STORAGE RINGS FOR ELECTRONS AND PROTONS

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I. THE PRINCETON - STANFORD EXPERIMENT ON QUANTUM ELECTRODYNAMIC LIMITS

A group consisting of Barber, Gittelman, O'Neill, Panofsky and Richter is constructing an experiment on the scattering of colliding 500 MeV electron beams [1]. This should test quantum electrodynamics (QED) at distances small compared to a nucleon radius. In the lowest-order Feymann diagram for Møller scattering (Fig. 1), the amplitude of the virtual photon (the "photon propagator") is the Fourier transform of the Coulomb potential 1/r. If $1/r$ were replaced by $(1/r)\,(1-e^{-\lambda r})$, the Møller scattering cross-section would be reduced by the factor $(1+(2q^2/h^2\lambda^2))$, where q is the momentum transferred by the virtual photon [2]. Existing experiments on electron-protron scattering and on the Lamb shift set an upper limit of 0.3×10^{-13} cm on λ^{-1}. If the ratio of differential cross-sections at 35° and 90° for electron-electron scattering at 500 MeV can be measured to 10 per cent, a value of λ^{-1} as small as 0.04×10^{-13} can be detected. The same experiment done with stationary target electrons would require a 1000 GeV electron accelerator. Experiments on the value of $g-2$ for the meson are in progress at various laboratories. Their limits are expected to be comparable with those already achieved by electron-proton scattering.

The colliding-beam experiment will use the 500 MeV central beam of the Stanford Mark 3 linac. It is hoped that the experiment can be carried out at several energies from 100 to 500 MeV.

A shielded vault has been built behind the experimental end station of the accelerator. (See Figs. 2, 3 and 4). The 500 MeV electrons will be deflected into one ring of a figure-8 storage-ring pair by d.c. magnets. The injection energy will be that of the central orbit in the storage ring. Part of the radial component of electron velocity will be removed by a delay-line inflector, turning on a field of 2 500 G over a 42 cm length. (Figs. 5, 6, 7.) The response time of the magnet will permit accepting electrons for 55×10^{-9} s. After the delay-line inflector is turned off, the residual radial betatron oscillation amplitude

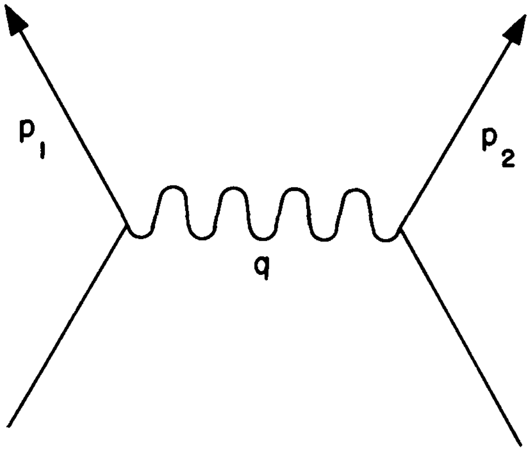

Fig. 1 Lowest-order Feynmann diagram for Møller scattering.

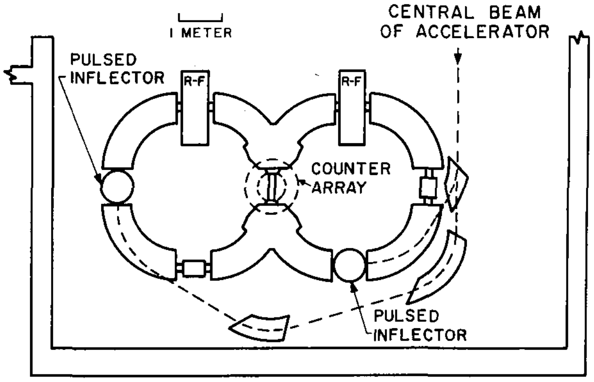

Fig. 2 Plan view of the colliding-beam vault at the Stanford Mk. III linear accelerator.

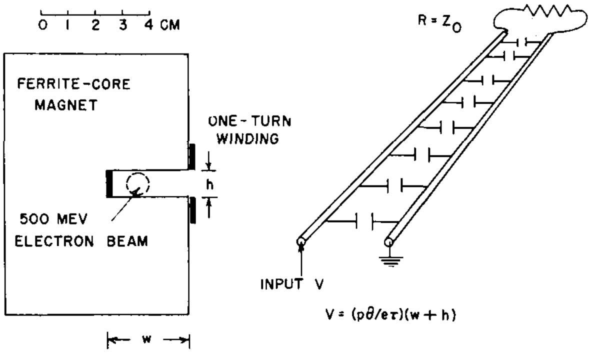

Fig. 5 Delay-line inflector cross-section and equivalent circuit.

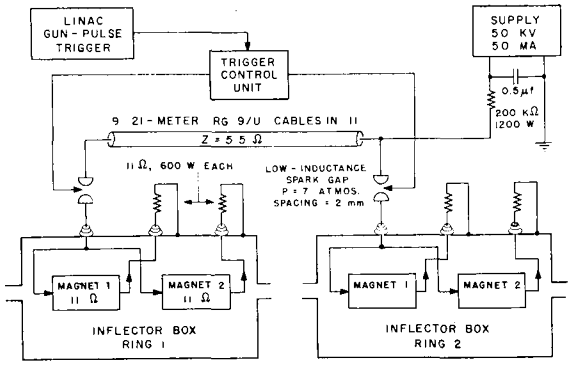

Fig. 7 Inflector control schematic.

