar venture for 130 MeV electron-electron collisions was undertaken about the same time by G. I. Budker and associates, at that time in Moscow. Experiments with these rings (VEP-1) were ultimately carried out at Akademgorod, Novosibirsk and results have been reported recently.[3] In the late 1950's a small storage ring (ADA) was constructed at Frascati.[4] ADA was used primarily to test understanding of processes which determined the lifetime of beams in storage rings. Although its accumulated beam intensity was rather low, ADA showed limitations caused by collective effects in the beam. In this case, it was the well-known Touschek effect in which particles traveling together in the beam scattered from each other in such a way as to cause the loss of particles from the beam.

Subsequently electron-positron storage ring projects have been initiated at Frascati (Adone, 1.5 GeV), Orsay (ACO, 450 MeV), Novosibirsk (VEPP-2, 750 MeV), MURA (250 MeV), Stanford (3 GeV), CEA (2-3 GeV using the CEA accelerator as a storage ring), and Novosibirsk (5 GeV).

## Choice of Magnet Structure

The primary distinction between light particle and heavy particle storage rings lies in the intensity of emission of synchrotron radiation. While negligible for protons, synchrotron radiation is a dominant feature of the electron-positron rings and influences almost every aspect of their design. The synchrotron radiation, of course, occurs by the emission of discrete photons. Nevertheless, it is useful to think in terms of a smooth or average rate of emission and a stochastic fluctuation about this average. The average emission contributes in first order to growth or diminution of the amplitudes of oscillations of particles in all three dimensions. Thus, it is necessary to choose a magnetic field configuration in which oscillations are damped by the radiation in all three dimensions. Several solutions to this problem have been found, ranging from the conventional weak focusing structure for small storage rings to the separated function structure for high energy storage rings. In passing, it is worth noting that the conventional

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

AGS structure, in which the radial betatron oscillations grow, can be remedied by fairly simple field corrections as has been done for the Cambridge Electron Accelerator.[5] Formulas describing the damping rates for a particular structure can be written as[6, 7, 8]

$$\beta_z = \frac{-P_\gamma}{E}$$

$$\beta_x = \frac{P_\gamma}{E}\,\frac{-\overline{\Omega^2} + 2R\,\overline{\Omega K g} - R\,\overline{\Omega^3 g}}{2}$$

$$\beta_s = \frac{P_\gamma}{E}\,\frac{-2\overline{\Omega^2} - 2R\,\overline{\Omega K g} + R\,\overline{\Omega^3 g}}{2}$$

where $P_\gamma$ = average radiated power

$E$ = particle energy

$\Omega$ = orbit curvature

$K = \frac{e}{Pc}\,\frac{\partial B_z}{\partial x}$ - field gradient

$g(s) = \frac{x\,(\Delta P)}{\Delta P/P}$ shape of the off momentum equilibrium orbit

$2\pi R$ = circumference of ring

It is seen that the problem in the AGS arises in the radially focusing magnet where the sign of the magnetic field and its gradient combine to give a large anti damping term. The choice of the separated function structure where magnetic fields and field gradients do not occur in the same region remedies this situation.

Having chosen the structures so that oscillations in all three dimensions are damped, the beam is now free to collapse to very small sizes. The size of the beam is then determined primarily by the fluctuating component of the radiation[9] or by gas scattering if the vacuum system pressure is too high. Typically, beams shrink to sizes of several hundred microns vertically, 1 millimeter radially, and 1 meter in length.

## Vacuum System Requirements

In order to perform experiments in a reasonable way, it is desirable that the beam lifetime be long compared to the time required to fill the storage ring with particles. In addition it is highly desirable to have a low gas pressure in the interaction region to reduce background rates due to collisions of beam particles with gas molecules. Thus, vacuum systems have, of necessity, been of the ultra high vacuum type, $10^{-9}$ to $10^{-10}$ Torr being the usual desired pressure range.

The dominant beam-induced complication to the vacuum system arises from the strong synchrotron radiation. The presence of many photons in the 100 eV range leads to a strong photo-desorption of the walls. Fortunately, careful design, adherence to strict rules of cleanliness, and avoidance of hydrocarbons in the system leads to a situation in which the system "cleans up" by continued operation.[10]

## Single Beam Instability

The compression of the beam by the radiation is such that for even modest currents the beam has very high charge density. This at first sight is useful since the total collision interaction rate from a given number of particles in each beam is proportional to the density. On the other hand, high density brings the beam into a regime where it is susceptible to a variety of instabilities. The compression of the beam reduces the natural stabilizing influences such as the spread of frequencies of collective oscillations of the beam. Thus, the beam is very coherent and can partake in a variety of collective oscillations which either increase the beam size, cause the beam to wander from its equilibrium position, or to miss the other beam in the machine.

