THE STORAGE-RING SYNCHROTRON *

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The usefulness of very high energy accelerators is limited by the fact that the energy available for creating new particles is that measured in the center-of-mass system of the target nucleon and the bombarding particle. In the relativistic limit, this energy rises only as the square root of the accelerator energy. However, if two particles of equal energy traveling in opposite directions could be made to collide, the available energy would be twice the whole energy of one particle. The MURA group has emphasized the advantages to be gained from such an arrangement, and in particular of building two FFAG accelerators with beams interacting in a common straight section[1].

The general interest in the use of interacting beams has, in recent months, prompted at least three independent proposals for machines in which the functions of particle acceleration and of beam storage are separated[2,3,4].

In the scheme which has been worked on at Princeton, two "storage rings", focusing magnets containing straight sections one of which is common to both rings, would be built near the accelerator. These magnets would be of solid iron and simple shape, operating at a high fixed field, and so would be both smaller and much cheaper than that of the accelerator at which they would be used. The full-energy beam of the accelerator would be brought out at the peak of each magnet cycle, focused, and bent so that beams from alternate magnet cycles would enter inflector sections on each of the storage rings. In order to prevent the beams striking the inflectors on subsequent turns, each ring would contain a set of foils, thick at the outer radius but thinning to zero about one inch inside the inflector radius. The injected beam particles would lose a few Mev in ionization in the foils; so their equilibrium orbit would shrink enough to clear the inflectors after the first turn. After several turns, the beam particles would have equilibrium orbits at radii at or less than the inside edge of the foils.

The possibility exists of storing a number of beam pulses in these storage rings, since space charge and gas scattering effects are small at high energies. Preliminary calculations have been carried out on a hypothetical set of storage rings for the 3 Gev, 20 cycle per second Princeton-Pennsylvania proton synchrotron. Since the storage rings would be simple and almost entirely passive devices, their total cost would only be a small fraction of the cost of the accelerator itself. For example, it was estimated that a pair of storage rings operating at 18,000 gauss with a $2'' \times 6''$ good-n region would weigh a total of 170 tons. The magnet of the synchrotron itself would weigh 350 tons, and would be of much more expensive laminated transformer iron. The total cost estimated for both storage rings, with dc generators, coils, foundations, vacuum chambers and a building, was 20% of that of the synchrotron. In the event that one could obtain an average current of 1 microampere from the synchrotron, and an average particle lifetime of a few seconds for the storage rings, there would be about 1000 strange-particle-producing reactions per second at each of two beam crossover points, for an estimated 1.5 millibarn total cross-section. The center-of-mass energy, 7.8 Gev, would be equivalent to that of a 31 Gev conventional accelerator. If storage rings could be added to the 25 Gev machines now being built at Brookhaven and Geneva, these machines would have equivalent energies of 1340 Gev, or 1.3 Tev. The use of storage rings on electron synchrotrons in the Gev range would allow measurement of the electron-electron interaction at center-of-mass energies about 100 times as great as are now available. The natural beam damping in such machines might make beam capture somewhat easier than in the case of protons.

Preliminary calculations indicate that the major difficulties in the use of storage rings of this design may result from the amplification of radial betatron oscillations by the slowing-down foils. The problem can be solved analytically for the case of a foil whose thickness changes linearly with orbit radius. For a positive linear taper betatron oscillations are undamped and synchrotron oscillations (if an rf is present) are damped, both with the same time constant. The effects are reversed with a negative taper. A result which may be of interest is that a positive taper would allow continuous irreversible capture of particles by a fixed-frequency, fixed-amplitude rf system. This capture would be at the expense of a slow increase in radial betatron oscillations. The problem of betatron oscillations has been set up for an electronic analog computer, and several combinations of non-linear foils have been examined. One combination of non-linear foils which should damp both betatron and synchrotron oscillations, at least over a certain range of amplitudes, has been found. Further work will be required to find

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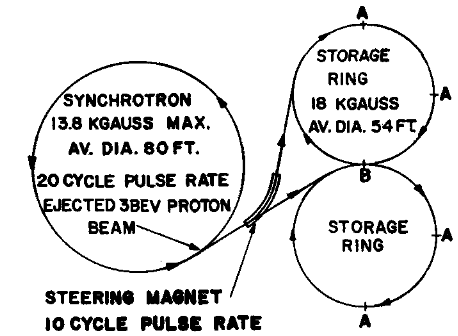
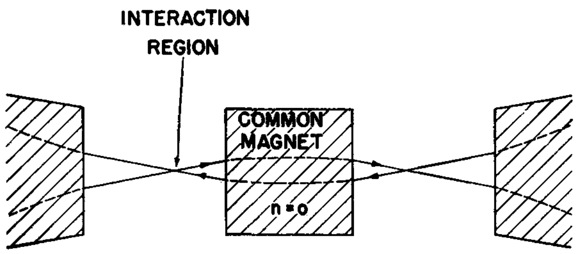
whether this or other foil combinations can damp both kinds of oscillation over every range of interest.

