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DESIGN OF ELECTRON-POSITRON COLLIDING BEAM RINGS

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(presented by F. Amman)

This paper outlines the considerations entering into the design of an electron-positron colliding-beam ring. The most important limitation is set by the space-charge interaction of two beams. This has been calculated in detail.

If positron and electron beams interact in a storage ring, the interaction rate at an interaction zone, for a reaction whose cross section is σ, is given by:

$$\dot{n} = \frac{f}{k}\frac{N_+N_-}{S}\sigma \quad \text{events per second,} \qquad (1)$$

where:

- f is the frequency of revolution;
- k is the number of rf bunches;
- N_-, N_+ are the numbers of electrons and positrons, respectively;
- $S = w(h + \ell\alpha)$ is the effective cross section of the beam, where
  - w is the radial width;
  - h is the vertical height;
  - ℓ is the length of a bunch;
  - α is the half-angle of crossing in a vertical plane.

The space-charge interactions set an upper limit to the value of $(pN)/(kS)$ which is proportional to the mean magnetic field along the orbit; p is the number of interaction regions per turn. If this limit is exceeded, the less intense beam becomes unstable and breaks up into a diffuse halo around the other beam. Thus, only a fraction of the particles will interact and the counting rate will drop.

Accordingly, an optimum machine should have a value of $(pN)/(kS)$ close to, but smaller than, the theoretical limit (which is about 10^{12} particles per cm^2).

The natural cross section S_0 of a beam of electrons or positrons, taking into account gas scattering and radiation effects, lies in the range of 10^{-3} to 10^{-4} cm^2 and thus the maximum number of particles N_0 for a cross section of these dimensions is about 10^9 to 10^{10}. For such low intensities the counting rate is given by:

$$\dot{n} = fN_+\frac{N_-}{kS_0}\sigma \text{ events per second} \qquad (2)$$

for $(pN)/kS_0) < 10^{12}$ particles/cm^2.

For higher intensities than N_0 it is necessary to increase the effective cross section S of the beam. This can be done by separating the beams spatially with an electric field and arranging for them to cross at an angle 2α. The electric field should be chosen so that the value $(pN)/(kS)$ for the more intense beam, which we assume to be the electron beam, is close to the theoretical space-charge limit.

Under these conditions $(pN_-)/kS)$ is proportional to $E/E_{\max}$ at different energies E, and is approximately equal to 10^{12} particles/cm^2 at the final machine energy $E_{\max}$. Noting that fN_+ is proportional to the current I_+ we find:

$$\dot{n} \cong \frac{4 \times 10^{30}}{p} I_+ \frac{E}{E_{\max}} \sigma \text{ events per second} \qquad (3)$$

where I_+ is expressed in amperes and σ in cm^2, for $(pN_-)/RS_0) > 10^{12}$ electrons/cm^2 and $N_- \geq N_+$.

Thus, the maximum interaction rate, attained by adjusting S near to the space-charge limit, depends only on the positron current. There is no advantage in making I_- greater than I_+ and, since a small interaction zone results when I_- is nearly equal to I_+, the best choice is I_- equal to I_+. This small interaction zone greatly simplifies experimental problems.

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In practice, it does not seem possible to use extremely large currents because the electric fields, necessary to give a correct value for S, become indefinitely large, and the vertical separation of the beams becomes commensurate with the doughnut size. For instance, a field of about 500 v/cm is necessary for $I_+ = I_- = 0.1$ amp at 750 Mev energy with a maximum vertical separation of the beams of about 8 mm, and a field of about 5 kv/cm with a separation of about 8 cm is necessary for a current of 1 amp.

The current of positrons that can be stored depends on the current i_+, from the injector, that is within the energy spread accepted by the machine (about ±0.3 percent for weak focusing and ±0.6 percent for strong focusing), and on the number of pulses M that can be injected.

Taking into account the number of turns in which injection occurs (two to three) and the capture efficiency in the ring (30 to 50 percent), we can write:

$$I_+ \cong M\, i_+$$

The time interval between injection pulses can be assumed to be equal to the damping time of the radial betatron oscillations, τ_r; the storage time T is then given by

$$T \cong M\, \tau_r \tag{5}$$

From equations (4) and (5) and the expression for τ_r, we find:

$$I_+ \cong 2\, i_+\, T\,(\text{sec})\,(B^2_{\max})/(E^2_{\max})\, E^3_{\text{inj}}\,, \tag{6}$$

where E_{inj} and $E_{\max}$ (in Gev) are the injection and final energies of particles in the ring, and $B_{\max}$ (in kgauss) is the magnetic field at the final energy.

