Figure 4 presents a plot of the internal region of the torus on an expanded scale. The high correlation of the experimental results to the theory is evident.

The experimental results of this investigation establish the validity of the assumptions of the principle of superposition of magnetic fields and the conservation of flux as used by de Launay[1] in describing the electromagnetic behavior of a superconducting torus under magnetic cycling. It is, therefore, felt that the results of his calculations can be applied with confidence to experimental investigations of the magnetic field distributions about superconducting tori.

PHYSICAL REVIEW VOLUME 78, NUMBER 1 APRIL 1, 1950

A New Method for Particle Injection into Accelerators

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(Received December 29, 1949)

THE purpose of this note is to describe briefly a new method by which electrons have been injected into a betatron. This new method has made possible the production of a reasonable electron beam in the betatron phase of operation of the non-ferromagnetic synchrotron now in construction* at the General Electric Research Laboratory. This betatron is characterized chiefly by a small aperture (vertical aperture $=0.05$ orbit diameter, radial aperture $=0.025$ orbit diameter) and low rate of acceleration (about 10 to 15 volts per orbital turn). It is believed that the method can be applied with success to other accelerators, especially those employing small relative apertures and small energy increase per orbital turn.

Most betatrons seem to work and there have been many attempts to explain satisfactorily how the electrons were injected so that they did not subsequently hit the structure of the injector itself after a few revolutions. These explanations have included many possible effects, e.g., resonance conditions between orbital, vertical, and radial oscillation frequencies, effects caused by injected current flux linkage, space-charge considerations either in the "donut" or near the injector gun, etc.[1] In our first attempt to obtain a betatron beam in the non-ferromagnetic synchrotron we found that, while these phenomena may provide a successful means of injection in conventional betatrons, they did not appear to provide enough of an effect to give us an appreciable beam. We were, however, successful in developing a scheme that did provide efficient injection and which appears to have the very desirable properties of being readily understood and easily applied. This scheme involves two steps; the first is to provide a means of rapidly damping the radial or vertical oscillations for as large a number of revolutions as possible, and the second is to remove this damping agent before it causes subsequent undamping. We have found that the first of these conditions can be very easily met, as shown below, by proper control of the azimuthal variation of the index, n.[2] The second of these conditions is easily obtained by making the azimuthal pattern of n time-dependent in the proper way; in our case the azimuthal variation (producing beam damping) is reduced to zero some time late in the gun injection pulse.

The best method by which rapid beam damping can be produced depends upon the particular design of the betatron and, for definiteness, the following description is limited to a discussion of the conditions which pertain to our non-ferromagnetic betatron. The injector gun is displaced from the orbit in the Z (axial) direction (perpendicular to the radius and to the tangent of the orbit). The value of n is (at injection) nominally 0.25; this, however, has been made adjustable over wide limits. In this case one expects vertical (Z) oscillations of about one-half the orbital frequency so that after two orbital turns the injected electrons will find themselves back at the gun, and, if the gun has any finite physical size, will be intercepted. By experimentally tracing the beam we have found this to be true only when great care was exercised in providing an index, n, which was quite uniform in azimuth. When a particular azimuthal "bump" in n was provided, the Z oscillation amplitude was found to change markedly even after two orbital turns. A qualitative explanation for this phenomenon is shown in Fig. 1. This scheme is one which is similar to those considered by Langmuir and Davis.[3] One full Z oscillation cycle is shown for two different conditions of $n(\theta)$; first, when n is uniform and equal to 0.25 one gets the solid curve with no damping or undamping. The injector gun is shown in its proper position, and it will be noticed that, apart from small damping effects not considered here,[4] after two orbital

* The construction and development of this accelerator has been supported in part by ONR under Contract N7onr-332 Task I.

[1] See for example D. W. Kerst, Phys. Rev. **74**, 503 (1948).

[2] In this definition the axial magnetic field is proportional to the minus nth power of the radius.

[3] R. V. Langmuir and L. Davis, Phys. Rev. **75**, 1457 (1949). Also private communication.