(10 cm peak-to-peak) will decay with a 10 ms lifetime, due to energy loss by synchrotron radiation [3]. 1/60 s later, the inflector can be pulsed on again without disturbing the stored beam. In this way it is planned to build up a circulating current of about one ampere over a period of minutes. The d.c. steering magnets will then be switched, and the second ring filled in the same manner. With both rings filled, the linac will be switched to other experiments and a colliding-beam counting run can go on for the lifetime of the stored beams. The guide-field structure of the storage rings (Fig. 8) will be weak focusing, so that synchrotron and vertical betatron oscillations will also be radiation damped with time constants of a few milliseconds. Phase-coherent accelerating cavities will provide 20 kV of 25.4 Mc RF in each of the 1.40 meter radius rings. Since the radiation losses are only 4 keV/turn, the lifetime against escape from the phase-stable region by quantum fluctuations is calculated to be at least many days (Fig. 9). Electrons can, however, be lost by bremsstrahlung and gas scattering in the residual gas of the vacuum chamber. Although the experiment could probably be performed with a gas pressure of 10^{-7} mm, a clean ultra-high vacuum system is being built, using vacuum-melted stainless steel, high-alumina ceramic insulators, and gold-ring gaskets. It is designed to be removable from the storage-ring magnets so that it can be baked out at 400° C. At the design operating pressure (10^{-9} mm), the lifetime against bremsstrahlung will be 30 hours, and against scattering 200 hours.

The equilibrium beam size will be set by a competition between classical radiation damping and quantum fluctuations in the radiation. Following Christy [3], the typical quantum energy is $E_\nu = \frac{3}{2}\hbar\omega\left(\frac{E}{mc^2}\right)^3 \sim$ $\sim 200\,\mathrm{eV}$ at $E = 500\,\mathrm{MeV}$. The r.m.s. amplitude of synchrotron oscillations is 0.10 cm in radius, and $\sim$ 30 cm in length. That of radial betatron oscillations should be 0.2 cm. The quantum-induced vertical oscillation size should be smaller by a factor (mc^2/E).

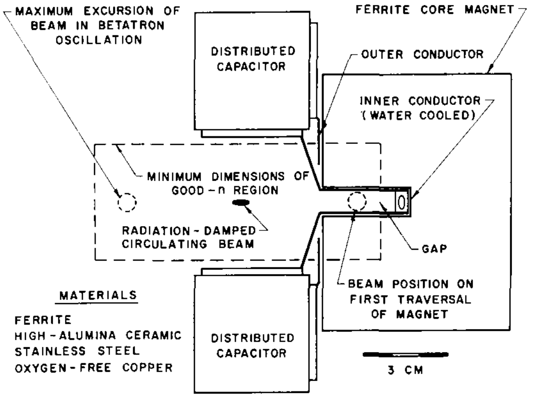

Fig. 6 Inflector with distributed capacitors.

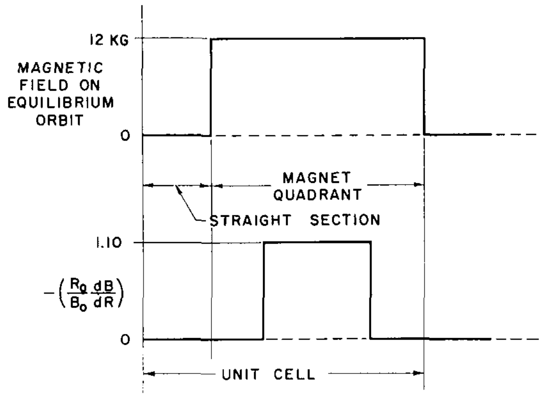

Fig. 8 Guide field cell-structure for figure-8 storage rings.

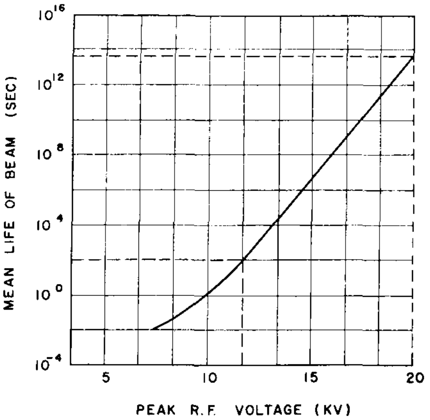

Fig. 9 Beam lifetime against quantum fluctuations vs. RF voltage.

TABLE I

Theoretical beam properties

Stable phase angle	12°	
Phase spread	21°	
Radiation loss/turn	4	keV
Typical quantum energy	214	eV
Oscillation damping times :		
Betatron vertical	10	ms
Betatron radial	10	ms
Synchrotron	5	ms
Oscillations/turn :		
Vertical	0.88	
Radial	0.77	
Circulating current (nominal)	1	A
Beam crossing angle	0.03	rad
Calculated beam lifetimes :		
Quantum fluctuations (20 kV)	10^{10}	h
Bremsstrahlung (10^{-9} mm)	30	h
Single gas scattering (10^{-9} mm)	200	h

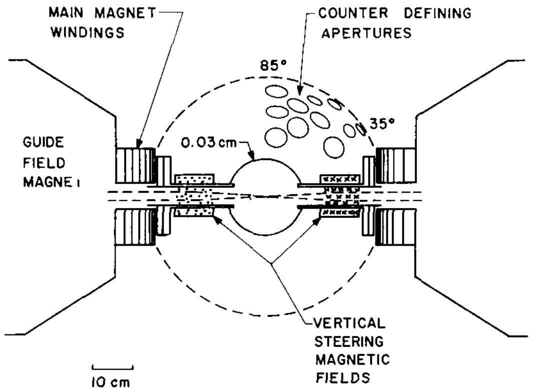

Fig. 10 Side view of interaction straight section.

Small steering magnets are being provided (Fig. 10), so that the circulating beams will cross in the vertical plane. This will localize the interaction region to an approximate point source, and will raise considerably the limit on circulating current set by instabilities. In this experiment, the beams should be stable against longitudinal oscillations of the kinds studied by Sturrock and by Nielsen, Symon and Sessler. The interactions between the two moving ribbons of charge will, however, alter the vertical betatron oscillation frequency. This effect will occur because there will be a difference of $2x/\theta$ in distance travelled above and below the opposing bunch for an electron x cm from the equilibrium orbit (Fig. 11). At the surface of a beam 70 cm long, 0.5 cm wide and h cm thick, where $h \ll 0.5$ cm, the field strength will be 13 kV/cm when the beam current is one ampere. The net vertical impulse picked up per revolution will be (900 keV)x. This will change the vertical Q value by roughly 4 per cent, which will not lead to instability. At 2 or 3 A, however, the beams should be unstable. If ions made by the circulating beams and trapped by their electric fields were permitted to remain in the vacuum chamber, instability due to alteration of the net focusing forces by the ions would set in quickly. Clearing fields are, however, being provided throughout the vacuum chamber to sweep out these ions.

