LABORATORY FOR PLASMA STUDIES

COLLEGE OF ENGINEERING

CORNELL UNIVERSITY

Technical Progress Report

on the

CORNELL RELATIVISTIC ELECTRON COIL EXPERIMENT (RECE) 21

under joint ESEERCO-USAEC - Sponsorship

during the period

July 1, 1973 through March 31, 1974

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I. SUMMARY

During the nine months of this report period, a number of experimental and theoretical results were obtained by the Cornell RECE-program which all give favorable indications concerning the usefulness of high-energy charged particle coils for a final fusion reactor. In particular, additional positive evidence was collected concerning the question of gross stability of our rings. It appears that, contrary to many opinions, this question may not constitute a major obstacle against the application of such internal particle coils. Amongst other results, clear field-reversal has been achieved very recently with RECE-Christa. At least equally important, experiments with "Ioffe" windings added to the magnetic field coils of RECE-Berta may have opened the way to generate the necessary ion rings considerably cheaper than had been assumed possible so far. Finally, an overall systems analysis performed for a particular fusion scheme based on such charged particle coils indicates considerable economic advantages when compared with the more conventional schemes.

Extensive experimental results again were obtained from the RECE-BERTA facility. Final detail measurements of the influence of gradients in the magnetic field strength across the rings and the good agreement with a theoretical analysis add to the earlier evidence for overall stability of our rings. An extension of these measurements lead to a final explanation of the "precessional dump" of our rings mentioned in earlier reports. Most important, it was observed that this mode can be stabilized by the addition of longitudinal external windings ("Ioffe field") to the basic mirror field. In addition to providing a means to

stabilize this mode without a metallic wall, this result indicates that it may be possible to create ion rings, as they will be needed in a final reactor, by slow steady-state injection of low-current ion beams. Such an arrangement would be considerably cheaper than any of the other schemes envisioned so far. Furthermore, the electron energy measurements started in the last period were completed, giving no indications for the existence of any microinstabilities in the ring. Finally, the successful trapping of rings without metallic walls may give us now the opportunity to perform a first test on the compressibility of the electron rings.

The experimental effort on RECE-Christa had to be curtailed due to the reduced overall funding of the project. Additional parameter studies of beam propagation in the injector tube reconfirmed our earlier results of poor beam propagation. Therefore, the injector tube had to be shortened to obtain a somewhat larger effective injection current. Furthermore, a small vertical magnetic field component had to be added to the basic field to avoid a hitherto unexplained vertical drift of the injected beam. After these changes were made, the strength and lifetime of our rings increased significantly, and clear field reversal (up to about 150%) coupled with a ring lifetime of up to 250 μ sec was achieved very recently. Presently, preparations are being completed to add a pulsed toroidal field comparable in strength to the maximum basic mirror field.

In the smaller Cusp injection experiment, beam injection into a pulsed gas puff led to the trapping of strong electron rings (80-100%) with lifetimes of up to 80 μ sec, corresponding to over 10^5 electron orbits. Presently, a coaxial plasma gun has been incorporated into the basic machine, which will allow injection of the electron beam into a

preionized gas, and thus - hopefully - will lead to further significant increases in the overall ring lifetime.

A theoretical systems analysis of a fusion reactor system based on internal rings of high-energy ions showed that a considerably larger density of power production can be achieved in such a machine than presently known scaling laws would indicate for a normal Tokamak reactor. At the same time, a sizable reduction of the necessary external magnetic fields is projected. Both of these facts should lead to sizable economic advantages.

Theoretical calculations of magnetic image field indices were performed which provided sizable improvements over some older calculations and which gave good agreement with the mentioned field gradient experiments.

Finally, a number of reports were completed describing some of our results. Also, as usual, a number of talks were presented at scientific meetings.

II. RECE-BERTA EXPERIMENTS

The RECE-Berta facility again was the "work horse" for most of the experimental investigations during this report period. First, the earlier investigations on the influence of gradients of the magnetic field strength across the ring diameter were completed. Detailed investigations of the time dependence of the various ring parameters together with related theoretical analyses showed that the shifts of ring position observed earlier corresponded quite accurately to a theoretically expected shift in the equilibrium position of the rings. This fact again supports our assumption of basic gross stability of these rings. In addition, this result also provided a clue that our final "dump" may be originated by a corresponding field strength gradient in the basic mirror field. Such gradient was observed, and the above conclusion could be substantiated by additional experiments. The dump level remaining after balancing of all field gradients seems to agree well with that expected for the well-known "precessional-instability". Very important and encouraging results were achieved in experiments where the addition of quadrupole "Ioffe" windings to the basic mirror field resulted in a stabilization of the remaining dump. Furthermore, the earlier measurements of the time dependence of the electron energies were completed reconfirming essentially our earlier conclusions that the observed energy losses can be accounted for by purely collisional effects. No indication of any microinstabilities was seen. Finally, very recently, trapping of electron rings without a conducting metal wall was observed, which may open the way for ring compression experiments on this facility.

Reports describing the results of our field gradient experiments and the energy measurements have been completed. Reports on the other results are in preparation.

1. Influence of Magnetic Field Gradients

In our last report, we showed first results on the influence of a perturbation of the basic mirror field which resulted in differences of the total magnetic field strength across the trapped ring. From the readings of magnetic probes above and beneath the rings, it had been concluded that the rings seemed to move towards the low-field region of the tank. During this report period, these earlier findings were investigated in more detail. The final results are described in a report

"Experiments and Theory on the Effects of Magnetic Field Gradients on Strong Relativistic Electron Rings", by R. A. Mager, et al., (LPS 140) which has been submitted for publication in the Physics of Fluids.

