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RESULTS OF FM-1 SPHERATOR
EXPERIMENTS AND POSSIBILITY
OF ELECTRON-COIL
FUSION REACTOR

BY

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PLASMA PHYSICS
LABORATORY

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Results of FM-1 Spherator Experiments and Possibility of
Electron-Coil Fusion Reactor*

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ABSTRACT

Experimental results of the FM-1 spherator experiments are reviewed. The important conclusions obtained so far are (1) that plasma confinement times are near classical if the plasma temperature is low enough for a fixed plasma density, (2) that the plasma confinement times are limited to 300 times the so-called Bohm time as the temperature increases, (3) plasma loss can be caused by several reasons, and (4) in particular, fluctuations which behave consistently with the theoretical prediction of trapped-particle instabilities appear to dominate the plasma loss processes. This result, along with the recently developed experiments and theories on electron-coil systems, suggests that an electron-coil fusion reactor may be a possible fusion reactor of comparatively stable property and compactness in size.

* Talk given at APS, Plasma Physics Division Meeting held at Monterey, California, November, 1972.

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The experiments on plasma confinement can be considered as the succession of experiments to find out the scaling laws. Until the middle of the decade of 1960, the plasma confinement times observed experimentally apparently followed the so-called Bohm law,^{1,2} which states that the confinement time is proportional to B and inversely proportional to T_e so that the plasma confinement time is 1 msec at 50 kG, 50 eV and the plasma radius of 5 cm. For a considerably large density range (10^9 to 10^{13}), this law held as well as for the wide range of the electron temperature (0.1 eV - 100 eV). The mechanism for this loss is attributed to plasma fluctuations which, from the present point of view, is only half-true. I think nobody disagrees that fluctuations are the major if not the sole causes of the plasma loss in this region, but it appears that the better confinement time does not necessarily mean less fluctuation.

Actually, no universal theory exists that predicts the fluctuations will lead to Bohm diffusion. I suspect Bohm confinement time is essentially the lower limit of the confinement time of MHD-stable plasmas and nothing else. Indeed, various assumptions lead to the diffusion coefficient $(\delta n/n)^2 kT_e/eB$ as shown in Table I. If the experimentally determined upper limit of $\delta n/n \sim 0.3$, we get roughly the Bohm diffusion.

The experiments on plasma confinement after 1965 start to show that the plasma confinement times are actually longer than predicted by the Bohm formula. Those experiments are done in tokamaks and multipoles including the spherator. The FM-1, which is a spherator, experiment is an end-product of a series of experiments to demonstrate that the plasma confinement does not follow the Bohm scaling law.

The results of these experiments up to 1970 can be best summarized as follows: The data show the disagreement with the Bohm and that the confinement time obeys the classical diffusion law in its dependence on density, electron temperature, and, rather in limited region, magnetic field. Except for the result of octupole at General Atomics,³ however, there is a reduction in the absolute magnitude from the classical calculation even including the neoclassical theories.

This coupled with the observation that theoretically there is no strong advantage of tokamak over stellarators as far as the stability concerned leads us to explore the assessment of fluctuations in enhancing the classical diffusion. In the region of large collision where the mean free path is short compared to the plasma scale length leads to the so-called pseudoclassical diffusion^{4,5} as shown in Table II. The important point is that the diffusion coefficient is determined by the poloidal magnetic field, not by the toroidal magnetic field. Indeed, for the C stellarator where equivalent poloidal magnetic field is approximately 1/100 of the toroidal magnetic field, we expect that the confinement time can be 10^{-4} of the classical confinement. The neoclassical effect, of course, reduces this theoretical classical value. The calculated pseudoclassical diffusion time for the C stellarator experimental ranges is usually less than the Bohm time. Thus, if we say that the Bohm time is the lower limit of the plasma confinement time, we expect that the confinement time is bounded from below by Bohm time and pseudoclassical diffusion time.

