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PARTICLE DIFFUSION IN A SPHE. MAK

By

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Particle diffusion in a spheromak

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Abstract

The local carbon particle diffusion coefficient was measured in the Proto S-1/C spheromak using a test particle injection scheme. When the plasma was not in a force-free Taylor state, and when there were pressure gradients in the plasma, the particle diffusion was five times that predicted by Bohm and was consistent with collisional drift wave diffusion. The diffusion appears to be driven by correlations of the fluctuating electric field and density. During the decay phase of the discharge when the plasma was in the Taylor state, the diffusion coefficient of the carbon was classical.

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The spheromak[1] is a compact toroidal magnetic fusion device with an aspect ratio close to one. It has features which are favorable for reactor design. The lack of magnetic field coils linking the plasma allows the translation and compression of the plasma, as well as a simple reactor blanket design.[2,3] The confining magnetic fields are generated primarily by the currents carried in the plasma, allowing high values of engineering β to be obtained. The engineering β is the ratio of the plasma pressure to that applied by external magnetic fields, and higher values may reduce reactor costs.

Spheromaks, and the closely related Reversed Field Pinches, have the tendency to relax to magnetic field configurations which are close to the minimum energy states predicted by Taylor.[4] The minimum energy states, subject to the conservation of the global helicity, are force-free,

$$\vec{j} \times \vec{B} = \vec{\nabla} p = 0 \tag{1}$$

and satisfy,

$$\vec{\nabla} \times \vec{B} = k\vec{B} \tag{2}$$

with k a constant throughout the plasma. It is worth noting that a plasma device with $p = 0$ at the edge cannot be in the Taylor state and have a finite temperature and density at the center, so the process of relaxing towards the Taylor state may enhance the energy loss mechanisms of the plasma. One energy loss mechanism is convection, the energy carried out of the plasma by particles which have a finite confinement time.

This Letter presents the results of direct measurement of the local carbon particle diffusion coefficient on the Proto S-1/C spheromak.[5] During the decay phase of the discharge, the diffusion of the carbon ions could be explained classically. During the relaxation phase of the discharge, the anomalous perpendicular diffusion coefficient, $D_{an} = D_{\perp} - D_{cl}$, was approximately five times that predicted by Bohm[6] and was caused by electric field fluctuation- induced velocities. The electric field fluctuations and the value of D_{an} were consistent with those expected from collisional drift waves.

For carbon ions in a hydrogen plasma, the classical diffusion coefficient is,[7,8]

$$D_{cl} = 3.5 \times 10^{-4} \frac{n_{H} \ln \Lambda}{\sqrt{T_{H}} B^{2}}, \tag{3}$$

where the Coulomb logarithm is $\ln \Lambda = 23 - \ln \sqrt{n_H}/T^{\frac{3}{2}}$. The spheromak is a $q < 1$ device, so that neoclassical transport is unimportant.

Bohm[6] proposed that fluctuating electric fields in the plasma would lead to a diffusion coefficient larger than classically predicted, and would scale inversely with the magnetic field,

$$D_{B} = \alpha \frac{cT}{eB}. \tag{4}$$

Bohm[6] took $\alpha = 1/16$. It has been found that the diffusion coefficient due to convective cells, has a similar form as Eq. (4).[9–11] Hassam and Kulsrud[12] pointed out that in a toroidal system the convective cell is an interchange mode to which spheromaks are expected to be unstable at relatively small values of plasma β.[1]

The Proto S-1/C spheromak plasma[5] was formed inductively using a flux core which has minor and major radii of 6 and 30 cm, respectively. The plasma typically had a major radius of 16 cm and a minor radius of 12 cm. The plasmas, which lasted for 100 μsec, had magnetic field strengths of $1-2$ kG, and electron temperatures and densities of 8 eV and 1×10^{14} cm^{-3}, respectively. The spatial and temporal evolution of the electron temperature and density were measured with a triple Langmuir probe.[13] The electron-ion equilibration time is roughly 5 μsec so the ion temperature is assumed to be equal to the electron temperature. By quasineutrality the ion density was assumed equal to the electron density. The ratio of kinetic to magnetic pressures in the plasma, β, was roughly 10%.

