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A LIST OF EXPERIMENTS AND EXPERIMENTAL APPARATUS FOR A 2 MeV STORAGE RING.

I. Introduction.

An attempt has been made to list some types of experiments that might be undertaken with the electron storage ring, presently being considered by the Accelerator Research Group of CERN.

The ultimate aim of such a list is to stimulate thought along these lines, and to call attention to the types of experimental apparatus that must be incorporated into the design of the storage ring.

II. Types of Experiments.

A list of several types of experiments and some of their specific capabilities is given below. The experiments are described in some detail in the next section.

1. Mechanical Probe Experiments.
   a. Position measurements on beam
   b. Betatron oscillation amplitudes.
   c. Destructive measure of beam current.
2. R.F. Knock-out Experiments.
   a. Betatron oscillation frequencies.
3. Induction Experiments.
   a. Non-destructive measure of stacked beam current.
   b. Azimuthal structure of beam.
   c. Arrangement of particles in R.F. bucket.
4. Spillout Experiments.
   a. Arrangement of particles in R.F. bucket.
5. Phase Space Sampling Experiment.
   a. Phase space density of stacked beam.

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Of course many experiments will involve the correlation of these experiments with various manipulations of the operating parameters. For example, the measurement of the rate of growth of the betatron oscillation amplitude due to multiple scattering, and/or radiation antidamping might involve several measurements of the amplitude (Exp. 1b) at slightly different times. As another example, one might study the effect on the arrangement of particles in an R.F. bucket (Exp. 3c, 4a) of some artificially introduced noise on the R.F. programme. Or one might study the effect on the phase space density (Exp. 5a) of passing empty R.F. buckets through the region of a stacked beam.

No attempt is made to include a description of the large number of such studies that present themselves. With the ability to perform the experiments on the list, a wide variety of studies may be accomplished.

The virtue of this list of experiments lies not in its completeness, but in its ability to guide us to a minimal set of experimental apparatus to be incorporated in the design of the storage ring.

III. Description of Experiments.

1. One finds many uses for a variety of mechanical probes in the investigation of a circulating electron beam.

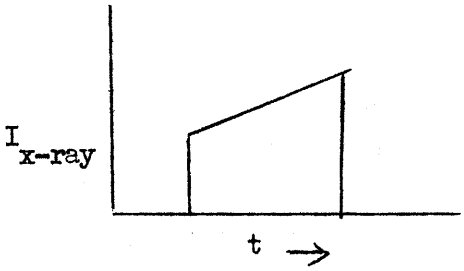
They provide a simple means of destroying a selected portion of the circulating beam, that portion intersecting the probe, and hence yield information on the position of the beam, amplitude of betatron oscillations and some measure of beam current.

The destruction of the beam may be detected by observing the charge collected on the probe, the decrease in the circulating beam, or the X-rays produced by the electrons which strike the probe.

One might describe a stationary-probe experiment as one where the probe is fixed for the duration of the experiment and the beam is moved upon the probe, thus being destroyed. Radial motion of beam may be produced by R.F. acceleration, betatron acceleration, or a forced oscillation on the equilibrium orbit, whereas only the forced oscillation method seems convenient for vertical displacement of the beam.

By observing the charge collected, or the X-rays produced, one is provided with a destructive measure of beam current.

By observing the X-ray intensity as a function of time, and knowing the rate of motion of the beam [*], one obtains information on the amplitude of betatron oscillations. As an example, an X-ray intensity as a function of time like the following,



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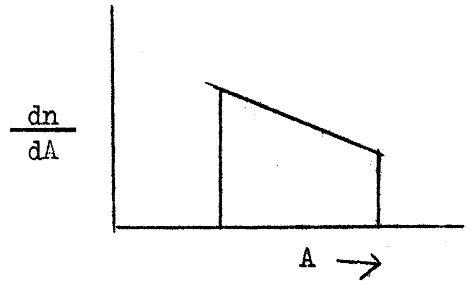

where dn/dA is the number of particles per unit of betatron oscillation amplitude.