Indeed, it is so, as shown in Fig. 1. This figure was made three years ago to summarize the then-existing data. Note that subsequently the experimental points were moved to merge into the main sequence. We note that for the ratio of τ/τ_B to 100, there is a reasonably good agreement. In PLT⁶ the

ratio τ_{pc}/τ_B reaches 1000.

The summary of conclusions from pseudoclassical diffusion is shown in Table III.

As a scientist, if confronted with this data, the obvious desire is to know what will happen as τ_{pc}/τ_B is increased. Does the τ/τ_B increase indefinitely? Well, present stellarators preclude, because of the expense involved in research devices, the possibility of reaching high τ_{pc}/τ_B . The tokamak does not have that difficulty, but the plasma density cannot be reduced. That leaves the floating ring experiment as only source of going to large τ_{pc}/τ_B . We have at present in our FM-1 this ratio reaching 3×10^5 experimentally in plasmas which are believed to be Maxwellian.

The FM-1, though initially conceived to test whether τ/τ_B can be made more than 10 to 100, is now, therefore, an ideal device to test the pseudoclassical diffusion law.

In Fig. 2, the cross-sectional view of FM-1 is shown. A superconducting coil formed in a jacket with the surface at room temperature is levitated by a levitation coil magnetically and stabilized by 5 sets of asymmetric stabilizing coils. Typical field error induced by these stabilization systems is much less than 0.2% as compared with 10% when we started the experiments in the spherator. The field error of $\sim 0.2\%$ of FM-1 is due mainly now by the asymmetry of the center ring. The external coils combined with this internal ring produce the magnetic surfaces. One of the magnetic surfaces is shown in the figure. The toroidal field is necessary to provide the stability by shear and minimum average B.

The parameters of experimental range are shown in Table 4. It is possible to keep the ring as long as 10 hours in levitation. Please note that the electron density is relatively low. This allows us to heat the plasma to high

temperature with modest means of heating. This in turn enables us to achieve the large τ_{pc}/τ_B ratio.

The procedure of the experiment is as follows. After the ring is completely levitated, neutrals are introduced to the desired value. Then discharge cleanup using the rf pulses, usually one per second or two, follows. After 1 or 2 hours of this, the experiment starts. For plasma confinement experiments, the resonant microwave pulse is followed by two different non-resonant microwave pulses of different power level as shown in Fig. 3. As the power level changes, the electron temperature changes. The temperature usually remains constant when the steady state level is attained. Computer calculation of time behavior can be done, assuming only the efficiencies of microwave heating and confinement times, the agreement between experiment and theory is satisfactory.⁷

This figure is only representative of the plasma confinement measurement. In fact, we measure the loss to the wall and indeed the loss increases as the density decay becomes faster. The electron temperature measurement shows that the ionization is not important, and, in fact, no excitation light of helium is seen after the resonant heating. The computer calculation also shows that there is practically no ionization. The temperature range we are talking about here is less than 5 eV.

The reason why we have two nonresonant heating pulses is that immediately after the resonant heating, the density profile is not the normal mode profile. Thus, we keep the plasma for awhile and study the confinement time later. At the second pulse, the initial condition is then essentially the same.

People may raise the possibility that runaway electrons may be produced. In fact, if we do not introduce neutrals, very nice runaway electrons can be produced as shown in Fig. 4. Here, synchrotron radiation coming out from the

runaway electrons produced by the resonant heating is shown as a function time after the heating was stopped. Note that the decay time is of the order of 50 seconds. Well, how do we know that there are no runaways in our regular discharge?

In testing that, we dropped a stainless ball through the confinement region as shown in Fig. 5. The top picture is the synchrotron radiation of Fig. 4 in a greatly expanded time scale. After the pellet was dropped, in 0.4 sec when the ball reaches the confinement region synchrotron radiation drops to zero level. Thus, we know the runaway electrons are wiped out. We do the same thing for regular discharges as shown in lower two traces. Both have identical conditions except that in one case, the pellet was dropped. As far as we can see, there is no change in the density decay as well as loss to the wall. Please also note that the loss to the wall increases as the nonresonant heating stops indicating that confinement time indeed becomes worse as the temperature cools down. This, of course, contradicts the Bohm diffusion law.