A final design for the storage-ring foil system will depend on more thorough calculations, probably with the help of an electronic computer. At present, the tentative design includes a set of thick tapered foils to allow clearing the inflector; two inches closer to the machine center there would be a thin movable foil, to reduce betatron oscillations and move the injected protons away from the outer foils. Injection could occur over a period of about 20 turns, and the second foil would be removed after thirty. During the 0.1 seconds or 600,000 turns before the next beam pulse, the most recent proton group would spiral in due to ionization in hydrogen jets, until captured by a low-power rf system.



Professor M. G. White has pointed out a possible alternative method of beam transfer from synchrotron to storage rings. In this plan H^- ions would be accelerated to 3 Gev, and the stripping of the weakly-bound extra electron by a thin gas jet would cause ejection of the neutral H atom to the storage ring, where stripping of the second electron would permit the protons to circulate for a very long time. Successful operation of such a method would require a very high vacuum in the synchrotron.



LIST OF REFERENCES

1. Kerst, D. W. et al. Attainment of very high energy by means of intersecting beams of particles. Phys. Rev., *102*, p. 590-1, 1956.
2. Brobeck, W. M. The design of high energy accelerators. See p. 60.
3. O'Neill, G. K. Storage-ring synchrotron: device for high-energy physics research. Phys. Rev., *102*, p. 1418-9, 1956.
4. Lichtenberg, et al. (private communication.)

DISCUSSION

V. I. Veksler: In his calculations on the stability of orbits did Kerst take into account Coulomb repulsion for such high density of particles which is needed in systems with intersecting ion beams?

D. W. Kerst: We have worried about this problem but have not carried out complete calculations. Simple particle dynamics does not hold in this case. If we have the collection of + and − ions in a stationary field, the local field gradient is changed. However, we do not yet know precisely what happens. There are two ways of approach to this problem, theoretical investigations and models, and we try to use both of them. In the case of intersecting beams if we can establish that a stable current distribution exists, we will know the resonance behaviour and the equivalent non-linear bumps will also be understood. (Bunches of radio-frequency accelerated particles give repetitive bumps and a single bump occurs in the case of intersecting beams.) The calculations were done only for perfect vacuum, relativistic velocities and high number of particles.

G. Salvini: When we have 2 beams, one of positive particles and one of negative particles (travelling in opposite directions), can we expect extra focusing by the magnetic field of one beam acting on the other, or will the particle simply collapse?

D. W. Kerst: There is extra focusing, but we do not know to what extent.

T. A. Welton: I would like to draw attention to the fact that it is not sufficient to consider Coulomb repulsion as such, but also the displacement of the working point due to these forces, possibly driving tino a resonance line.

D. W. Kerst: This is a different problem and tuning may be needed as a function of current.

P. B. Moon: Little help to the focusing situation will be provided by electrons because they escape through their own oscillation between passages of successive proton bunches.

V. I. Veksler: Has Symon considered the situation when in storage systems two beams of nearly equal velocities move side by side. It is known that this gives rise to turbulence in phase space (as in travelling wave tube with electron beams).

K. R. Symon: Yes we have studied this problem and are continuing our studies. Preliminary computations show that the turbulence in phase space is not bad, provided the buckets are brought up correctly. The interactions of the R.F. with betatron oscillations are more serious.

M. H. Hamermesh: Did you consider the motion of relativistic beams and the effect of collective interactions on the stability of the beams?

In the relativistic region the repulsion forces will be reduced. However, to get there it is necessary to cross the non-relativistic region where the repulsion forces do not compensate. How do you estimate the maximum current in both regions?

K. R. Symon: Computation of maximum current have been carried out at the injection energy which is the most critical region for these forces.

A.A.Kolomenski: What is the criterion for high vacuum for construction of the above accelerator (described by Symon?)

K. R. Symon: Scattering is important in the low energy region. In some proposals which involve slow acceleration of buckets in the low energy region (that is the buckets remain for a long time in the low energy region) a vacuum of 10^{-6} would be satisfactory from the point of view of multiple scattering.

A. A. Kolomenski: We have heard very interesting papers about FFAG accelerators. There can be no doubt that the use of constant magnetic field has a great future. This is especially true in the case of a ring accelerator with constant magnetic field.