[4] D. W. Kerst and R. Serber, Phys. Rev. **60**, 47 (1941), showed the damping of oscillations caused by the increase of magnetic field (and hence restoring force) during a few orbital turns. How-

turns the electron is intercepted by the gun structure. However, if one provides, in the shaded region a value of n smaller than 0.25, denoted by n_1, and in the unshaded region a value of n larger than 0.25, called n_2, such that in each region one quarter-cycle of Z oscillation occurs, the Z oscillation amplitude will change monotonically (see dotted curve). This is caused by the requirement that the first quarter-cycle ray traced in the n_1 region must join in space and direction with the second quarter-cycle ray in the n_2 region; this requirement shows that the amplitude of each of these quarter-cycle oscillations is proportional to its wavelength, which in this case is inversely proportional to $(n)^{\frac{1}{2}}$. Thus the amplitude A_2 after two orbital turns in terms of the original amplitude A_0 will be

$$A_2/A_0 = n_1/n_2,$$

and it is clear that one can very easily provide extremely rapid damping or undamping by the appropriate choice of n_1 and n_2. It is evident that the condition for damping requires that the first harmonic of $n(\theta)$ have a minimum in the half-orbital turn just following the gun and a corresponding maximum in the half-turn just preceding the gun. This condition is most readily produced by providing a "bump" in n at an azimuth of $\pm\pi/2$ from the gun; the sign of the bump is chosen to produce damping.

Damping by the above method is not a sufficient means of injecting electrons; satisfactory injection would require the practically impossible condition that the relative phase of the orbital and vertical oscillation remain fixed in time. Actually one can never quite adjust the values of n so that the damping shown in Fig. 1 continues indefinitely; after a while the particle instead of starting into a shaded region exactly at its extreme amplitude position will start into an unshaded region. In this case undamping will occur. In particular the Z oscillation amplitude will "beat" slowly at a rate which is the difference in frequency between the actual Z oscillation frequency and the synchronous Z oscillation frequency (one-half the orbital frequency). This feature makes two points evident; first, that large damping effects for a few turns can be experienced even though the average value of n is not very close to the synchronous value of $\frac{1}{4}$, and second (especially when n is not very near $\frac{1}{4}$), that if damping of this variety is used to clear the gun structure after two turns, undamping is sure to increase subsequently the Z oscillation amplitude to a value higher than its initial value. This essentially guarantees that if the beam goes more than two turns it will not last very many more without hitting the gun. This event can only be avoided by arranging the damping to be time-dependent; in particular, if the means of damping is suddenly removed before the Z oscillations can undamp beyond their initial amplitude, the injected beam will not be intercepted by the gun structure.

This is essentially the scheme we have tried successfully. We have used a coil system shown schematically in Fig. 2 to reduce the value of n over about an octant centered at an azimuth $+\pi/2$ after the gun. This particular scheme, one of many possible varieties, uses current in two coils, one above and one below the orbit, so arranged as to produce essentially a radial magnetic field proportional to Z (the coordinate perpendicular to the orbit radius and to the tangent and having its zero at the orbit).[5] Current in these coils produces strong damping; it is easy to turn off the damping current quickly because of the small inductance of the coil combination.

In practice, the damping current (in our case derived from a vacuum-tube cathode follower) is started by the same trigger which activates the pulse applied to the gun. At a controllable time later (during the time when the pulse on the gun has its proper value for injection), the current is switched off (actually decays with a time constant of 5×10^{-8} sec.). It is found experimentally that this switching-off time must be made just right or no beam is captured; if it comes too early the gun voltage is wrong, and if it comes too late the undamping effect described ruins the beam. In our case the switching-off time is critical to about one microsecond.

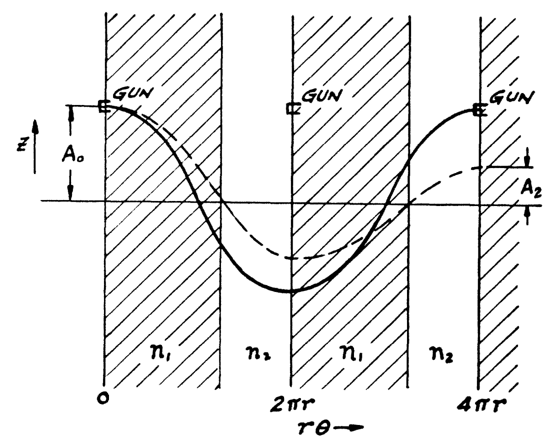

FIG. 1. Vertical (Z) oscillations.

ever, we are here concerned with a very slow rate of increase of field and will neglect this effect.