Now, how do the results look? They are shown in Fig. 6. We see that the plasma confinement indeed increases with the temperature up to certain limit and then goes down. In the rising part, there is density dependence consistent with the classical or pseudoclassical diffusion. In fact, numerical calculation shows that our results are about $1/4$ of the classical confinement time and comparable to the pseudoclassical diffusion time. However, above 1 or 2 eV, the confinement time is limited to 300 times Bohm as shown. The result of the smaller levitated spherator is also shown and shows the same behavior. I think it is important to summarize this result in Table V. Because the conclusion drawn from this experiment has a very important implication for future toroidal confinement experiments.

As you know, for a given experimental device, it is usually very difficult to change the plasma parameter. Recently, we have been applying high resonant power to achieve the high electron temperature and determine the plasma confinement times. So far, we have obtained preliminary information of electron temperature and its decay through the diamagnetic signal. The decay may be caused completely by the inelastic collision of electrons. The results are shown in Fig. 7. We may conclude that the results are certainly not inconsistent with our view that the confinement time is less than $300 \tau_B$ although we need a little more measurements to be really certain. There is an experimental point at the right hand corner, this is the confinement time of tenuous 100 keV plasma but presumably isotropic in velocity distribution. I put it there to warn that our extrapolation may or may not work to still higher electron temperature.

In terms of the diagram of τ/τ_B vs τ_{pc}/τ_B of Fig. 1, we get the result presented in Fig. 8. We then ask two key questions. One is, is this universal effect or limited to the spherator? The second is, if universal, what can be responsible? At present, we do not know but we can guess. For the first question, we might say that fluctuations are responsible but fluctuations are somehow connected with this particular heating. To answer that we only point out that the loss does not immediately rise as the microwave power is applied, but appears to increase only when the electron temperature is increased. Also, in the tokamak, as the density decreases so that τ_{pc}/τ_B increases, there is a tendency for the confinement time to become less than the pseudoclassical prediction. Finally, even in an octupole of Gulf General Atomic,³ there appears to be limitations. Thus, I think, the answer to the question of whether this is a universal phenomena is tentatively, yes.

The second question of what is responsible for fluctuations, is presently under investigation and I think, it is fair to say that no agreement as to the

cause is obtained, although it is almost certain that fluctuations and/or field error are responsible. Yet the pseudoclassical diffusion law is supposed to show the upper limit. Then why is there a discrepancy? The answer appears to be that the dissipation of the diamagnetic current is enhanced by the electron-plasma interaction⁸ as shown in Table VI. This is probably right, but a little more theoretical calculation is necessary.

For the particular mechanisms which restrict the plasma confinement experiments including ours have shed considerable amount of light recently. Contrary to the commonly-held belief of the sixties, now we know various effects such as (1) fluctuations, (2) field error,¹⁰ and (3) impurity (e.g., air in helium) contribute to the reduction in the plasma confinement. Some of the results are given elsewhere, so I will not elaborate here. Each effect is equally important. Indeed in the FM-1, the effects of fluctuations and field error are about equally important. For if we reduce the stability condition slightly or if field error is increased over the designed value, the plasma loss can be reduced in half very easily. The effect of impurity is as bad. We have to insist on very good background pressure to obtain the best confinement time such as 2.5 sec.

In principle, however, we can avoid causes (2) and (3) but cause (1) cannot be avoided, unless stable configuration is found. Although the spherator configuration is supposed to be stable against almost all instabilities including trapped particle instabilities, the system is not stable against collisional trapped particle instability. The fluctuations are observed which may or may not be related to this instability in the temperature range between 0.1 eV to 10 eV to be discussed elsewhere in detail by Dr. Meade et al.