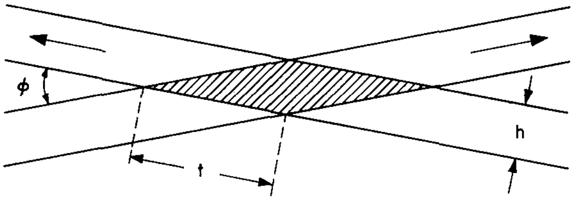

Fig. 11 Shape of crossing beams in the interaction region.

The geometry of the storage rings will permit an array of counters at angles from 35° to 90°. The differential cross-sections vary from 0.18×10^{-30} to 2.4×10^{-30} cm²/sterad in this range, and 50 pairs of scintillation or Cherenkov counters should detect a total of 3 coincidence counts/s with one-ampere beam currents. (Table II.)

TABLE II

Detection parameters

Minimum angle (c.m.s)	35°	
Number of counters	100 (max)	
$\partial\sigma/\partial\Omega$ (35°)	2.4×10^{-30}	cm²
$\Delta\Omega$ at 35°	0.18	sterad
Count rate at 35°	1.3	counts/s
$\partial\sigma/\partial\Omega$ (90°)	0.18×10^{-30}	cm²
$\Delta\Omega$ at 90°	0.62	sterad
Count rate at 90°	0.32	counts/s

TABLE III

Signal and counting rates for one counter pair. The calculations assume $A = 20\ \mathrm{cm}^2$, $L = 30$ cm, $D = 1/16$, $I = 1$ amp, $\tau = 5 \times 10^{-9}$ sec.

Process	Singles (counts/sec)		Coincidence (counts/sec)		Comments
	$\theta = 35°$	$\theta = 90°$	$\theta = 35°$	$\theta = 90°$	
e-e scattering	325×10^{-3}	23×10^{-3}	325×10^{-3}	23×10^{-3}	
Gas scattering (elastic) $p = 10^{-7}$mm	3.0	4.8×10^{-4}	negligible		Coincidence rate is proportional to p^2. Pressure should be $< 10^{-6}$ mm.
Meson production in gas $p = 10^{-7}$ mm	11×10^{-3}	11×10^{-3}	negligible		
Meson production—correlated events from π^0 and π-pairs; $p = 10^{-7}$ mm	negligible		0.2×10^{-3}	0.2×10^{-3}	Grossly overestimated because of assumption that all secondary particles are oppositely directed.
Spillout; $\lambda = 10^{-3}\ \mathrm{sec}^{-1}$	< 170	$\ll 170$	$< 3 \times 10^{-3}$	$\ll 3 \times 10^{-3}$	From dummy experiment
Cosmic rays—counters in plane containing zenith	0.2	0.2	0.36×10^{-3}	1.1×10^{-3}	
Cosmic rays—averaged over all zenith angles	0.2	0.2	$\sim 0.18 \times 10^{-3}$	0.55×10^{-3}	10^{-8} sec gates would reduce cosmic-ray counting rates a factor of ~ 3.

Backgrounds of several kinds have been estimated (Table III). Of these, the most important appeared to be chance coincidences due to electrons lost from the circulating beams. A mock-up of the storage-ring interaction region and adjacent magnets was made, and the 500 MeV linac beam was used to test the response of counters with and without shielding to electrons striking the vacuum chamber walls at various points. The measured singles rates were satisfactorily low. Adjustable metal flags will however be included in the vacuum chamber to permit control over beam dump positions.

II. PROTON STORAGE RINGS

We have studied the possibility of transferring full-energy beam pulses from any accelerator (strong or weak focusing) into storage-ring guide fields made by simple magnet shapes, and stacking many full-energy pulses in the storage rings (see Fig. 12). This approach depends critically on the development of a good ejector and injector. However, the ejection problem is simplified by the adiabatic damping as the magnetic field increases during the acceleration cycle. This allows the full energy beam to be deflected by a pulsed magnet of small aperture.

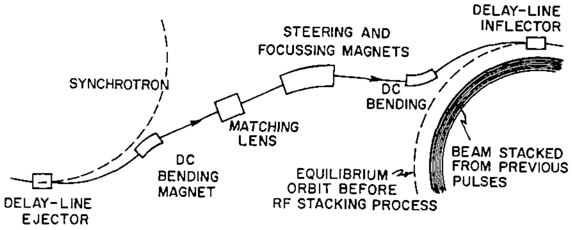

Fig. 12 Components of a separate-storage colliding-beam system.

In comparing two-way synchrotrons and storage rings of the same energy, the first question to be raised is whether there are essential differences in the circulating currents which can be set up in the two different arrangements. The following effects in particular must be considered:

(a) Interaction-region forces.

(b) Losses of particles from the stacked beams by gas scattering or nuclear interactions.

(c) The limited synchrotron and betatron oscillation phase space available at the stacking energy.