One might define a <u>slow-moving probe experiment</u> as one in which a probe moves a very small distance in one period of the acceleration system. One use of this technique provides a convenient measure of the distribution of particles with vertical betatron oscillation amplitudes. Consider a storage ring in which particles are injected and accelerated onto a target at the repetition rate of the system. The intensity of each pulse can be measured by the intensity of X-ray produced at the target. A slow moving vertical probe can be used to scrape off particles with vertical oscillations greater than Y . By changing Y slowly, the intensity of the beam which reaches the target changes such that:

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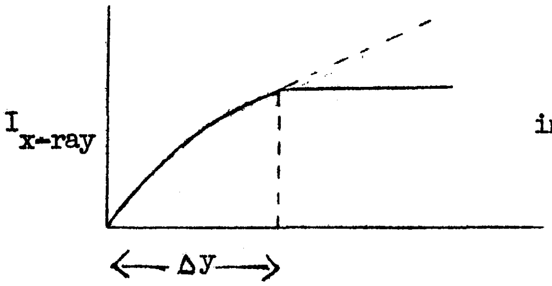
[*] In order that this measurement be meaningful, two conditions must be met. The first being that the radial spread of the beam due to the energy spread must be small compared to the maximum amplitude of betatron oscillations. Secondly, the rate of motion of the beam should be such that the particles pass the probe a large number of times while the beam is moving by 1/10 the maximum betatron amplitude. This condition makes it highly probable that the particle will strike the probe and produce X-rays at a time when the equilibrium orbit and the probe are separated by 90 - 100 o/o of its betatron oscillation amplitude.

$$I_{x\text{-ray}} \sim \int_0^Y \frac{d\,n}{dA_y}\, dA_y$$

where dn/dA_y is the population of particles per unit of vertical betatron oscillation amplitude.



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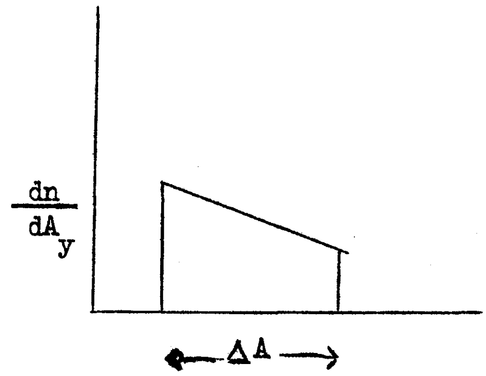


A slow-moving probe may be used in conjunction with a stacked beam if a non-destructive measure of the stacked beam current is available.

A fast-moving probe might be defined as one which could move from outside the beam to the centre of the beam in something like 10^{-3} sec. This would allow the rate of destruction of the beam, and hence the population of the betatron oscillation amplitude, to be correlated with intensities of X-rays produced by the probe.

This technique presents some engineering problems which are complicated by the requirements of the vacuum system, and by the limited space available.

2. R.F. knockout experiments are adequately described elsewhere (MURA 133, 260, MURA-KMT-3). They consist essentially of the application of either radial or vertical R.F. electric fields in the vicinity of a beam of particles. These R.F. forces, if of the correct frequency, can drive the betatron oscillations to larger and larger amplitudes and finally will produce a detectable modification in the beam. By determining these frequencies experimentally, one gets a value for the betatron oscillation frequency.

3. Induction experiments are primarily, of course, of two types, electrostatic and electromagnetic induction; and each type may be divided into two classes of operation, namely A.C. or D.C. A.C. induction experiments may be sufficient in

cases where the particle density of the beam is a function of the azimuthal coordinate. On the other hand, in stacked beams where this is probably not the case, a D.C. induction device is required. A.C. induction experiments would seem to work with either electrostatic or electromagnetic induction, whereas the D.C. induction experiments would seem to be limited to the electromagnetic type. The presence of stray charges and beam neutralization would confuse the D.C. electrostatic electrode.