If we accept our existing theoretical analysis at face value, the plasma stability is very much dependent on whether trapped particles are trapped in bad curvature or in good curvature as shown in Fig. 9. We have done an

experiment to compare the result. The result is shown in Figs. 10 and 11. We note that the plasma confinement is greatly reduced in the unstable configuration. But, as I said, even the stabler configuration still has a finite theoretical growth rate and, in fact, experimentally we observed the existence of the fluctuation.

Theoretically, however, at higher temperature in good curvature, such as 100 eV for the same density, the plasma should be stable as the growth rate of the collisional trapped particle instability will go down as shown schematically in Fig. 12. If the curvature is bad, however, we expect the result shown in the dashed line in Fig. 12. We are currently investigating this prediction in the FM-1 by going high electron temperature.

There are many other experiments which were performed on the FM-1. Some of them have been reported already, and I shall show you just the titles and the physicists in Table VII.

The summary of FM-1 results that I covered is shown in Table 8. Each one of the results is important in assessing the future of tokamak-type plasma confinement. In particular, the number (1) applied to the tokamak indicates that the plasma confinement may not exceed 200 msec (at $T_e = 5$ keV) even for the PLT tokamak being constructed at Princeton and, in fact, the situation may be worse than that if the result (3) holds for the tokamak, as PLT operates closer to the collisionless limit where collisionless trapped particle instability becomes important. In this context it is significant to remember that the observed maximum confinement time in tokamaks has only doubled in this current five years (from 1968 to 1972) from 5 - 10 msec to 10 - 20 msec, and the maximum τ/τ_B is perhaps less than 10 to 100. Also, the agreement between theory and experiment in tokamaks is at present purely limited to MHD theory,

and fluctuations due to micro-instability have not been studied. Thus, if we extrapolate, we may have rather unpleasant surprises in store for the tokamak. Unfortunately, this important aspect was rather ignored compared with the understandable, optimistic desire of everybody to win the race of building a fusion reactor first.

In order to study the physics of the tokamak, perhaps we should be more modest and try to build research-oriented tokamaks to gain the understanding of mechanisms operating in tokamaks. At the same time, it is useful to try to expand the parameter range of multipole devices, such as the FM-1, to bridge the gap which now exists with tokamaks. The second important inference I can make is as an alternative to the tokamak that is, is it possible to make a spherator-like fusion reactor? I think the answer is Yes. This leads to the second title of my talk, namely, electron coil. If we can replace the superconducting coil by a relativistic-electron coil, the plasma could be contained equally well. Although probably we are limited to $300 \tau_B$, the relativistic electron coil system can allow the particles trapped in a good curvature section, thus avoiding the problem(3).

The configuration I call spherator-astron, is shown in Fig. 13. The relativistic electron-beam can be used to create the rotational transform, shear, and magnetic well. The problem, if our experience with FM-1 can be any guide, is then the stability of the electron ring and not the plasma. If you recall, I have mentioned that high energy electrons can be contained for 50 seconds or more in the spherator, and, at the Oak Ridge National Laboratory, it is reported that much higher density electrons were kept for several seconds. Thus, I am rather optimistic about the containment of electrons. The fact that electrons carry current, makes this ring susceptible to kink instability.¹² But Dr. Lee's calculation shows that the ring may be stable

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Please insert Table X which was
omitted in error.

Table X. Possible Parameters of Astron-Spherator
As a Fusion Feasibility Experimental Device

Aspect Ratio R/a	2
$q = 2\pi/l$	0.5
B_t	20 kgauss
a	20 cm
Volume	$3.2 \times 10^5 \text{ cm}^3$
Power Required	320 kWatt (for $\tau = 1 \text{ sec}$)

J. Gust D

even for a rotational transform higher than 2π if the beam energy is high. This makes the spherator configuration possible with attending stabler plasma configuration. Theoretical equilibrium calculation and experimental evidence also show that the ring current can exceed easily the so-called Alfvén limit with relatively low synchrotron radiation loss.⁸

The electron-coil construction is not so difficult at least on paper and there have been many instances of that in Oak Ridge, Cornell, and Livermore. Also various toroidal devices have demonstrated the existence of electron coils for the time up to 1/10 of a second. There are several methods of making coils: they are shown in Table IX. I think it is harder to make preference at this stage, I think a continuation in study of all 5 methods is necessary at this stage. One advantage of this as a fusion machine is a compactness, especially of the pseudoclassical diffusion law somehow applies. An example of fusion reactor is shown in Table 10. Note that the plasma volume is even smaller than the FM-1 and the magnetic field is relatively weak.