(a) was studied in connection with our experiment on electron-electron scattering. For charges travelling in opposite directions at relativistic speeds, the repulsive force is approximately twice that given by Coulomb's law for stationary charges. Consider a single particle crossing, at a small angle ψ, a cylinder of charge of radius r carrying a current I. If the crossing occurs at height x above the center of the charge cylinder, the impulse transferred to the single particle is approximately

$$M_1 = \frac{4Ixe}{\varepsilon_0 \pi r c \psi},$$

where e is the electron charge (Coulombs) and ε_0 is the permittivity of free space (farad/meter). In the normal guide field, the impulse transferred to the particle in traveling a distance y is (averaging over many magnet sectors)

$$M_2 = \frac{ecy\, B_0 x}{\bar{\lambda}},$$

where B_0 is the central magnetic field and $2\pi\bar{\lambda}$ is the betatron wavelength. Setting $M_1 = M_2$, the interaction region is a defocusing lens roughly equivalent to a length

$$y = \frac{4I\bar{\lambda}}{\pi \varepsilon_0 c^2 B_0 \psi r}$$

of the normal guide field. If two ribbons of charge of height h and width w cross in the vertical plane at angle ψ, and if the ribbons are of length comparable to the interaction straight-section length, the factor $2/\pi r$ in the expression for y is replaced by $1/w$. y can be of the order of one meter in most guide field systems without causing significant detuning, so that the circulating current I can be about two to three ampere for a 500 MeV electron system, or about 1000 A for a 3 GeV storage ring with $r \sim 0.5$ cm. This limit does not therefore appear to be serious for a large proton colliding-beam system. The space charge limited circulating current for a single beam depends in detail on the magnet and vacuum chamber cross-sections, but is in most designs of the same order or higher than the limit set by interaction-region forces.

At the very low pressures characteristic of baked-out vacuum systems [4] (10^{-9} mm or better), the lifetime of stored particles against multiple scattering, single scattering and nuclear interactions with the residual gas would be from one to several hours. Even a synchrotron of low pulse-rate (1 pulse/5s) could therefore raise several hundred pulses to the beam stacking energy within the available lifetime.

The ultimate circulating current limit set by phase space depends on the original low-energy injector, on the area in betatron phase space filled at injection time, and on the adiabatic damping of betatron and synchrotron oscillations taking place during the acceleration cycle. Finally, the circulating current density and total current depend on the betatron wavelength, momentum compaction and available radial width in the beam-stacking device. Here one must note that betatron and synchrotron oscillations damp adiabatically as $B^{-1/2}$ and B^{-1} respectively, both in fixed-field and time-varying accelerators [5, 6]. This equivalence leaves us free to make the beam-stacking device separate from the accelerator if we choose, providing that an efficient transfer system can be developed.

Beam transfer

In order to obtain efficient beam transfer, one should pulse on a uniform magnetic field of well-controlled focusing properties in a time which is small compared to one beam revolution period. This magnetic field should then be held constant for one turn. The deflected beam can then pass through a d.c. magnet capable of producing a large bending angle; identical units would be used to inject the transferred beam into the storage ring.

The delay-line inflector [7], which was designed for this purpose, consists of a ferrite-core magnet with a shaped air gap. (Figs. 5, 6, 7.) It is convenient to consider the ferrite-core magnet as having a distributed inductance of L henry/m. If the magnet is loaded with a distributed capacitance of C farad/m, it becomes a delay line with characteristic impedance $Z_0 = (L/C)^{1/2}$.

The delay time is $\tau = l\,(lC)^{1/2}$, where l is the physical length of the magnet. This delay line is terminated in its characteristic impedance and driven by a charged co-axial cable through a spark gap. After the delay time τ the magnetic field throughout the line assumes a constant value. The duration of the magnetic field is twice the delay time of the source cable. In order to bend particles of momentum p (MKS units) through an angle θ, the pulse voltage required to turn on the magnet in time τ is $V = (p\theta/e\tau)\,(w+h)$ where w and h are the width and height respectively of the magnetic gap. To minimize the required voltage V, τ is made as large as tolerable.

It must be kept small compared to a particle circulation time. Possible values for the parameters at 25 GeV are $\tau = 0.25\ \mu s$ (in order to lose only 10% of the synchrotron beam on ejection) and $w+h = 4$ cm. A single magnet with a pulse voltage of 20 kV would produce a bending angle of 0.12°. Three such magnets, operating in series on the beam but in parallel electrically, could displace the 25 GeV beam by 9 cm into the gap of a d.c. magnet for further deflection. Although the delay-line inflector is limited to a peak field of about 3 kG by ferrite saturation, the straight-section lengths required for the inflector are not excessive. At 25 GeV the 3-section magnet needed for a 9 cm beam deflection would be only 6 ft long, and would weigh about 200 pounds. Such a mass could easily be moved into position during the acceleration cycle of a large synchrotron. The high-voltage power supply to charge the co-axial cable for driving the inflector would need to deliver only 200 W.

It is important to note that *no* betatron oscillations need be induced by such a process, and that the beam would emerge from the synchrotron within one revolution period with almost no loss of particle density. This is in contrast to existing methods of high-energy beam deflection, which lose most of the original particle density through scattering (as in the Brookhaven 3 GeV ejector), or through the excitation of large betatron oscillations (as in the regenerative extractor system).

Small errors in pulse height applied to the deflectors would cause no loss of density in synchrotron-oscillation phase space, because these magnets would not affect particle energy. The small increase in radial betatron oscillation amplitudes caused by such errors would not, in most simple beam-stacking systems, affect the current density in ordinary coordinate space.

Experimental results on inflector

A delay-line inflector magnet, 10 cm long with a 1 cm vertical aperture, has been built to operate at a characteristic impedance of 10 ohms. It is pulsed through a triggered three-element spark gap from a 10 ohm cable charged to 50 kV. The delay cable provides a pulse 100 mμs long, 25 kV high. With these parameters the magnetic field in the gap of the inflector reaches a peak of 3 000 G. The delay time through the inflector is 50 mμs and its contribution to the rise time (due to the lumped-constant condensers used in place of true distributed capacity) is less than 20 mμs. Although the inductance of the spark gap distorts the rectangular pulse which should be applied to the inflector, the observed pulse shape on the terminating resistor beyond the inflector is almost identical to that which is applied at the inflector input. (Fig. 13.) The magnetic field within the gap, as measured by a shielded one-turn pick-up coil and integrating network, follows the applied signal with little distortion. As expected, the behavior of the inflector as a circuit element is linear both for 200 V and 25 kV pulses. Since these oscilloscope pictures were taken, a low-inductance high-pressure spark gap has been built which gives better pulse shapes than those shown.