First, a calibration of the ratios of the probe readings above and beneath the rings was obtained using a dummy coil substituting for the trapped electron rings. As shown in Figure 1, a homogeneously wound single-layer coil of varying radius, R_c , and varying length, L_c , was placed in the center of the RECE-Berta tank where the electron rings normally are trapped. This coil was energized from a 2 μ F capacitor, producing magnetic fields oscillating with a quarter-cycle time between 20 - 30 μ sec. These fields were observed with our magnetic probes placed in the usual positions above and beneath the rings. An example of the recordings is shown in Figure 1b. After absolute calibrations of all probes, the resulting amplitude ratios, ρ , for the two probes were recorded as function of the vertical displacement of the dummy coil from

SAMPLE TEST COIL DATA

FIGURE 1. (a) Arrangement for dummy coil experiment (top)
 (b) Sample trace (bottom).

the tank axis. Sample results from these measurements are shown in Figure 2 for a given coil radius and three different coil lengths. Surprisingly, the signal ratios, ρ , are very nearly exponentially dependent on the vertical shift, ϵ , of the coil. Thus,

$$\epsilon = A(R_c, L_c) \log \rho, \quad (1)$$

where $A(R_c, L_c)$ corresponds to the slope of the lines in Figure 2. The experimentally observed functional dependence of this quantity on R_c and L_c is shown in Figure 3. These points, and the interpolating curves were used to extract the actual displacement of the electron rings from the mentioned signal ratios observed from our electron rings.

After these calibration measurements, more careful measurements of a number of electron rings were performed using the usual complement of magnetic probes on the tank axis and tank wall. Figure 4 shows the signal ratios observed from the probes above and beneath the electron rings as function of time for a number of shots. For the same shots and times, the other ring parameters (radius, length and strength) were derived from the other probe recordings. These data then were used to convert the measured probe signal ratios, of Figure 4, into actual displacements of the rings. The resulting ring movements are plotted in Figure 5, solid lines).

From these plots, an asymmetry of the measured ring displacements with regard to the sign of the perturbation coil is clearly apparent. This asymmetry had been mentioned in our last report, and was ascribed to the change of the effective field gradient with the deflection of the coil. During this report period, this explanation was partially modified. From the fact that a 20-turn perturbation resulted in relatively small deflections, it was concluded that a field

FIGURE 2. Signal ratio vs location of test coil.

FIGURE 3. Functional dependence of $A(R_c L_c)$

FIGURE 4. Measured signal ratios for electron coil.

FIGURE 5. Experimental (full lines) and theoretical (doubled) vertical displacement of electron rings.

gradient of corresponding magnitude was present in the basic mirror field of RECE-Berta.. This conclusion then was reconfirmed by direct field measurements which revealed the existence of a gradient corresponding to a negative 23-turn perturbation coil. Thus, the total field gradient was very nearly zero when a perturbation coil with +20 turns was applied, in which case the rings stayed centered around the tank axis. The mechanism considered earlier to cause the mentioned asymmetry, still causes a slightly faster deflection of the rings for small or negative perturbation values, but, certainly is not as dominant as it had been assumed.

To explain the physics of these ring displacements, a theoretical analysis of shifts in ring equilibria to be expected from such field gradients was performed. This analysis is based on the idea that such equilibria will be defined by an effective balance of the external magnetic field gradients and the differences in magnetic field strength across the rings generated by the asymmetric image currents in the metallic tank wall. To test this idea, the magnetic forces on the rings generated by the external field gradient were calculated

$$\begin{aligned}
 F_x^{\text{pert}} &= 2r_E(I_E/c)B_{z0}^{\text{pert}} \left\{ \int_0^\pi d\theta \cos\theta \left[1 + \frac{r_E^2}{d^2} - 2 \frac{r_E}{d} \cos\theta \right]^{-3/2} \right. \\
 &\quad \left. + (3\epsilon/d) \int_0^\pi d\theta \cos\theta \left[1 - \frac{r_E}{d} \cos\theta \right] \left[1 + \frac{r_E^2}{d^2} - 2 \frac{r_E}{d} \cos\theta \right]^{-5/2} \right\} \\
 &= -\pi r_E(I_E/c)B_{z0}^{\text{pert}} \left\{ 2J_1 + 6 \frac{\epsilon}{d} J_2 \right\} \quad (2)
 \end{aligned}$$

and then balanced by the forces resulting from the image currents in the tank wall. From this force balance, the deflection, ϵ , was calculated to be:

$$\frac{\epsilon}{r_E} = - \frac{2J_1 \frac{B_{z0}^{pert}}{B_{z0}} + \frac{r_E}{B_{z0}} \left(\frac{dB_z}{dx} \right)_{grad}}{\eta_{ex} + \eta_{im} + 6 \frac{r_E}{d} \frac{B_{z0}^{pert}}{B_{z0}} J_2} \quad (3)$$

where r_E is the radius of the electron ring, B_{z0}^{pert} is the strength of the perturbation field at the tank axis, (dB_z/dx) is the basic field gradient, d is the distance of the perturbation coil from the tank axis, $\eta_{ex} = (r_E/B_{z0})(dB_z/dr)$ is the external radial field index, η_{im} is the corresponding image field index, and J_1 and J_2 are the integrals defined in Equation (2).

Equation (3) including the two integrals J_1 and J_2 were evaluated on a computer using the ring parameters (radius, length, and strength) mentioned earlier. For this purpose, the external field index η_{ex} was measured. Since published calculations of the image field index were insufficient for our case, additional theoretical investigations and calculations had to be performed. These calculations which are equally important for an analysis of our final dump are described in Section VI. Image index values applicable to our case and their dependence on various parameters are shown in Figure 6.