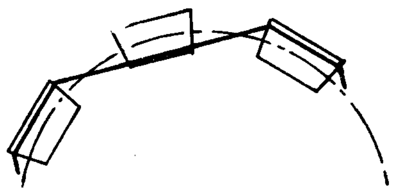
This fact already attracted the attention of Russian physicists some time ago. Early in 1953 together with V.A. Petukhov and M.S. Rabinovich I suggested a new accelerator which we called "ring phasotron" (see Lebedev Physical Institute Report, Moscow, 1953 and other Soviet publications). This accelerator provides a stable acceleration regime (strong focusing) up to high energies in a narrow ring with a constant magnetic field. The directions of the field in adjacent sectors are reversed, and therefore this accelerator belongs to the so-called radial sector type (to use the terminology of the MURA group). Then with my collaborators I made calculations in order to establish the stability of betatron oscillations and that of the acceleration regime in such a system which may be built in different forms.

A few words about the modified accelerator with a constant magnetic field which I proposed and which could be named " ring cyclotron".

If besides H = const we have also W = const (where W is the frequency of rotation) we evidently get a continuous acceleration in such a system (line in a cyclotron) and the particle beam intensity can be (in principle) considerably increased. This system may be obtained by combining periodical elements of two types of the above mentioned ring phasotron. In the first type the orbit radius decreases with the increase of energy ($d < 0$), in the second one it gets larger ($a > 0$). The parameter α is defined by $\delta\Pi/\Pi = \alpha\ (\delta p/p)$, where Π is the orbit length and p- momentum.

Let us consider for instance the case of a relativistic cyclotron which in its simplest form may consist of two rings (in one $\alpha > 0$, and in the other $\alpha < 0$) coupled in form of an "8". With the increase of energy in such a system Π = const. The point of connection of the two rings may be chosen in such a way as to be located in straight sections. Such a system perhaps could also be used for obtaining intersections of particle beams.

L. W. Jones: In our Mark 4 accelerator we have employed sections with alternating sign of the momentum compaction factor.



With this scheme it is possible to obtain almost any transition energy.

M. Sands: Experimental evidence on the instability of high intensity circulating beams of electrons in the 500 Mev Cal Tec synchrotron was observed. Focusing forces vanished in either direction for beams of 10^{10} electrons and pressures of 10^{-5} to 10^{-6} mm. Hg. Electrons were lost on the vacuum chamber walls. No theoretical explanation is known.

K. Johnsen: Symons pointed out that the density in phase space is constant when one treats the beam adiabatically. There are several cases where one deliberately makes the beam behave non-adiabatically; in these cases also, the density in phase space stays constant. One then tries to treat the beam linearly in order to facilitate the recovery of the bunches into the wanted shapes. Typical examples are the buncher at linac input, the debuncher at the end of linac, and the phase transition, where we tilt the whole bunch in phase space and tilt it back when we come again into an adiabatic region.

G. K. Green: In treating phase space areas, one is tempted to draw figures of constant area and little varying shape. But in reality in a machine the shape is quickly turned into a complicated form, which for the Cosmotron looks like a U or an S, the ends of which are chopped off because they fall out of the stable region. All machines do so, and this results in heavy losses of particles.

V. I. Veksler: Regarding the instability of beams in electron synchrotrons as mentioned by Sands, I would like to mention that bremsstrahlung of electrons on the residual gas will increase the area of the beam in phase space.

M. Sands: Although we have not studied the effect of bremsstrahlung, we do not think it a sufficient explanation, because the phenomenon is very pressure dependent and depends on the sign of the derivative of the magnetic field with time. When the magnetic field is increasing, we have vertical instability. When it is decreasing we have the other kind of instability.

R. F. Bacher: The motion of the beam in the electron synchrotron of Cal Tec was detected by the visible radiation, emitted by the beam at high energies. One observes vertical oscillations, then oscillations in both vertical and horizontal directions. The beam did not defocus and covered in its movement nearly all the aperture, but its oscillations were still contained because the vacuum chamber was large enough. This was discovered towards the end of operation at 500 Mev as vacuum troubles occurred. We tried different gases, the effect set in at different pressures according to the gas. Moreover, the pressure varied around the azimuth of the machine, so that plasma oscillations could be excited at the right frequency to couple into betatron oscillations.

J. D. Lawson: I would like to know if the intensity of light radiated from the electron synchrotron is in accordance with theory.

M. Sands: The intensity of total radiation was not measured. Visible radiation seems to have remained constant as expected from classical theory. Also the total energy loss agrees with theory.