Injection

The particles to be stored would pass through the following sequence : acceleration in the synchrotron, delay-line deflector, d.c. ejector, steering magnets, d.c. injector, delay-line inflector. During the interval before the next acceleration cycle, the newly injected pulse could be stacked next to previously stacked beam pulses at the far side of the vacuum chamber.

The practical circulating current limits for concentric storage rings (CSR) of 3 GeV and 25 GeV, assuming no stacking in the available radial or vertical betatron phase space, appear to be 3 to 50 A at the lower energy, and 10 to 60 A at the higher, depending in each case on how closely the accelerators can work to their theoretical current limits, and on practical efficiencies of beam transfer. In the case of injection from a spiral-ridge FFAG accelerator, or from a weak-focusing synchrotron of large aperture, it would probably be possible to achieve somewhat higher circulating currents by stacking in betatron phase space at the original injection energy. Injection from a high-current linac of 20 to 50 MeV would permit much better use of the available phase space than would Van de Graaff injection, because the small energy spread of a Van de Graaff cannot be matched by a synchrotron separatrix except at unreasonably high RF harmonic orders. For most practical designs, it appears that a few hundred pulses from an accelerator would fill a storage ring.

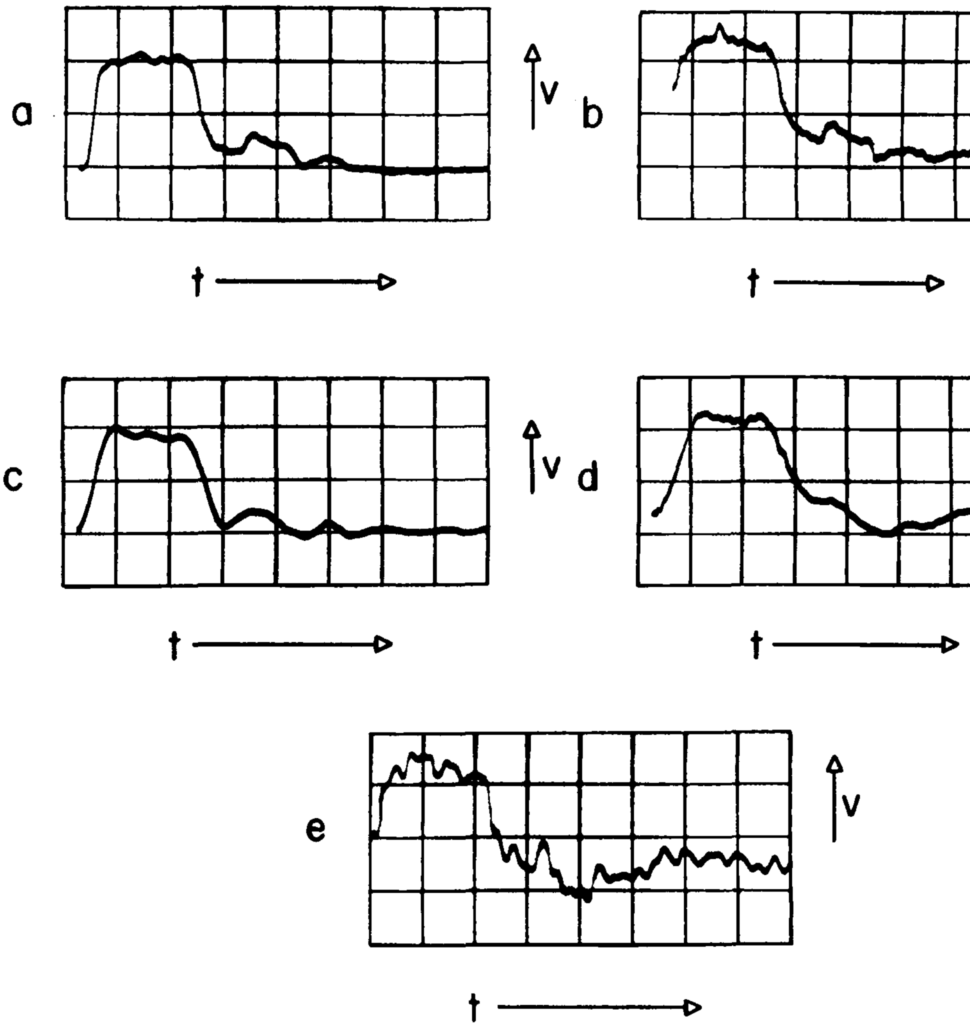

Fig. 13 Behavior of a delay-line inflector driven by a 10 ohm cable. The pulse length is 100 $m\mu s$. (a) Cable discharged into a 10 ohm resistor. (b) Same, except delay-line inflector interposed between switch and resistor. (c) Same as (a) except 25 kV pulse, with spark switch substituted for mercury switch pulser. (d) Same as (c), except inflector inserted before terminating resistor. (e) Magnetic field in gap of inflector, observed by shielded loop with integrating circuit, through oscilloscope amplifier. Traces (a) through (d) are observed directly on oscilloscope plates.

Storage ring design

Several geometries are possible for the storage rings in which the accelerated particles would be stacked. For maximum utility in carrying out experiments, it is desirable that several easily accessible interaction regions be available simultaneously. In these regions, the vacuum chamber should have a small cross-section, and the nearest guide field magnets should subtend the smallest possible solid angle.