The theoretically expected shifts in ring equilibrium position are also plotted in Figure 5 (dashed lines). For a comparison of the

FIGURE 6. Newly calculated image indices for RECE-Berta.

experimental and theoretical displacements, an overall accuracy of about 25% of the measured shifts plus a shift of ± 0.2 cm initially ranging up to ± 0.4 cm at the end of the ring's lifetime is estimated. The agreement between the respective theoretical and experimental curves in Figure 5 generally falls well within this limit. This agreement indicates that the observed ring displacements actually correspond to a shift of the equilibrium positions, and are not indicative of any instabilities. If such gross instabilities were present, one would expect that they would be seriously speeded up by perturbations in the external field. The fact that they still are not observed, thus, is very encouraging.

2. Dump vs Field Gradient

The presence of a gradient of the field strength in the basic mirror field of RECC-Berta which was found in the above perturbation measurements, also may produce a final explanation of the dump observed in that machine. The level at which this dump occurred seemed somewhat high compared with the level at which the precessional instability would be expected to set in. This became even more so, when the newly corrected, (see Section VI), values for the image indices became available to determine this level. On the other hand, the apparent high level of the dump can be explained when one considers the radial displacement of the rings resulting from the field gradient associated with the basic mirror field. As seen in the first section, this basic gradient tends to move the rings upward from the tank axis. This movement reduces the available radial space for the diffusion of the rings, and thus, leads to a somewhat faster decay of the rings. According to Equation 3, this effect becomes

particularly strong (η_{im} is proportional to the ring strength) when the ring strength has decayed to levels of the order of the expected precessional dump. In this case, the rings have to move quite far, and the space reduction becomes increasingly significant. Due to this faster decay, the rings have to move even further, and the whole process accelerates to an apparent dump.

To test this possibility, the dependence of the observed dump level on the strength of the gradient field was determined. Figure 7 shows some preliminary results of these measurements. As is apparent, the dump level reaches a minimum for about 25 turns of the perturbation coil. As mentioned earlier, the gradient in the basic mirror field is approximately balanced at that point by the external gradient. The remaining dump level is quite compatible with the expected onset of the precessional instability.

3. Quadrupole Stabilization of Precession

As mentioned in the last section, the dump remaining after balancing the gradient in the basic mirror field can be explained quite well as due to the well-known precessional instability of weak electron rings. This instability basically originates from the slight radial decrease of the magnetic field strength in any simple mirror field. The same field decrease also is the reason for the well-known "flute instabilities" observed in all the earlier mirror fusion experiments at Livermore and elsewhere. In 1963, the Russian Ioffe showed that these flute modes can be stabilized by adding a perpendicular "quadrupole field" (now called Ioffe field) generated by four longitudinal conductors (see.

NORMAL CONFIGURATION

41 " probe
10 mv/cm

38.5" probe
10 mv/cm

2 μsec/cm

36" probe
5 mv/cm

Unintegrated 41"
.2 v/cm

NO GRADIENT

41" probe
10 mv/cm

38.5" probe
10 mv/cm

FIGURE 7. (a) Effect of field
gradient on dump level.

36" probe
5 mv/cm

Unintegrated 41"
.2 v/cm

FIGURE 7(b)

COIL STRENGTH AT DUMP
versus

NUMBER OF TURNS ON COIL

re 8) to the basic mirror field. It appeared that it may be similarly possible, to stabilize our precessional mode by such an addition. Simple theoretical arguments indicated that such stabilization should occur when the strength of total magnetic field (i.e., basic mirror field plus Ioffe field) no longer decreases radially towards the outside. (This is the same condition under which the flute modes became stable.)

To test this idea, a Ioffe field coil, consisting of four longitudinal conductors outside of the mirror coils and the corresponding cross connections at the end of the vacuum tank were added to RECE-Berta.

This coil (variable up to 35 turns) was energized in series with the normal

field coils, and the dependence of the dump level (on the number of Ioffe

windings was investigated using a vanishing total field gradient. Figure

9 shows some of the results for various number of windings. (One picture

each shows the normal magnetic probe traces, and one picture each shows

the non-integrated recordings which are proportional to dB/dt , and there-

fore, emphasize any existing dump more clearly. It appears that the dump

level actually decreases to zero when more than about 25 Ioffe turns are

applied. Figure 10 shows this dependence in more detail. For the exist-

ing geometry of the various coils, the total magnetic field strength no

longer decreases radially when 27 or more Ioffe field windings are ener-

gized, i.e., the observed stabilization of the precessional mode seems

to occur approximately at the expected point. More detailed experiments

are now being performed.

4. Completion of Energy Measurements

In the last report, preliminary results of measurements on

dependence of the energy of the trapped electrons have been reported.

QUADRUPOLE FIELD COIL

FIGURE 8. Arrangement of quadrupole Ioffe windings.

EFFECT OF QUADRUPOLE FIELD ON DUMP

NO-GRADIENT CONFIG

41" probe
10 mv/cm

38.5" probe
10 mv/cm

2 μ sec/cm

36" probe
5 mv/cm

Unintegrated 41"
.2 v/cm

25 WINDINGS OF QUAD

41" probe
10 mv/cm

38.5" probe
10 mv/cm

36" probe
5 mv/cm

Unintegrated 41"
.2 v/cm

FIGURE 9. Sample traces for effect of Ioffe fields on dump.

FIGURE 10.

COIL STRENGTH AT DUMP
versus
STRENGTH OF QUADRUPOLE
FIELD

These measurements were performed using absorption measurements of the Bremsstrahlung X-rays produced by the trapped electrons striking a thin tungsten wire placed radially across the rings. During this report period, similar measurements were made using an improved X-ray detection geometry. The results of these experiments were analyzed in more detail and are described in a report "Experiments on the Long-Time Interaction of Trapped Relativistic Electron Beams with a Slightly-Collisional Plasma" by A. C. Smith, et al. (LPS 139), which has been submitted for publication in Phys. Rev. Letters.