The first serious instability to be encountered has been called the coherent vertical instability or dipole instability and can be described simply as a coherent betatron oscillation of the beam bunch as a whole.[11] The driving force for this instability arises from the currents induced in the wall of the vacuum chamber as the beam bunches pass by. Because of the finite resistivity of the wall, currents induced by the beam's magnetic field diffuse into the wall and are trapped. When the beam has passed these trapped currents give rise to a magnetic field, the so-called wake field, which exerts a force on following beam bunches. Although the wake field falls off relatively slowly in time, the sign of the effect is determined by the first passage of the bunch subsequent to the formation of the wake field. Thus, we would expect that for a single beam the question of whether coherent oscillation grows or diminishes because of the wake field should be determined by the elapsed phase of the coherent oscillations in the first passage around the machine. This has been shown to be true by Courant and Sessler and leads to the simple conclusion that, for the dipole instability, the beam should be stable if the betatron oscillation frequency $\nu$ is between an integer and the next half integer.

Other coherent oscillations can be driven by the wake fields corresponding to all multipoles of beam charge distribution.[12] In particular, for quadrupole oscillations, a similar instability criterion is set which holds for $2\nu$ rather than $\nu$. Similar criteria exist for higher order multipoles. Interestingly enough the thresholds for onset of the higher order multipole instabilities are not appreciably different from the dipole threshold. Fortunately, the growth rates for these instabilities drop rapidly with multipolarity for the storage ring configuration and should be damped by radiation. Figure 1 shows the beam motion and equivalent charge distribution for several multipoles.

These coherent oscillations can be stabilized by several means. The first method which has been employed successfully has been to add nonlinear magnetic fields to the storage ring to increase the natural frequency spread in the beam. The addition of an octupole magnetic field causes the betatron oscillation frequency to be a function of the amplitude of betatron oscillation. The threshold for onset of stability, which is primarily determined by the frequency spread in the beam, has been increased appreciably. The advantage of this method lies primarily in its simplicity and also in the fact that it is applicable to all multipoles of coherent oscillation. This method is limited by the available strength of nonlinearity and by the difficulties caused by the nonlinearities in injection when betatron oscillation amplitudes are large.

A second method which has been employed for the dipole oscillation has been to use electronic feedback schemes. In essence, these methods detect the coherent oscillation of a bunch and feed back a force to the same bunch at such a phase and strength as to overcome the effects of the wake fields. The feedback schemes have been very successful for dipole instabilities but it is not as yet clear that it will be feasible to apply them to higher order multipoles.

The third method which has been successful has been to alter the reactive component of the wall impedance through special plates, coils, or surface layers which cause phase shifts grossly altering the properties of the wake field. Such a system has been used with VEPP-2 for the dipole instability but it is not yet clear whether such systems will be applicable either to beams with more than one bunch or to higher multipoles of coherent oscillation.

## Two Beam Instabilities

It can happen and, indeed has happened, that when one attempts to cause beams to collide they refuse to do so and, in fact, miss each other because of their mutual interactions. In the first place, they can do so because of the coherent oscillations described above. When the second beam is taken into account a new set of modes describing the dipole instability arises for the coupled system.[13] It has been shown that if each beam by itself is stable for the mode in which all beam bunches oscillate with the same phase then the two beam system will be stable. Secondly, if the betatron oscillation frequencies of the two beams can be made sufficiently different the two beams will not oscillate coherently. The betatron oscillation frequencies are split by the addition of electric focusing fields to the storage ring which treat the electrons and positrons differently.

The second type of two beam interaction which can cause the beams effectively to miss each other can be described as an incoherent phenomena. The beams can by their mutual interaction strongly alter their shapes in such a way that only part of one beam passes through the other.[14] One can see how this arises by inspecting the shape of the charge distribution and associated electric and magnetic field of the beam. Inside the beam the fields grow until they reach the boundary of the beam and then fall off near the wall. This is a very nonlinear situation which can provoke unusual beam behavior. For example, if the betatron frequency can be written $p/q$, where $p$ and $q$ are coprime, then nonlinearity in the field of the other beam corresponding to the $q^{th}$ power dependence can cause the phase plane to exhibit "islands" or "strings of pearls." These "islands" are regions of stable oscillation with equilibrium orbits which do not pass through the other beam. Thus, the second beam can find itself so disposed that most of it misses the first beam. Of course, such phenomena will be exhibited in both transverse coordinates of the beam. Furthermore, the situation just described corresponds to a strong beam and a weak beam, the reaction of the second beam back on the first not accounted for.