The two-way FFAG synchrotron design of Ohkawa[8] satisfies the first requirement, having several experimental areas. An improved storage ring geometry, (suggested by a consideration of the advantages and limitations of the Ohkawa design) has been developed[9] (see Figs. 14, 15). In this CSR design, each beam particle would travel through the following sequence: a sector of radius R_1, a straight-section of length l, another sector of radius R_2 and another straight section (also of length l). In the Ohkawa design, it is necessary to use reversed field magnets in order that two beams may circulate in opposite directions in a single guide field containing a wide momentum spread. Consequently, the Ohkawa synchrotron has a large circumference factor. In the CSR no reversed field magnets are used. The

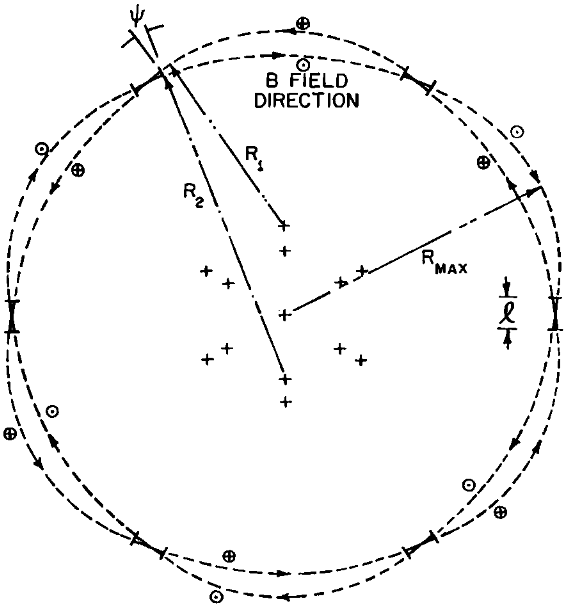

Fig. 14 CSR plan view.

momentum spread contained in the CSR can be small, because acceleration takes place in the separate guide field of the injecting synchrotron. For these reasons the magnet weight in the CSR design is reduced from that of the Ohkawa synchrotron.

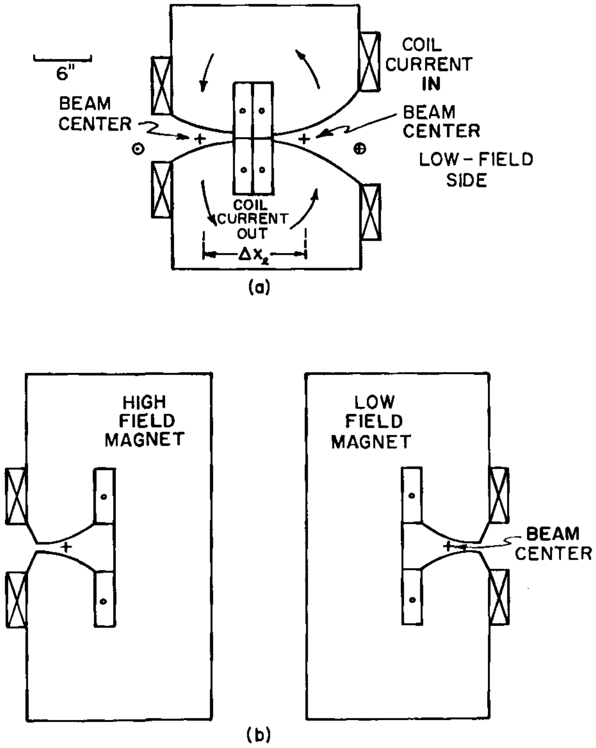

Fig. 15 CSR magnet cross-section.

CSR parameters

The ideal design would have a large number of long straight sections and a small beam crossing angle. In the choice of design parameters, however, it should be noted that the separation between the circulating beams at the end of each straight section, ΔX_ℓ (see Fig. 16), must be large enough to permit placing magnet coils between the circulating beams at the magnet ends. For a given straight section length, this sets a minimum value on the beam crossing angle ψ, and hence on the circumference factor.

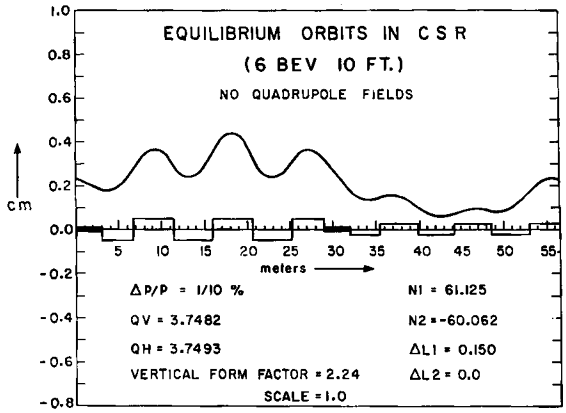

Fig. 16 Computed orbit in CSR of simplest form. Heavy lines in cell structure are straight sections.

With the notation of Table III, an approximate formula for the circumference factor is

$$C.F. \cong 1+\frac{\sin(\psi/2)+l/2R_1}{\sin(\theta/2)}.$$

The physical size of a CSR would exceed by about 25% that of a conventional synchrotron, having the same number and length of straight sections, and limited to the same peak magnetic field. Parameters for three possible CSR designs are listed in Table IV. W_S+W_{CSR} is the total magnet weight including that of the injecting synchrotron.

Recently E. J. Woods and P. Herzberg have written a set of flexible programs for computing CSR orbits on an IBM-704. These are:

(1) Necktie plotting. This program computes vertical and horizontal Q values, β's, and form factors

TABLE IV

Parameters for possible colliding-beam designs.

Parameter	CSR	CSR	FFAG	CSR	Unit	Remarks
Energy	3	15	15	25	GeV	
T_E	30	540	540	1500	GeV	
$r_{\max}$	16.8	74	183	114	meter	
$B_{\max}$	11	11	18	11	kgauss	(a)
Circumference factor	1.45	1.35	5.8	1.25		(b)
N	6	8	4	8		(c)
Straight section length	1.8	4.9	9.5	6.1	meter	(d)
Crossing angle	0.29	0.155	0.18	0.126	radian	
Δx_I	0.27	0.38		0.38	meter	(e)
Superperiods/revol.	3	4	2	4		
Radial betatron wavelength	26	70	40	116	meter	
Vertical betatron wavelength	24	64	226	107	meter	
W_{CSR}	600	4 300		7 000	ton	(f)
$W_S + W_{CSR}$	950	6 700	65 500	11 000	ton	(g)
W (Iron alone)	900	6 200	65 200	10 000	ton	
W (Copper alone)	50	500	3 000	1 000	ton	
Power	2	10	45	15	MW	
Vacuum chamber	5×15	5×15	15×480	5×15	centimeter	(h)

(a) Held to 11 kG in CSR to permit varying energy without changing interaction region position.
(b) Should be doubled if CSR located outside synchroton.
(c) Number of straight sections available for intersecting beam experiments.
(d) Interaction region located close to one end in FFAG case.
(e) Orbit separation at ends of straight sections.
(f) For 15 GeV CSR, magnet cross section same as BNL 25 GeV synchroton.
(g) Total weight of synchroton plus CSR.
(h) Vacuum chamber is double walled in FFAG case.

for any given $N1$, $N2$ point. $N1$ and $N2$ are the n-values in the focusing and defocusing sectors.