As mentioned, mainly geometric improvements were incorporated in the experimental arrangement during this report period. In particular, the distance between the wire and the detectors was decreased to 24" and the collimator apertures were increased to $1/2" \times 1/2"$. Thus, an intensity increase by about an order of magnitude was obtained, which permitted us to do measurements also with the wire positioned at the outer fringe of the trapped rings. At the same time, the electronic response time of the detectors was improved to about 250 nsec, thus reducing possible errors from this source. Also, the theoretical absorption curves of X-rays generated by a monoenergetic electron beam have been recalculated.

Using this new arrangement, a series of measurements were performed, with the tungsten wire placed both in the ring center and at the outer parts of the rings. Sample traces from these measurements are shown in Figure 11. Absorption ratios for the various absorbers were derived from these traces using an optical averaging over about 1 μ sec. After normalizing these ratios with experimentally determined calibration factors for the basic detector efficiencies, etc., the corresponding

(a)²⁶

.177" Pb
.02 V/DIV

.264" Pb
.02 V/DIV
.088" Pb
.05 V/DIV

ELECTRON
RING
δ B - PROBE

FIGURE 11. Sample traces from energy measurements. With equal absorbers, signal intensities were roughly equal.

average electron energies were derived using the calculated transmission ratios which are shown in Figure 12. Examples of the time dependences of the derived average electron energies are shown in Figure 13 for the two cases with the tungsten wire at the ring periphery (Figure 13a) and with the wire in the ring center (Figure 13b).

From these results, an overall energy decrease of about 7 ± 3 keV/ μ sec and 2 ± 2 keV/ μ sec was derived for the wire at the periphery or at the center, respectively. Under the conditions present in the experiments (450 mTorr hydrogen, + about 15 mTorr background pressure), a collisional energy loss of the electrons of about 7 keV/ μ sec is expected. Energy gains of the electrons due to the simultaneous decay of the magnetic self-field of the rings ("Betatron acceleration") were calculated from the measured decay of the axial magnetic field and the inductivity of a magnetic coil with dimensions comparable to the trapped electron rings. These energy changes are estimated to be $+ 2.6 \pm 1.5$ keV/ μ sec and $+ 4.2 \pm 2$ keV/ μ sec, respectively. Thus, the measured changes in the average electron energies can be easily explained by purely classical effects; any microinstabilities, if they are present, do not appear to play any major role.

5. Trapping without Conducting Walls

In a final fusion reactor of the Ring Compressor type (see Section V), the compression of field-reversing rings is to be used. While no particular difficulties and obstacles are expected from this procedure, an experimental test of such ring compression and the associated gains in electron energy would appear worthwhile. Such a compression is difficult

FIGURE 12. Transmission energy.

FIGURE 13. Results of energy measurements with tungsten. Wire at periphery (top) and center (bottom) of electron ring.

to perform in our present arrangement, because of the relatively long time necessary for penetration of any externally applied magnetic compression field through the metallic tank walls. In order to stabilize the rings against the precessional instability, this penetration time has to be large compared with the lifetime of the rings, and therefore, these walls will essentially exclude any compression fields. However, due to the recently achieved stabilization of the precessional mode by quadrupole Ioffe fields, it appears possible to generate and contain strong electron rings also in vacuum tanks without metallic walls, or within metallic walls the penetration time of which is no longer large compared with the ring lifetimes.

To test this possibility, a few trapping experiments were recently performed in RECE-Berta with the metal walls removed. A preliminary result of this experiment is shown in Figure 14. It shows that a sizable electron ring (generating axial field changes of about 50%) was trapped for several microseconds. Further experiments in this direction are in progress.

LAYER WITHOUT CONDUCTING BOUNDARY

(Stabilized by 30 Windings of Quadrupole coils)

46" probe

43" probe

all 1.5 mv/cm

2 μ sec/cm

41" probe

38.5" probe

FIGURE 14.

III. RECE-CHRISTA EXPERIMENTS

As mentioned before, the activity on the RECE-Christa facility had to be curtailed during this report period due to the reduction of available operating funds. The remaining experimental work with this facility was hindered by two unexpected effects. First, additional beam propagation studies did not succeed to improve sufficiently our earlier findings of poor beam transportation through the injector tube. After some experimentation, the injector tube was shortened and thus a significant increase of the injection current into the tank achieved. Using this larger beam, a vertical drift of the beam which had been observed earlier, became so pronounced that the beam trapping became seriously insufficient. At the end of this report period, means to avoid this drift were found. This led to a significant improvement of the trapping efficiency. Most recently, the successful trapping of an electron ring sufficiently strong to reverse the direction of the axial magnetic field and exhibiting an overall lifetime of about 250 μ sec was observed for the first time in this machine. The toroidal field capability which is presently being added is expected to increase the reproducibility of the trapping and make possible a number of very important investigations.

1. Beam Propagation Studies

Additional beam propagation studies were undertaken in an attempt to improve electron transport from the diode to the mirror field. These experiments were carried out using a 4.5 foot long, transparent, gas filled plastic tube with a copper screen liner. The diagnostics included X-ray pin hole photography, time integrated visible light

tography and calorimetric measurements of the total energy transported. The parameters varied were gas filling pressure, gas type, anode foil thickness, and cathode material and geometry. The effect of cathode centering was also checked. The filling pressure was varied from 1 to 10 mTorr for hydrogen and from 1 to 5 mTorr for air. Anode foils ranging from .5 mil aluminized Mylar to 10 mil titanium were used. Among the cathode materials tested were molybdenum, tantalum and plasma sprayed tungsten on stainless steel or aluminum. Cylindrical cathodes with diameters from .25 to 1.25 inches as well as a 4 inch diameter, stainless steel spherical cathode with a tungsten sprayed front surface were employed. Finally, the beams were propagated using copper liners having diameters of 2.5 inches and 4.5 inches. In Figure 15, an X-ray pin hole photograph and a visible-light picture is displayed for a typical shot. Beam propagation is from right to left.