[5] There are many coil configurations which accomplish this; the one we have chosen has small inductance and is still efficient as a damper. We have also considered electrostatic means for altering the restoring forces on the electrons; this is clearly equivalent to the magnetic case and in many instances would be very practical. Electrostatic plates charged to potentials of the order of one hundred volts and arranged in the proper way can easily produce these effects. It is important to note that, since such small potentials can have such a marked effect on the beam, one needs to consider in detail the influence of the coating resistance on the walls of the "donut." With strong emission from the gun and resistance of the order 1000 ohms per square one can easily produce electrostatic fields of the magnitude we are here considering. Incidentally this effect may be responsible for assisting injection in many existing accelerators.

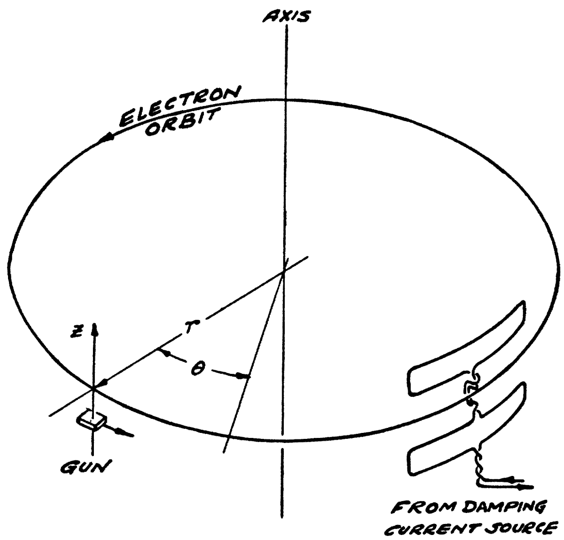

FIG. 2. Coil system to reduce value of n.

We find experimentally a number of necessary conditions for a strong betatron beam which substantiate the explanation given:

(1) The damping current must be switched off at the right time. As stated, virtually no beam is obtained unless the damping current is removed during the injection gun pulse.

(2) After the damping current is off, the azimuthal variation in n must be adjusted. After one has damped the beam it is necessary that no serious undamping occurs, and especially if one is near the $n=0.25$ resonance value it is imperative that the azimuthal variation in n be quite small.[6] In our case we have provided for local n controls in each octant; we find it necessary to adjust these controls to obtain a good beam.

(3) The best beam is obtained with a particular value of n. According to the principles outlined, the longest damping time (before undamping) occurs when the Z oscillation frequency is nearly synchronous with the orbital frequency. A little calculation shows that collection of electrons over our full "match" time of one microsecond requires the average value of n to be set within 0.01. We find experimentally that the best beam is obtained when the average n is set at about 0.25 (actually measured within ± 0.05) and that the beam is quite sensitive to a change in n of 0.01. Under the best condition we have traced the beam statically for eight to ten revolutions with no ambiguity. The beam was still damping satisfactorily and we have no reason to believe that damping would not occur for the whole match time of one microsecond.

(4) The condition for obtaining a beam is not sensitive to gun position; a good beam is obtained in our case for gun positions ranging from $1\frac{1}{2}$ in. from the orbit to $\frac{1}{2}$ in. (the minimum adjustment provided in the gun mount).

(5) A good beam is obtained even through small apertures. In one experiment an aperture ($\pm\frac{3}{8}$ in. in Z and $\pm\frac{1}{2}$ in. in radius) was inserted a half-turn around from the gun and the gun itself was moved to $\frac{1}{2}$ in. from the orbit (orbit radius $=24$ in.). No difficulty was experienced in getting a satisfactory beam through this combination.

Unfortunately we have not had time to measure the total beam current or even to compare it with others. We have, however, measured the beam current after a few revolutions directly on a small collector, and find it to be about 0.1 ma for a duration of about one microsecond. There seems to be no obvious reason why this charge is not caught into the final beam; a qualitative substantiation that a fairly large beam is actually caught is the observation that the beam pulse on a zinc-oxide photo-multiplier detector is considerably larger than the "main bang" (pulse produced by incidental collection of the initial electrons going only one half-turn) even when the injected electrons of 70 kev are accelerated to only 100 kev.

It is obvious that, while this above description applies to our injection scheme where the gun is displaced in the Z direction from the orbit, one uses the same arguments for radial injection. In the latter case one talks of radial oscillations instead of Z oscillations and adjusts $(1-n)$ instead of n to be nearly $\frac{1}{4}$. To produce damping one arranges $(1-n)$ to be somewhat smaller in the half-orbital turn after the gun than in the half-orbital turn just preceding the gun.

[6] See, for example, E. D. Courant, J. App. Phys. **20**, 611 (1949).