(2) For specified values of Q_V and Q_R, this program finds the corresponding $N1$ and $N2$, computes β's and form factors, then varies one of the geometrical parameters by a small increment and repeats. In this way form factor optimization can be carried out for fixed Q_V and Q_R.

(3) In linear approximation, this program plots equilibrium orbits when fed either a Q_V, Q_R point or an $N1$, $N2$ point.

(4) A non-linear program which calculates particle orbits by integrating the equations of motion step-by-step around the CSR. This has been checked against (2) and (3) for small momentum deviations.

Courant and Terwilliger have each suggested a modification of the CSR cell structure which should add greatly to its experimental usefulness. By the addition of quadrupole fields, the equilibrium orbits in a CSR can be made to cross at the centers of the straight-sections. Our program (3) was used to find the phase and amplitude of a 6th-harmonic quadrupole perturbation producing point crossings of all equilibrium orbits in a CSR (Figs. 16, 17). This came out of a very brief search, and will be checked and followed up by the non-linear program (4).

All of the programs used so far are limited to only six magnets between straight sections. This is a much coarser structure than should be used, and makes

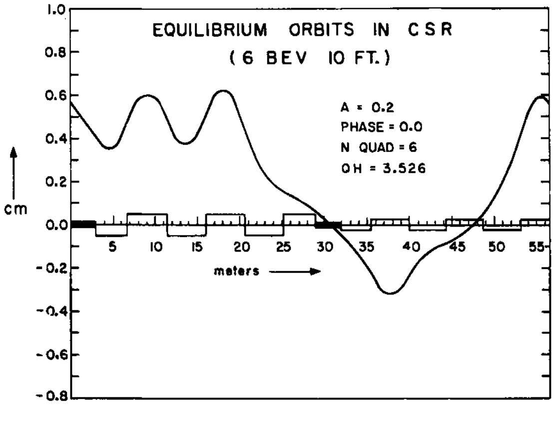

Fig. 17 Computed orbit in CSR with 6th harmonic quadrupole perturbation.

form factors rather poor. Even so, it appears possible to make straight sections quite long in a CSR. We have concentrated recently on a design for 6 GeV, in which acceleration of the stacked beam from 3 to 6 GeV would take place within the CSR over a period of 30 s or more. In this case, for a given Q_V, Q_R point the form factors were calculated to change by only 5% when straight section lengths were increased from 2.5 m to 4 m. At 6 GeV, with 3 m straight-sections, a typical operating point would be $N1 \approx N2 \approx 60$, $Q_V \approx Q_R \approx 3.75$, with form factors of about 2.2. The present programs will, of course, be improved to deal with fringe fields, extra magnets and additional straight-sections.

Our conclusion from these design studies and inflector tests is that the construction of storage rings in the 6 to 30 GeV range should not be difficult, and that it is not necessary to lose much phase density in the transfer process. It appears that a construction project no larger than those now being completed would permit experiments at lab. equivalent energies nearly two orders of magnitude higher than will be available in 1960.

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DISCUSSION

Pentz: I want just to make an observation on the cost of the linac storage ring alternative to a two-way FFAG accelerator for electrons. We have guessed that at 100 MeV the cost of such a system would be about 4 or 5 times the cost of a two-way FFAG, including in both cases building and staff. I think that if one pushed the energy up to the neighbourhood of 200 MeV the two-way FFAG alternative would become more expensive than that of a linac and storage rings.

I would like to ask O'Neill a question if I may, and that is whether they have actually baked ferrites at 400°C and measured their properties before and after baking, and, if so, with what results; and, on the same point, whether they have measured out-gassing rates from ferrite surfaces and with what results?

O'Neill: Yes. We took a piece of ferrite whose RF properties had been measured and put it into an ultra-high vacuum system and baked it. We got rather peculiar results. We baked it three or four times and each time we were impatient, we waited for the system to cool down, pumped for a few hours, and then wondered why the pressure was never less than about 10^{-8}mm Hg. However, we then got a little more patient, and took the ferrite and only baked it out once but were then willing to pump for two days and when we did that the pressure went down to rather less than 10^{-9} mm Hg, and the out-gassing from the ferrite was essentially in the same range as that of the already baked-out, clean stainless steel of the rest of the system. The second question was what the RF properties were like. They were identical after bake-out, as I think one would expect, since the ferrites are, after all made at far higher temperatures than 400°.

Kolomenskij: With storage of electrons at energies of several hundred MeV there is the important advantage of the radiation damping caused by intensive classical radiation. I have not understood well what O'Neill intends to use in proton storage-rings instead of this radiation damping. I have read

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(*) See note on reports, p. 696.

(**) Internal memoranda not generally distributed but possibly available from author.

and have heard at the previous conference the ideas of O'Neill about foils. I think this is not an effective method, but I want to hear O'Neill's opinion of this.

There is a great difference between the magnitudes of the currents in O'Neill's storage ring and Pentz's machine. Is it explained mainly by the difference in energy, or are there other factors?

If I understand correctly, the most dangerous phenomenon in the Stanford storage ring is bremsstrahlung. I would like to ask O'Neill if he and his collaborators have taken carefully into account the influence of damping when considering this effect. I think that multiple scattering of the residual gas would be dangerous too, but it is greatly diminished by the damping. What is the situation with bremsstrahlung?