Coming back to my conclusion, I think, at present, FM-1 results try to tell us that there may be difficulty ahead in the tokamak and we should prepare for it.

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Table I. Bohm Diffusion

$$\tau = \frac{B(kG)}{T_e(eV)} \left(\frac{a(cm)}{5} \right)^2 \text{ msec}$$

Comes from:

$$D = \frac{1}{10} \frac{kT_e}{eB} \quad (\text{M.K.S.})$$

This can be derived from

$$D \approx \frac{a \langle \delta n E \rangle}{B n_o} \rightarrow \left(\frac{\delta n}{n_o} \right)^2 \frac{kT_e}{eB}$$

Also should be less than

$$\left| \frac{\delta n}{n_o} \right| \frac{kT_e}{eB}$$

a: density scale distance

δn : density fluctuation

Table II. Pseudoclassical Diffusion

$n = n_o + \delta n \rightarrow$ for given density gradient, $J_{||} \neq 0$

Calculate $\sqrt{J_{||}^2 + J_{\perp}^2}$

The diffusion coefficient $D_{pc} = D_{cl} \left(1 + \frac{J_{||}^2}{J_{\perp}^2} \right)$

$$D = D_{cl} \left[\left\langle \frac{k_{\perp}^2}{k_{||}^2} \right\rangle \left(\frac{\delta n}{n} \right)^2 + 1 \right]$$

In toroidal device $\langle k_{\perp}^2/k_{||}^2 \rangle \gg 1$

Then

$$D \lesssim CD_{cl} \left(\frac{L_{||}^2}{L_{\perp}^2} \right) \approx CD_{clp} \propto \frac{n}{(T_e)^{+1/2}} \frac{1}{B_p^2}$$

$$\tau_{pc} \gtrsim \frac{a^2}{CD_{clp}} \propto \frac{L^2 (T_e)^{+1/2}}{n}$$

Table III. Pseudoclassical Diffusion Theory Explains

- (a) The difference between stellarator and tokamak.
- (b) The confinement times of multipoles, stellarators, and tokamaks in wide range (100 μ sec to 2.5 seconds).
- (c) That fluctuations or convective cells are equally bad for plasma loss.
- (d) Why β_p is constant in tokamaks.

Table IV. FM-1 Parameters (as of Nov. 1972)

Ring current	150 - 250 kA
Typical magnetic field	2 - 3 kG
Toroidal field current	0 - 250 kA
Base pressure	2×10^{-8} Torr (best)
Filling pressure	5×10^{-7} - 2×10^{-6} Torr
Plasma volume	5×10^5 cc
Plasma radius	5 - 10 cm
Gases used	Helium (mainly), D ₂ , A, etc.
Electron density	10^{10} - 10^{12} /cc
Electron temperature	0.1 - 100 eV (or more)
Ion temperature	Less than 5 eV
Confinement time	1 ms - 3 sec
Methods of plasma production	Microwave heating and others
Stabilization	Shear, Minimum $\bar{B}$, short connection length
Field error	Typically 0.2 %

Table V. FM-1 and LSP Experimental Results

T_e 0.1 - 10 eV (reasonably secure)

10 eV - 100 eV (less secure - following slide)

$$\tau = \text{Min} (300 \tau_B, \tau_{pc})$$

Experimentally τ_{pc}/τ_B to 5000 (secure)

to 3×10^5 (less secure)