As reported for the earlier studies, the results exhibited considerable shot-to-shot fluctuations, making it difficult to draw conclusions without making a large number of shots for each set of parameters. The obtained results can be briefly summarized as follows:

- (1) The beam was unstable and struck the copper-liner in some way in nearly all cases.
- (2) The average energy transport was poor being only about 15% of the energy input to the diode.

One additional problem area mentioned in the previous report was the rather severe damage to the cathodes which limited their life. Again, it was found that the cathodes plasma-sprayed with tungsten were prior to all others in their resistance to damage. However, in the

OPEN-SHUTTER PHOTOGRAPH

TOP VIEW

SIDE VIEW

X-RAY PINHOLE PHOTOGRAPH - SIDE VIEW

TYPICAL BEAM PROPAGATION DATA

ENERGY TRANSFER - 720 J, 3.9 MV, 70 KA

3 T. OF AIR, 1.25 INCH DIAMETER TUNGSTEN CATHODE

FIGURE 15. Open-shutter and X-ray photograph of beam propagation in RECE-Christa.

Course of subsequent trapping experiments it was discovered that high density graphite was even more resistant, and that good layers could be trapped using this cathode material. Therefore, these cathodes are now used as standard.

In order to circumvent the problem of poor beam transport, the drift tube was shortened from 5 feet to 2.5 feet. This change required extending the diode envelope by one foot since the mirror machine could not be moved closer to the diode. In the final configuration, typically 20 to 30 per cent of the diode current was measured at the drift tube end. This proved to be adequate for the trapping of strong electron layers.

2. Extension of Ring Lifetime Rings

To date several hundred shots were made to study the trapping and long-time behavior of electron rings in neutral hydrogen gas. The principal parameters varied were magnetic field strength, mirror configuration, background pressure and drift tube pressure. In addition, different injection angles, injector radii and drift tube foil thickness were checked.

The principal diagnostic employed were magnetic field probes which measured the magnetic field, changes produced by the fast electrons and by plasma currents, (the transient plasma currents decay to zero about one microsecond after injection). These probes were positioned just inside the Cu-liner. Originally seven probes were placed along the tank top and spaced axially from each other by 9 inches. Recently, an additional set of probes were installed on the bottom of the tank, and at

one axial position 4 probes displaced by 90 degrees azimuthally are now also in place. Other diagnostics included time integrated pictures of the plasma luminosity taken from various positions and Rogowski coil measurements at the injector tube end to measure the injected current. In addition, diode current and voltage were monitored on each shot.

To date, about 25 electron rings with lifetimes exceeding 100 μ sec have been observed. Typical operating conditions under which such rings were trapped are:

Drift tube pressure	1.7 - 3.2 Torr
Tank pressure	.5 - 1.2 Torr
Field configuration,	about as shown in Figure 16
Diode voltage	3.5 - 4.2 MV
Diode current	65 - 80 KA
Drift tube current	10 - 25 KA
Injector angle	10°
Injection radius	17 cm

From the relative magnitude of the magnetic field changes recorded by the various axially distributed probes, it is estimated that the axial length of these rings usually is smaller than their diameter. This finding agrees with similar observations on the two other machines.

The largest ring observed so far showed clear field reversal at the outset (about 150% of the applied field of 370 Gauss) and an overall lifetime of about 250 μ sec. The corresponding probe recordings are shown in Figures 17 and 18. The top trace in Figure 17 shows the injected current (upper trace), and the magnetic field change at the position 2

MIRROR
COILS

1 2 3 4 5 6 7 8 9 10

COILS 1, 3, 9

SOLENOID CURRENT 410 A

MIRROR CURRENT 265 A

6.0E 02

5.0E 02

4.0E 02

INJECTOR

PROBES

2 3 4 5 6 7

3.0E 02

0.0E 01

1.0E 00

2.0E 00

3.0E 00

4.0E 00

5.0E 00

CHRISTA MAGNETIC FIELD DISPLAY USING ADVANCED COMPUTER GRAPHIC TECHNIQUE

TYPICAL MAGNETIC FIELD CONFIGURATION

FIGURE 16. Calculated magnetic field distribution in RECE-Christa.

INJECTOR CURRENT
17.4 KA/DIV

PROBE #2
28 G/DIV

200 ns/DIV

PROBE #3
28 G/DIV
RC=300 μ s

PROBE #4
45 G/DIV
RC=955 μ s

PROBE #5
70 G/DIV
RC=300 μ s

50 μ s/DIV

RES 17 & 18. Recordings for first
field-reversing electron ring
rod in RECD-Christa.