Typical values might be $i_+ \cong 2$ μamp, $T \cong 3 \times 10^3$ sec, $M \cong 10^5$ and hence $I_+ \cong 0.2$ amp.

From equation (6) we note that if the size of the machine is changed, with the same values for i_+, T, and $B_{\max}$, the injection energy must be increased in proportion to $(E_{\max})^{2/3}$ to obtain the same counting rate at a different final energy $E_{\max}$.

Summarizing our conclusions, we find that:

(a) The machine should use equal positron and electron currents (higher electron currents are readily attainable, but are of no advantage and lead to a large interaction zone).

(b) The counting rate is proportional to the magnetic field B; storage rings with the same positron current give essentially the same interaction rate for given values of σ and I_+, at the final energy, independent of this energy.

(c) The measurable cross sections are limited by the maximum interaction rate given by equation (3).

(d) The use of currents in excess of one ampere would become difficult.

(e) The injection energy necessary to obtain a given counting rate for a cross section σ must be increased as $(E_{\max})^{2/3}$ where $E_{\max}$ is the final machine energy.

Tabulated in Table I are typical parameters for a 750-Mev weak-focusing machine and a 1.5-Gev strong-focusing machine[2,3,4].

TABLE I

Final energy	(Mev)	750	1,500
Focusing		weak	strong
Mean radius R	(m)	2.9	10
Magnetic field at the final energy	(kgauss)	13	10 (rad. D sectors) 5 (rad. F sectors)
Q—radial		0.90	2.25
Q—vertical		0.83	1.80
Momentum compaction		1.23	0.20
Radiation losses	(Kev/turn)	14.2	67
RF voltage	(kv)	50	120
Energy spread accepted at injection		~±0.3%	~±0.6%
Injection energy:			
for $\tau_r = 1$ sec	(Mev)	145	315
$\tau_r = 0.1$ sec	(Mev)	310	680
$\tau_r = 0.01$ sec	(Mev)	675	1,470
Natural beam across section S_0, at a pressure of 10^{-9} mm Hg	(cm²)	5×10^{-4}	3×10^{-4}
Beam lifetime, at a pressure of 10^{-9} mm Hg	(hrs)	25	25
Number of bunches, k		2	2
Number of interaction regions, p		2	4
Crossing angle α for $I_+ \cong 0.1$ amp	(rad)	$\sim 10^{-3}$	$\sim 10^{-3}$

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DISCUSSION

(on all three previous papers)

L. VAN HOVE: I would like to mention that Dr. R. Gatto, of the Frascati group, has written a report concerning the physics of the electron-positron storage ring. This report was forwarded to me but, unfortunately, time did not permit me to include a discussion of its contents in my lecture in the opening session of this Conference.

In addition to the cross sections which have been already listed, Dr. Gatto has given some detailed discussion of the physical interest of these experiments; the particularly nice feature of them is that, in addition to testing electrodynamics, they allow also for the systematic study of other particles. These include both strongly interacting particles, like pions and strange particles for which one could measure form factors, and also particles like muons or possibly intermediate bosons, with which one could study features of the weak interactions.

A. SCHOCH: I would like to ask whether the beam cross section which appeared in the photograph, that was shown by Dr. Bernardini (Fig. 5 of his paper) and that was taken by means of the radiated light, is consistent with what one would expect in the equilibrium state due to the rf accelerating voltage, and bremsstrahlung, which I think determines the width of the beam.

C. BERNARDINI: The linear dimensions of the cross section of the beam agree with the expected ones within the uncertainty of about 10 percent.

A. YOKOSAWA: I have a question for Dr. O'Neill about the high-vacuum system. What vacuum did you say you would like to achieve in this vacuum tank? And also I would like to know the volume or size of this vacuum system.

G. K. O'NEILL: With respect to the vacuum, we felt that the poorest vacuum, with which we could do the experiment that we had in mind, was about 10^{-7} mm Hg. But, at the time that we planned the experiment, we felt that, because of its unusual nature, we really needed quite large safety factors everywhere. So we decided to go all the way to a gold-ring gasketed system. The pressure that we have already attained represents an improvement by a factor of 20 over what we need but we would like to go still further, because there are great conveniences (stability of counting rates and operation after the linac is shut off) that become possible if we can store beams for long lifetimes. Concerning the size of the vacuum system, it is about 24 meters long, the cross section is about 5 cm by 15 cm, and there are in addition two rather large tanks about 50 cm in diameter and 50 cm in length.