An indication of the strength of the weak-strong incoherent effect is given by the small amplitude tune shift of the weak beam caused by the strong beam.[15]

$$\Delta\nu = \frac{N r_e \beta_I}{2\pi\gamma w h\, k}$$

$N$ = number of particles in the bunch

$r_e$ = classical electron radius

$\beta_I$ = betatron oscillation amplitude function at interaction region

$w$ = radial beam width

$h$ = vertical beam height

$\gamma$ = relativistic factor

$k$ = number of bunches in each beam

Experimentally, stable operation has been achieved for $\Delta\nu \lesssim .025$.

## Low - $\beta$ Sections

The limitation by the nonlinear effects appear at present to be the principal limitation on the effectiveness of the storage ring to produce interactions. To be more precise, we can define the "luminosity" of the rings to be the factor which, when multiplied by the interaction cross section, yields the reaction rate.

$$L = \frac{N_1\ N_2\ f}{4\ k\pi\ w\ h}$$

$N_1$, $N_2$ - Number of particles in each beam

$f$ - Revolution frequency

If we now substitute the value of N obtained from the formula, we obtain

$$L = \frac{N\ f\ \gamma\,\Delta\nu}{2\ \ r_e \beta_I}$$

This shows the most promising means to ameliorate the nonlinear limitation. For $\beta_I$ is under the control of the designer. It is possible to alter the focusing structure of the magnet configuration to reduce greatly the value of $\beta_I$ and, hence, increase the luminosity. This feature has been incorporated into the design of ACO, and a paper describing such a section for the SLAC 3 BeV rings has been given at this conference.[16]

## Summary

In summary, I have touched on only a few of the high points of the development of electron-positron storage rings. These endeavors have been characterized at all stages by difficult problems, but these problems have been overcome by hard work and ingenuity. It is perhaps for this reason that a growing number of researchers consider the future of storage rings to be bright.

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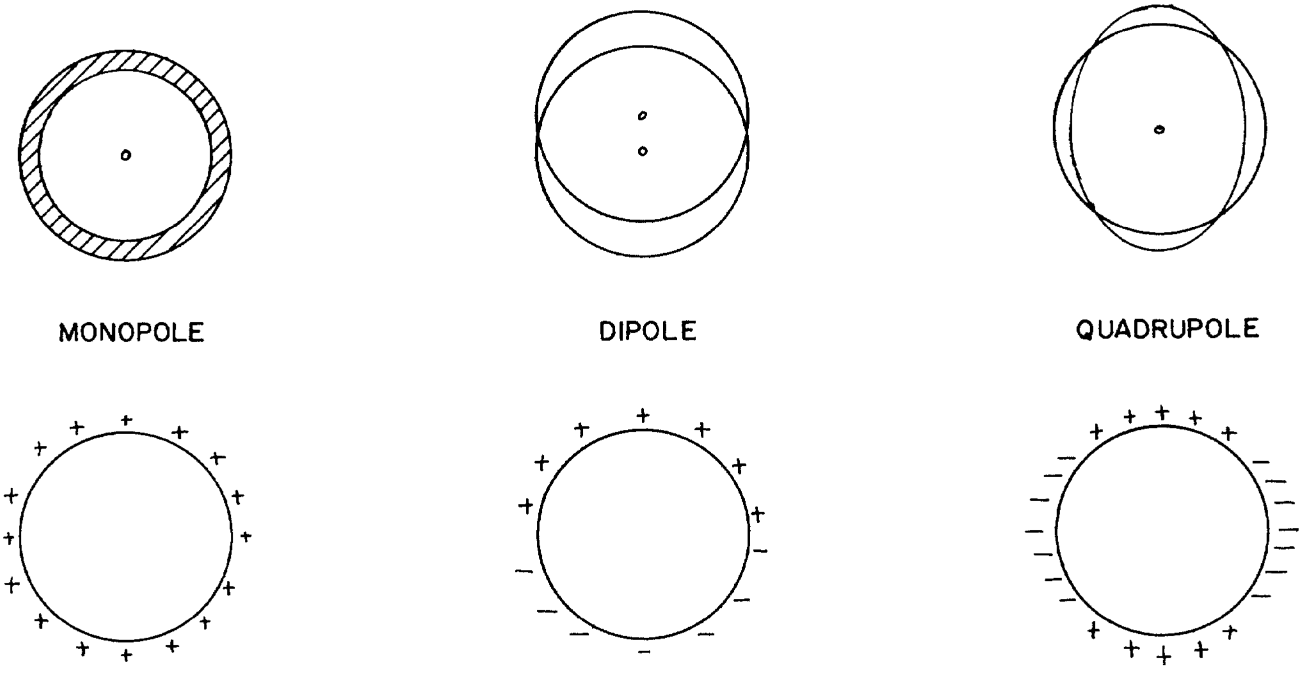

Fig. 1. Coherent Oscillation Modes and Equivalent Charge Distributions.