The D.C. electromagnetic pick-up might well provide the most accurate non-destructive measure of the stacked beam current. The pick-up would consist of a closed magnetic circuit surrounding the circulating beam with a provision for measuring the D.C. magnetic flux in the circuit. A hall generator inserted in a narrow gap in the magnetic circuit would provide a suitable measure of the magnetic flux. The magnetic circuit should surround both the stacked beam and the injection orbit, and could be placed inside the vacuum chamber to minimize its length, or outside the vacuum chamber for convenience.

The A.C. electromagnetic pickup would have to have frequency response high compared to the revolution frequency of $\sim$ 12 mc/sec. A multiturn, low-capacity, "air core" pick-up would probably take the form of a toroidal coil with a gap in the windings on one side to allow entry of the individual buckets of beam.

An A.C. electrostatic electrode would probably be a cylindrical or a C-shaped electrode, large enough to pass the beam, but as small as possible to reduce the capacity to the vacuum chamber.

Such an electrode can yield information on the azimuthal arrangement of particles in the circulating beam. Azimuthal structure in the circulating beam can arise from the negative mass instability, the injection process, the application of R.F. fields, and other causes.

Efforts to observe any structure due to the negative mass instability may be seriously limited by band pass requirements placed on the apparatus.

The azimuthal arrangement of particles in an R.F. bucket is related to the phase area occupied by the particles. This experiment might also be hampered if one uses R.F. buckets of high harmonic number (i.e. $h = 10$). It may be desirable to carry out some R.F. experiments at the fundamental frequency of the particles.

Efforts in connection with the C.P.S. have produced such an electrode with a frequency response up to 300 mc. With special amplifiers, this signal can be displayed on present oscilloscopes.

One can argue the merit of having an A.C. electrode surrounding the stacked beam, since it is primarily of a D.C. nature. It is probable that on occasions, one would want a C-shaped electrostatic electrode surrounding the stacked beam, but this type of electrode will probably be most useful for studies of the azimuthal structure of the injected beam and single buckets of particles.

4. There is another interesting class of experiments, Spillout Experiments, which allow one to measure the arrangement of particles in an R.F. bucket. The ability to measure such arrangements, either with spillout experiments or induction experiments, will allow studies of the adiabaticity of R.F. manipulations and the effects of R.F. phase noise.

A spillout experiment might consist simply of altering the moving R.F. bucket itself; that is to make a reduction in the size of the bucket, thus spilling-out what was previously stable phase space into the wake of the moving bucket. If there are electrons in the spilled-out phase space, they can be detected either by detecting their absence in the remaining R.F. bucket, or by searching for their presence in the spillout region.

As an example, suppose we choose an R.F. bucket of a storage ring system described in PS/Int. AR/60-8 having the properties that $R = 4.0$ metres, $E = 2.51$ MeV, $\gamma_{tr} = 3.0$, $H = 10$, $\varphi = 45^{o}$, $V_{o} = 17$ volts. This moving bucket has an energy width $\Delta E_{m} = 5 \times 10^{3}$ volts, an area $A_{oM} = 1 \times 10^{-3}$ volt sec. and a rate of energy gain of $\dot{E}_{o} = V_{o} \Gamma_{o} f = 144$ volts/µsec. Suppose we choose to spill the particles out of this bucket by successively reducing the bucket from A_{o} , to $0.8\ A_{o}$, to $0.6\ A_{o}$, etc., while likewise reducing the rate of frequency modulation so as to keep $\Gamma = \Gamma_{o} = \sin \varphi_{so}$. One must allow sufficient time between the individual spillout operations in order that the particles remaining in the bucket may be moved out of the spillout region. If we choose that the particles in a given bucket should be moved 5 times the width of the bucket before the next spillout operation we arrive at the conclusion that 1.8 msec will be required to spill the phase space into 5 discrete bunches, and that the total debris will lie in an energy band of 50 kV and a radial spread (neglecting betatron oscillation amplitudes) of 0.9 cm.