Table VI. Modification of Pseudoclassical
Diffusion at High Temperature

If v_e is so small that

$$v_e \ll \omega_b = \frac{v_e}{L}$$

L: characteristic length

Then v_e may be replaced by the electron wave interaction
(or electron-phonon). Then

$$v_e \rightarrow Ck, v_e$$

If so,

$$D \sim T_e^{3/2}$$

Nonlinear effect may make $D \sim T_e$

Table VII. Experiments Carried Out in FM-1

1. Runaway electrons	Chen et al.
2. Hybrid resonance heating	Hooke et al.
3. OH heating & ICRH	Schmidt et al.
4. Fluctuation studies	Meade et al.
5. Perpendicular conductivity measurement	Okabayashi et al.
6. Confinement studies	Okabayashi et al.
7. Field error studies	Schmidt et al.

Table VIII. Conclusions of FM-1 Results

1. Agrees with pseudoclassical diffusion to τ/τ and is limited to $300 \tau_B$.
2. Several factors can be responsible for anomalous plasma loss.
3. Field configurations such as whether trapped particles in good curvature or bad curvature are important.

Table IX. Five Methods of Electron Coil Production

- (1) Runaway discharge tokamak.
- (2) Relativistic-electron cloud + OH.
- (3) Astron (Injection of good quality beam and slowdown by resistor).
- (4) Injection of high intensity beams, use of diode-device and injection
- (5) Production of intense beam in the toroidal chamber itself by applying a very strong electric field.

Note: Possibly combination of these methods may be necessary.

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Fig. 1. The observed confinement times vs the pseudoclassical diffusion time. Both times are normalized by Bohm time (from Ref. 4).

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Fig. 2. The cross-sectional view of the FM-1 spherator.

723574

Fig. 3. The behavior of helium plasmas as different levels of microwave heating were applied.

723606

Fig. 4. The decay of synchrotron radiation by high-energy-electrons after the microwave heating was terminated.

723131

Fig. 5. The effect of dropping a stainless ball of a quarter-inch diameter. The ball traverses through the plasma in approximately 100 msec. The upper picture is a synchrotron radiation of the previous figure in a greatly-expanded time scale. The radiation drops to zero as the ball wipes out the high-energy electrons. The lower pictures are the density (interferometer) signals and the plasma loss measurement of normal discharge where synchrotron radiation is not observed. The dropping of the ball does not affect the plasma behavior.

723441

Fig. 6. Plasma confinement times vs the electron temperature. Both FM-1 and LSP (predecessor of FM-1) results are shown. The plasma was tested by the methods of Fig. 3.

723575

Fig. 7. Confinement times vs the electron temperature extended to higher electron temperatures by means of high power heating.

723576

Fig. 8. The summary of the results in terms of confinement times vs pseudoclassical diffusion times as normalized by Bohm time.

713559

Fig. 9. The schematic view of plasma particle trappings. If the particles are trapped between the levitated ring and the center conductor, they tend to see a stable curvature drift.

Comparison of Two Magnetic Field Configurations

Particles Trapped in Good Curvature

Particles Trapped in Bad Curvature

STANDARD: $I_{EF} = 2.0$ kA

$I_{EF} = 1.2$ kA

200 ms/div →

200 ms/div →

20 cm 10 cm
ring outside

20 cm 10 cm

J^+
500/d
 δJ^+
20/d

723592

Fig. 10. The result of two experiments where the externally applied field was changed to move the trapping from the good curvature section (strictly speaking either good or less bad curvature) to the bad curvature section. Note that the plasma density decays much faster, and that the density profiles show marked fluctuations. The density profiles spread out in the bad curvature case as the magnetic surfaces bulge outwards.

713606

Fig. 11. Plasma confinement times vs different external magnetic field coil current. As the coil current is lowered, the trapping tends to be more at the bad curvature. Two different pressures were used, as, at lower coil current, the breakdown becomes much more difficult. This was done in the LSP spherator.

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Fig. 12. Schematical presentation of growth rate of the instability.

713174

Fig. 13. The spherator-astron. The internal conductor is replaced by a relativistic electron ring (see Ref. 8).

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