(see Fig. 15) (lower trace). The sweep speed in both cases is 200 nsec per division. From these figures, injection current of 35 kA and a maximum field change of 42 Gauss at position 2 is derived. Figure 18 shows magnetic probe signals on a sweep speed of 50 μ sec/div. The recording of probe 5 indicates an initial field change of 130 Gauss. Using a ratio 4.4 between the field changes at the wall and at the tank axis, as it had been observed in the two other machines, one obtains an axial field change of about 570 Gauss generated by the electron ring. The field changes indicated by probe 5 drop rather rapidly to about one half the initial value in about 10 μ sec. On the other hand, the signal from probe 4 increases quite significantly during the same time. This indicates that the ring center moves from a position near probe 5 to a position closer to probe 4. For times larger than 10 μ sec, the signals from probes 4 and 5 are more equal in magnitude indicating that the ring is centered roughly in the middle between the two probes. Thus, the fields measured by these probes are smaller than the fields at the ring center, and the initial decay of the ring strength is clearly smaller than indicated by the mentioned rapid decay of the signal of probe 5 in Figure 18. A more detailed analysis of the actual initial decay rate of this ring is in progress. At present, it appears that this decay is rather smooth. A photographic recording from the side of the tank also shows the ring positioned between the two probes.

3. Vertical Drift of Injected Beam

During the injection studies described in the last section, somewhat odd problem developed, the origin of which presently is not yet

known, though we were able to solve it empirically. From photographs of the downstream lucite flange, it was observed that the electron beam that was not trapped in the mirror produced on this flange an illuminous pattern the center of which usually appeared about 10 - 15 cm above the tank axis. Similar patterns also were observed when the downstream mirror coils were not energized. Furthermore, side pictures clearly indicated that the axis of the primary beam spiral was inclined upward with respect to the tank axis. Also, lucite blocks mounted on the inside top of the metal liner exhibited sizable radiation damage (with the block most downstream showing the largest damage), whereas blocks placed at the bottom of the tank were not effected. Since it appeared that such a drift of the initial electron beam could seriously hinder the trapping of strong electron rings, an explanation of this phenomenon was sought.

A number of possible explanations were proposed and discarded. First, such a drift could be caused by a horizontal gradient of the magnetic field strength. However, a gauss-meter check for field gradients did not reveal any field strength differences of the required magnitudes. Secondly, such a drift could be caused by a canting of the basic mirror field lines relative to the tank axis. This would have required a vertical field of about 10 Gauss and more. However, again no vertical field component even close to this magnitude could be found. Similarly, an interaction of the longitudinal beam current with small field inhomogeneities was considered, but could not bring a satisfactory explanation.

After some experimentation, it was found that this drift could be avoided by 1-2 turns of wire horizontally around the tank and energizing

this coil in series with the basic field coils. In this case, the downstream pattern became almost symmetric around the tank axis (see Figure 19 which shows both the deflected and the corrected beam pattern). The vertical field produced by these additional windings was only about 2 Gauss.

4. Construction of Toroidal Field

Preparations are being made to add a toroidal field coil system to the basic mirror field of RECE-Christa. The system consists of a bundle of four conductors along the tank axis and eight return conductors (2 each in parallel) on the outside of the tank. This coil which is to be driven by a separate 20-kilojoule capacitor bank will produce an azimuthal magnetic field around the tank axis the strength of which is inversely proportional to the radius.

The addition of such a field component is expected to enhance further the stability of the electron rings and the plasma confinement, and more importantly, help to increase the trapping efficiency of the machine. Experiments done previously at Livermore and on the RECE-Berta machine have demonstrated such effects. The stabilization of the precessional dump is well known. In addition, Livermore has reported a dramatic increase of the efficiency of trapping when a large toroidal field $B_\theta \lesssim B_z$ was applied. Also, a number of other effects potentially advantageous for a fusion reactor have been observed. We intend to investigate these effects in more detail and extend the parameter range to $B_\theta > B_z$. Amongst other possibilities, such large toroidal fields will enable us to investigate field configurations similar to the Spherator-Astron scheme,

FIGURE 19. End view of RECE-Christa tank with normal field (top) and with 2 Gauss vertical field added (bottom).

and at the same time, to examine the transition between the Spherator-Astron and the normal Tokamak.

With all the above uses in mind the toroidal field system currently being installed on the Christa machine has been designed to provide maximum flexibility in investigating its effect on the Z-rings. The system itself consists of a 15 kV, 180 micro-farad capacitor bank which is fired through an inductive load of some 60 microhenries. This gives the system a quarter cycle rise time of approximately 150 microseconds to its maximum current point of nearly 30 kA. As the voltage on the bank swings negative the bank is crowbarred giving the decaying current pulse an L/R time of approximately 5 milliseconds. The coil system consists of four loops around the machine giving a total maximum current on axis of 120 kA. This produces a maximum toroidal field of 1 K-Gauss at an average electron ring radius. This field is approximately twice the axial field presently used for 3 MeV electron beam injection and about equal to that used for 5 MeV injection. The short rise time will provide a fast rise time field for compressional studies while the long L/R time will provide an essentially constant toroidal field for trapping and stability studies.

Various components are presently being completed and experiments utilizing this system should begin in June.

IV. CUSP INJECTION EXPERIMENT

Additional experiments were performed also on the small cusp experiment (CHIP) mentioned in the last report. These experiments included both electron beam injection into gas puff introduced by an extra fast acting gas valve and preparations for beam injection into a pre-formed plasma. Puffed-gas injection recently led to the generation of electron rings of about field reversal strength and a lifetime of up to 30 μ sec. This lifetime which corresponds to 10^5 electron orbits significantly adds to our general conclusion that these rings will not be subject to any gross instabilities.

1. Pulsed-Gas Injection

As mentioned in the last report, the lifetime of strong electron rings obtained in the cusp experiment by beam injection into a stationary gas filling was limited to about 10 μ sec. To overcome this limitation, injection experiments using a pulsed gas filling have now been started. For this purpose a pulsed gas valve having an opening time of about 400 μ sec and introducing about 5 at. $\cdot$ cm³ of hydrogen gas into the system was added to the system. The gas flows through various small openings and channels and fills the tank in several hundred microseconds to a final pressure of a few Torr. The electron beam is injected after a variable delay of up to 1 msec. The best results obtained so far are shown in Figure 20. Transient-pressure measurements are in progress to determine the tank pressure distribution existent at injection time.