Of course the spilling-out process alone is not sufficient to produce data on the arrangement of particles in a bucket. The debris left behind must be analyzed. In the example above a radial betatron amplitude of 0.2 cm will destroy the radial separations of the spillout bunches, and hence the analysis must be made in synchrotron phase space; that is, by probing the spillout regions with an analyzing R.F. system.

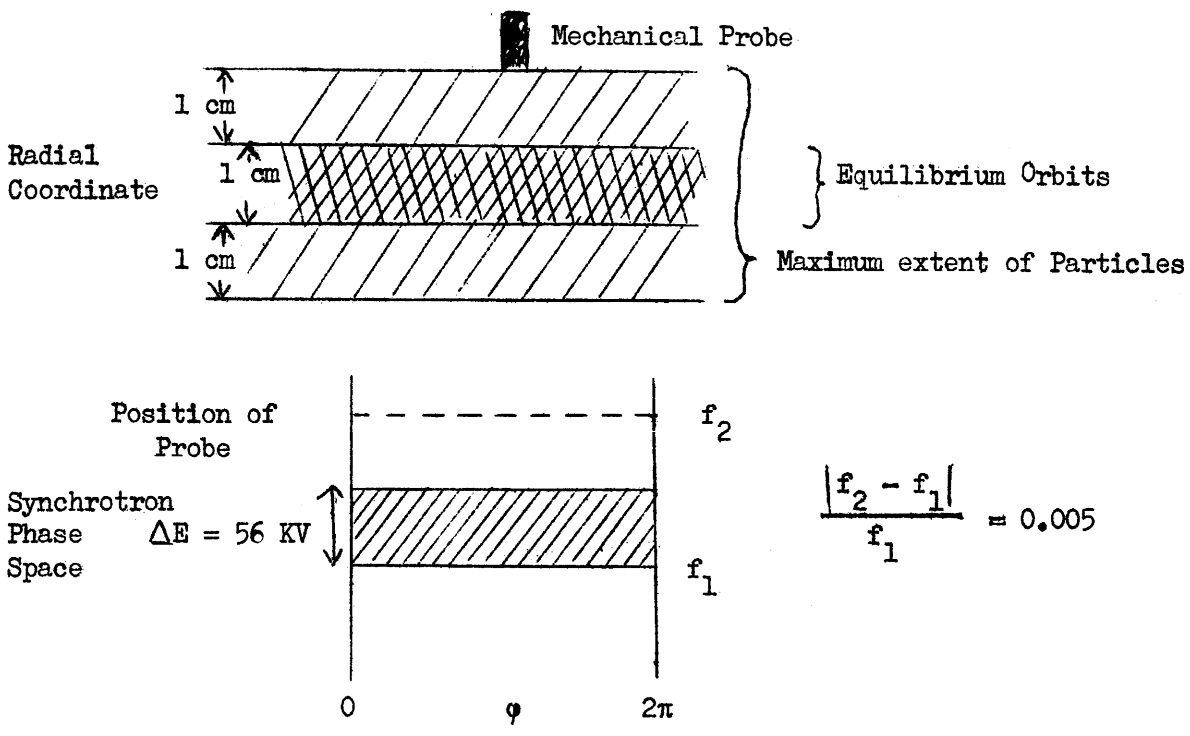
Let us analyze the regions by capturing the particles in each spillout region and accelerating them into a stationary mechanical probe, thus producing X-rays in proportion to the number of electrons striking the probe. Care must be taken that the analyzing bucket is neither to small to contain the phase area of each spillout region, nor so large that it scatters the particles in a neighbouring spillout region. For the example, this condition is met by capturing particles in a stationary bucket with properties $h = 10$, $V = 1.8$ volts, $\Delta E_s = 4$ kV and then in 1/2 msec, converting to a moving bucket of $V_2 = 10$ volts, $\Gamma_2 = 0.5$. This bucket will move the captured particles about 1 cm per msec. If the probe were placed 1 cm from the last spillout region, the analyzing process would require about 2 msec per group or about 10 msec for the 5 spillout groups.