O'NEILL : The first question, as to the suggestions I made three years ago on the use of foils for damping, can be answered very quickly, namely that they were wrong. At the time that I gave this discussion at the CERN Conference 1) I mentioned that the only kinds of foil systems that we had looked at so far did not work but that we were still trying to find a system which would. In the next few weeks, fortunately, Symon and his collaborators were kind enough to develop a general theorem which proved to us that we could never find such a solution, so after that we contented ourselves with solving the problem in the same way that the people who built FFAG machines must solve it, namely by attempting to conserve the phase-space as carefully as possible—to stack in phase-space. However we have not found any successful equivalent of the radiation damping which exists for electrons.

On the question about the magnitude of the stacked current I should point out that in the case of the Princeton - Stanford experiment, our interest is in the physics of the electron scattering interaction. One ampere is plenty for us to do the experiment. Now we will indeed try to go up to the space charge limit, whatever that is. Our own calculation has indicated that it would be a few amperes. I am a little surprised that it is in Pentz's case as high as he indicates. The third question was, as I recall, why, since we have radiation damping, we are troubled at all by the bremsstrahlung. Multiple bremsstrahlung does not do any harm, as you say, because there is radiation damping. However, there is a small but finite probability that in one event there would be a radiation of so much energy that the electron would be taken outside the RF bucket and lost, and it turns out that one is allowed to go, as I recall, about seven radiation lengths before this happens. Similarly, multiple gas scattering should cause no trouble in an electron storage ring, but large angle single scattering can cause losses.

SYMON : I have a comment which may bear on the second question which was asked in attempting to compare storage rings with FFAG machines. There is one difference between the problem of stacking in a storage ring and stacking in an FFAG machine which may or may not be fundamental, but which I think is worth pointing out. If you assume that there is some limiting energy spread which you will allow in the stacked beam and, if you assume some factor—we usually take a factor between 5 and 10 as a safety factor—in preserving the phase-space density, and calculate the theoretical maximum number of pulses or the maximum current density which you can stack, then in an FFAG accelerator—or in fact in any accelerator—this quantity depends upon the energy spread of the initial beam which is picked up by the RF system. It does not depend upon the energy spread at the stacking point. Now, in an FFAG accelerator you pick up the beam at the injector. Hence, it is the energy spread at injection, say 0.1%, which determines the phase density. However, if you stack in a storage ring, you are picking up the beam with the RF at the full energy. If you assume that you can do this with a precision which is again 0.1% of the final energy, you will get a much lower theoretical density. Now, whether or not this is fundamental depends upon whether one can find ways of keeping the energy width of the transferred beam very small and ways of starting up the RF voltage in very precise synchronism with the transferred beam. We have done some recent studies which suggest that there may be difficulties here. There are interactions between the beam and the cavity which increase the energy spread of the beam and which may make a fundamental difference between the two places at which stacking may be carried out.

PENTZ : Kolomenskij should also keep in mind, in making a comparison between a weak focusing storage ring and a strong focusing FFAG, precisely that the latter is strong focusing, and consequently that the space-charge limit is higher. Also in estimating whether you are near a given space-charge limit with a given stacked charge you have to take into account the point which Symon has just mentioned, which includes the radial spread of the beam. This may well be larger in our case than in the case which has been discussed by O'Neill.

LAWSON : I should like to ask whether O'Neill or Symon have given much thought to the detailed nature of the perturbation in the interaction region. The force seen by a single electron or proton depends on the total beam configuration. Furthermore, it depends on the position of the particle in the bunch, and is non-linear. To determine the beam profile one must solve a quite complicated self-consistent field problem. It may turn out that the " effective periodicity " is many revolutions, and that the betatron oscillation amplitude is rather large. Further, any noise due, for example, to beam fluctuations, will tend to make the betatron oscillation amplitude build up, and for long storage times this might be serious. In the electron machine any noise in the RF system will contribute to the anti-damping, and might influence the beam diameter. I do not know whether these effects are at all serious, but I wondered whether they had been looked into.

E. D. COURANT : I have a comment about the electron scattering experiment. You said that at 500 MeV you are depending on the radiation damping to move your beam to where you want it but that you wanted to be able to do the electron scattering experiment at energies below 500 MeV, down as low as 100 MeV. Now there you would hardly get this effect. Do you plan to use RF acceleration as you discussed for the proton case, or how do you propose to do this?

O'NEILL : Courant is, of course, quite right. It would be very impractical to inject into a storage ring at 100 MeV in the way that I have described for 500 MeV. If we are able to do the experiment at 100 MeV it will be because we have injected at 300 to 500 MeV and then with the RF system left on very slowly decrease the magnetic field, so slowly that the beam has time to radiation damp. In that case the radiation damping has only to make up for the adiabatic undamping as we run the field down, but even when the characteristic times are of the order of seconds one still has plenty of time to turn down the field.

I shall try to answer the questions raised by Lawson. As for the first question, we have not done any non-linear calculations. Our only calculations have been of two kinds: in the first, one checks the first order change of the equilibrium orbit depending on whether a particle is at the leading edge or at the centre of the circulating bunch; the second is a simple kind of transverse instability calculation based on linear theory. We have also checked the incoherent multiple scattering of one beam by the other, and found it small. Perhaps the MURA people have done more than that. As for the noise, we must recall that in a big proton colliding-beam system, particularly a storage ring, the RF acceleration system is on for only a very small fraction of the time. In fact, it is on for a period of perhaps a millisecond about 200 or 300 times and after that is turned off for the duration of the beam lifetime. So, from that source, at least, it is hard to see that where will be any significant introduction of noise.

PANOFSKY: I think there was a misunderstanding in the last question of Lawson, namely that in the electron case the storage time had some relation to the build-up caused by noise. The time which is important here is the damping time. The noise only gets integrated over the damping time — not over the storage time — and that is only 10 ms.

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