2. Preparations for Plasma Injection

To increase the lifetime of our rings into the important

8B PROBE SIGNALS

ST'D H₂
5/30/73

PULSED H₂
2/24/74

PULSED H₂
2/24/74

long-time
the cusp
solid and
H₂ gas filling.

msec regime, it will be necessary to reduce the density of scattering centers even further. This could be achieved either by pulsed-gas injection if higher energies are used, or by preionization of the gas filling. In this case, sufficiently fast space charge neutralization is easier than with a neutral gas filling of similar density. To test this idea some first pilot experiments have been and will be performed on CHIP.

The arrangement constructed for this purpose is shown in Figure 21. A magnetic-arc plasma gun was attached to the down-stream end of the cusp chamber. The center-electrode diameter of this gun is 1.2 cm, the outer electrode diameter 3.4 cm. A magnetic coil which is pulsed in series with the main field coil generates a field of 2-4 kGauss in the discharge channel. A puff of gas is introduced by a pulsed valve at the end of the gun. Additional field coils insure a smooth transition between the magnetic field in the gun and the much lower field in the confinement section. Thus, the plasma is expected to flow mainly along these field lines, and the diameter of plasma density distribution will be comparable to the expected diameter of the electron rings. A typical magnetic field distribution along the tank axis is shown in Figure 22. The gun has already operated. First experiments are in progress. Quite important results are expected from this experiment during the coming period.

EXPERIMENTAL APPARATUS

FIGURE 21. Cusp arrangement with plasma gun at right.

FIGURE 22. Magnetic field distribution in cusp experiment with plasma gun.

V. SYSTEMS ANALYSIS FOR A FINAL FUSION REACTOR

During this report period, a detailed systems analysis was performed of the applicability of plasma-internal coils made of high-energy charged particles to the problems of Controlled Thermonuclear Research (CTR). The results of this analysis which is described in a recent report "The High-Energy Particle Coil Approach to Fusion", by H. H. Fleischmann (LPS 143), more technical details will be contained in another forthcoming report, can be summarized as follows: .

- i) The present major fusion approaches, in particular the Tokamak and the Laser-Pellet approaches in their present form, may be able to lead to a successful scientific breakthrough experiment, although some relevant scientific questions still have not yet been answered. However, it appears that considerable improvements, in particular with regard to the achievable power density in Tokamaks and the laser efficiency and economy in the laser-pellet approach, will be needed to make these schemes economically viable.
- ii) The use of internal rings of high-energy ions, in particular in the "Ring Compressor" scheme can bring considerable improvements and economic savings (compared with the normal Tokamak scheme) in the achievable power density and in the magnitude of the necessary external magnetic fields. Although some of the relevant scientific questions cannot yet be answered at this point, the experimental and theoretical results achieved so far, both by the RECE-program and by

other groups, give very encouraging indications concerning a final feasibility of such a scheme. As usual in this report, some of the details of the analysis will be described in the following sections.

1. Analysis of Major Fusion Approaches

A brief analysis of the two major fusion approaches, the Tokamak and the laser fusion approach was made regarding their prospects to achieve the scientific break-even point and economic viability as a fusion reactor concept. Concerning the Tokamak scheme, it appears that the hopes for a successful scientific feasibility test are based mainly on scaling laws observed and developed empirically from the results of present Tokamak machines. Although some questions have been raised by experimental results from the Princeton Spherator, it is generally hoped that these scaling laws can be extrapolated to fusion conditions. In that case, these scaling laws indicate that the Lawson condition can be achieved by increasing all linear dimensions of the ST-Tokamak by a factor 5 - 10, and a simultaneous slight increase in the magnetic field strength. The necessary temperatures are to be reached by neutral-atom injection.

Although it seems that scientific feasibility may be achievable with a Tokamak device, still sizable improvements over presently observed scaling laws and limits have to be accomplished, to produce an economic fusion reactor of this type. These limits mainly are determined by the Freckal-Shafranov stability requiring that $B_{pol} \leq (a/R) (1/q) B_{toroidal}$ (a = minor radius, R = major radius, q = 3 "safety factor"). For all

experimental cases so far this necessitates $B_{pol} \leq (1/10) B_{toroidal}$. On the other hand, it was found in all Tokamaks so far that $nKT = \mu_0 B_{pol}^2 / 2$ (with $B_{pol} = .3 \dots .7$). Therefore, considering that $B_{toroidal} = 60$ kGauss would constitute an upper limit for a large reactor (caused by technological and engineering considerations), these scaling laws limit the average density of power production to about $50 - 100 \text{ kW/m}^3$. Thus, with $a/R = 1/3$, one obtains a major radius, $R \approx 15 \text{ m}$, and a minor radius $a \approx 5 \text{ m}$. Considering that the entire vessel has to be covered by a lithium heat exchanger, that the entire volume (incl. heat exchanger) has to be filled with an average magnetic field of 60 kGauss, and that also a large neutral-atom beam (20-30 keV and several thousand amperes) is needed for plasma heating, it appears unlikely that such a reactor can economically compete with power generation from fossil fuels.

Concerning the laser-pellet scheme, it appears that most of our hopes presently rest almost exclusively on theoretical calculations. No conclusive experimental tests of the various possible scientific obstacles have been performed so far. Also, so far none of the lasers has reached the necessary energy density, and possibly even more important, the per-shot operating costs of present high-power laser systems is larger by about 6 orders-of-magnitude than the value of the energy to be gained from one shot of a 10 - 100 times stronger laser. Thus, the economics of such a system appear at least as strained even if such a reactor could be built technically.