A considerably simpler <u>spillout experiment</u> might consist of a single spillout by reducing the area of a bucket from A to ηA where $0 < \eta < 1$. The particles remaining in the bucket could be accelerated by this bucket into a mechanical probe, and the debris could be swept against a probe by a time dependent perturbation which produces a forced oscillation on the equilibrium orbit. This experiment would provide a measure of the number of particles remaining in the bucket ηA and number of particles spilled from the bucket A. And by changing the fraction η either manually or in some programmed fashion, a fair amount of data is obtainable on the arrangement of particles in a bucket. The experiment requires that the arrangement of particles in the bucket be reproducible.

<u>5.</u> It is of utmost importance that some scheme be available for the study of the phase space density of a stacked beam. The most promising scheme seems to depend on a phase space sampling R.F. system which is capable of plucking small areas of synchrotron phase space out of the stacked beam and measuring the number of particles trapped in the area. One such sampling system is described.

Let us consider a system whereby the area to be sampled is captured in a moving bucket, which is allowed to accelerate the captured particles out of the stacked beam and into a mechanical probe, thus producing X-rays. This process can be repeated at a high repetition rate, and if the position of the area to be sampled is changed from cycle to cycle by the energy width of the sampling bucket, one gets data pertaining to the phase space density of particles in the stacked beam.

Let us assume that we wish to analyze a stacked beam with a radial extent of 1 cm and with radial betatron oscillation amplitudes up to 1 cm. A sketch of the beam and the mechanical probe are shown both in the radial coordinate and in synchrotron phase space.



$$\frac{|f_2 - f_1|}{f_1} = 0.005$$

The frequency modulation programme might consist of a sawtooth function, which begins each cycle at f_1 upon receiving a starting pulse, and increases linearly to f_2 at some well-defined rate. The point in the stacked beam to be sampled could be controlled by the time at which the voltage on the R.F. accelerating gap is turned on.

Substituting the voltage $V = 25$ volts, and choosing $\varphi_s = 75^\circ$ or $\Gamma = 0.964$ one gets a rate of energy gain of about 300 KeV per msec. Each cycle of the analysis would require about 1/2 msec and would involve a moving bucket with an energy width of about 1 KeV. Hence in 25 msec one could chop out 50 chunks of phase space each about 1 KeV wide, from a stacked beam about 50 KeV wide.

In order that these 50 chunks span the stacked beam, the time delay between the starting pulse for the frequency programme and the turn-on-time for the R.F. voltage must be decreased linearly from 1/4 msec to 0 msec.

IV. Comments on Experimental Apparatus.

At first glance, the experimental apparatus would seem to include the following items:

1. 8 symmetrically located flanges on the vacuum system facing towards the centre of the machine to accommodate the mounting of mechanical probes.
2. 8 more flanges, to accommodate electrostatic bump electrodes, R.F. knockout electrodes, electromagnetic induction pick-ups, etc.
3. A D.C. electromagnetic pick-up, perhaps external to vacuum chamber.
4. An A.C. electrostatic pick-up, mounted in an enlarged region of vacuum chamber, to reduce capacity to ground.
5. An injector and inflector.
6. An accelerating R.F. system.
7. A phase space sampling system.
8. A betatron core.

Notice that items 3, 4, 5, 6, 7 and 8 must be located in straight sections of the storage ring. In view of the great demand for straight section space, it would seem advisable that the 8 flanges listed as item 1, and perhaps the flanges listed as item 2, be located elsewhere than in a straight-section (i.e. perhaps between a pair of quadrupoles).

One should beam in mind that this is an initial listing of such apparatus. There are bound to be additions and deletions. Perhaps the list can be revised to be more meaningful in a few months.

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