2. The Ring Compressor Scheme

As an example for the application of trapped high-energy charged particles for field forming in a fusion reactor, a new "Ring

Compressor" scheme has been considered. According to this scheme (see Figure 23) the fusion plasma is to be confined in a Spherator-Astron-like configuration in the center of the machine. This current ring is to be maintained by trapped high-energy (several hundred MeV) ions. To generate it, a larger ring is produced by injection of lower-energy ions on the left side. This large ring is then compressed magnetically into the center, whereby the energy of the ions and the temperature of the contained plasma is increased very efficiently by a factor 10-20. The energy remaining in the ring after its fusion burn in the machine center can be extracted quite efficiently by subsequent adiabatic expansion into the right chamber. The inherently high efficiency of the magnetic compression and expansion cycles permit an energy gain factor of about 10 when the generated fusion energy is compared with the expended energy per cycle.

The externally applied magnetic fields in this scheme could be limited to about 15-20 kGauss axial field in the center decreasing to about 1.5-2 kGauss in the outer chambers. The toroidal field generated by current along the tank axis is expected to be of similar size (i.e., in the vicinity of the plasma ring).

The plasma confinement characteristics of such absolute minimum-B configurations have not yet been tested experimentally. However, both theoretical considerations and experimental results on average-minimum-B machines are very encouraging, indicating classical confinement in some cases. Considering also the close geometric similarity of these rings with a Tokamak discharge, it is felt that the plasma pressure that can be confined in such an arrangement is limited by the total field pressure of the self-field of

Fig.23 Basic Ring Compressor scheme

the rings which is roughly equal to the externally applied fields. Thus, it should be possible to obtain actually confining fields of around 15-20 kGauss. Since the achievable power density increases proportional to the fourth power of the magnetic field, this increase in B would mean an increase by a factor of 40 - 100. Even if such a factor could not be fully achieved in an actual reactor, still a considerable reduction in the size of the rather expensive plasma burn region could be expected, which in turn only would have to be filled with 15- 20 kGauss fields instead of the 60 kGauss necessary in Tokamaks. From this fact, very sizable economic savings could be expected.

As any of the other prospective fusion systems, this Ring Compressor scheme raises a number of presently unknown scientific questions. These questions concern the generation and gross stability of these rings, its stability against micro-instabilities, and its plasma confining qualities. The Cornell experiments have shown that electron rings of this type actually can be generated. Furthermore, the recently successful stabilization of the precessional dump by external quadrupole fields has a good chance to open the way for a generation of proton rings by (relatively cheap) slow injection of H_2^+ -ion beams of about 10 A and several MeV. The question of gross stability appears increasingly less menacing. Strong electron rings have now been observed in RECE-Christa, for up to 250 μ sec, and in the cusp experiment for over 80 μ sec. Also, the observed stability of the rings even against external field perturbations constitutes a very encouraging evidence in this direction. Concerning the question of micro-stability, the present experiments cannot

yet provide a definite answer, however, the present results are also very encouraging in this area. More detailed theoretical estimates which include all effects in a realistic reactor are not available at this time. Most of these effects tend to make the rings more stable when compared with the idealized cases treated theoretically. As mentioned, the question of plasma confinement is argued well both by earlier theoretical results and by experimental observations on average-minimum-B configurations.

VI. THEORETICAL CALCULATIONS OF MAGNETIC IMAGE INDICES

Both for the theoretical analysis of the equilibrium displacements under the influence of magnetic field gradients and for the analysis of the dump remaining after cancellation of the external gradients, the magnetic field indices associated with the image currents in the tank wall generated by the trapped rings were needed. Since the corresponding "image indices" were not available from the literature for the parameter range of the experiment, they had to be calculated separately. The details of this calculation will be described in a report "Calculation of Magnetic Image Indices for Short Electron Rings", by D. M. Wsodall et al., which is presently being prepared.

Earlier calculations of these indices by two theoretical groups had considered only the case of a very thin current cylinder with periodic current density. However, for the strong short rings obtained in our experiments, this approximation can no longer be maintained since adjacent current loops can seriously influence the magnetic field distribution in the vicinity of another ring. Therefore, a harmonic expansion of various finite current distributions was made, and the resulting magnetic field distributions calculated. Figure 24 gives an example of the results comparing them with the earlier results of Beal et al., and Berk and Sudan. Very clearly, the latter results provide much too small values for the image index, for short rings where the full-width-half-maximum (FWHM) of the current distribution is comparable or smaller than the wall radius, R_{wall} . As further addition of our theory, the proper averages of the field

COMPARISON OF MODEL 6

FIGURE 24. Comparison of newly calculated image indices with the earlier results of Beal et al., and Berk and Sudan.

indices over the current distribution of the rings was calculated ($\bar{K}$'s). As to be expected, these average indices are about equal to the non-averaged for very short rings but smaller for long rings. Figure 25 shows the corresponding results for various current density distributions along the rings. It appears that the results for the various distributions do not vary seriously, so that average values could be used for the analysis of our experiments. Figure 26 finally shows the same calculations for a rectangular current distribution which can be compared directly with some results of our dummy coil experiments. The agreement between the calculated and measured values certainly is quite consoling.

Furthermore, a number of cases have been calculated in which electron rings with a finite radial thickness were simulated by superposition of a few thin rings of different radius. Again, no significant differences of the final indices are obtained if these rings are normalized to comparable magnetic field distributions.

VARIATION WITH AXIAL SHAPE

FIGURE 25. Comparison of image field indices for various current distributions.

FIGURE 26. Image indices for rectangular current distribution with experimental check points.