The plasma lifetime can be divided into distinct phases. After the breakdown of the initial fill gas, the plasma undergoes a violent relaxation towards the minimum energy Taylor state.[4,14] During this phase, there are large magnetic fluctuations, $\frac{\delta B}{B} \gtrsim 10\%$, throughout the plasma. The magnetic fluctuations were measured with internal and external, glass encased probes. The observed fluctuation levels were unaffected by the number of probes in the plasma. At roughly 30 μsec, there is a large drop in the total poloidal flux in the plasma, accompanied by externally observed global magnetic modes, with poloidal and toroidal mode numbers, $m = 1$, and

$n = 2 \sim 4$. These appear to be due to the relaxation of resonant modes[14,15] as was observed in the S-1 spheromak.[14] After the reconnection of the modes, the plasma, with $\vec{\nabla} p \neq 0$, continues to evolve towards the Taylor state, which has $\vec{\nabla} p = 0$, while the magnetic fluctuation level at the center of the plasma was less than 1%. This relaxation phase of the discharge, lasted from $30 \sim 60\,\mu$sec. From $60 \sim 100\,\mu$sec, the plasma was in the force-free Taylor state,[1,4] referred to as the decay phase of the discharge, as the currents in the plasma were no longer externally driven. After $100\,\mu$sec, the plasma was terminated by a global, $n = 1$, tilt instability.[16]

The carbon particle diffusion coefficient was measured by injecting a delta function source of carbon ions at the midplane of the plasma and observing the evolution of the injected density spectroscopically. The technique. which has been described in detail elsewhere,[17] allows both $D_{\parallel}$ and $D_{\perp}$ to be locally measured. A schematic of the basic setup is shown in Fig. 1. A probe, with two graphite tips is discharged in the plasma, injecting primarily CII ions (spectroscopic notation) into the center of the plasma. The cross-field evolution of the injected density is determined by the perpendicular diffusion coefficient. The gradient lengths and time scales for change of the injected carbon ions were shorter than those in the background plasma so that the changes in the background plasma were ignored. This was also consistent with the short equilibration times in the plasma, and the small amount of carbon injected compared to the amount in the device. The analysis of the diffusion coefficients included the effect of convection and ionization, with all of the convection observed due to the motion of the magnetic surfaces.

During the decay phase of the discharge, the measured diffusion coefficients on the closed flux surfaces were compared directly to the classical values. For all of the discharges examined the electron temperature had a constant value of 8 eV within the error bars. Figure 2 shows the electron density versus magnetic field during the decay phase of the discharge. The electron density can be taken as a linear function of the magnetic field strength leading to a classical carbon diffusion coefficient of

$$D_{\rm cl} = \frac{1.3 \times 10^8}{B} ({\rm cm}^2/{\rm sec}),$$

with B in Gauss with a roughly 30% error. The measured values of the carbon diffusion coefficient in the decay phase are compared to this value in Fig. 3. Also shown is the calculated value for $D_\perp = D_{\rm cl} + 5D_{\rm Bohm}$, which is discussed below.

The diffusion coefficient during the relaxation phase of the discharge was higher than classically predicted. Figure 4 shows the carbon diffusion coefficients measured during the relaxation phase compared to $D_\perp = D_{\rm cl} + 5D_{\rm Bohm}$. During this phase of the discharge, the density was independent of the magnetic field strength so the classically predicted diffusion coefficient was $D_{\rm cl} = 1.25 \times 10^{11}/B^2$. In this case, $D_{\rm Bohm}$ includes the factor of 1/16,

$$5D_{\rm Bohm} = \frac{2.5 \times 10^8}{B}(\mathrm{cm}^2/\mathrm{sec})$$

with a 40% error. At this time, the magnetic fluctuation level was less than 1%. Thus, it appears that a combination of classical and Bohm diffusion is sufficient to explain the measured carbon diffusion coefficients.

A triple probe was used to measure the correlations of the electric field and density fluctuations.[18] The electric field in the direction perpendicular to the magnetic field in the flux surface was measured with a pair of tips, while a third measured the density. The particles undergo an average $\vec{E} \times \vec{B}$ drift when the fluctuations are correlated,[18]

$$v_{\vec{E}\times\vec{B}} = \frac{c}{B} < \frac{\delta n}{n}\delta\vec{E} > .$$

The measurements of the correlation of the electric field and density fluctuations led to velocities, $v_{\vec{E}\times\vec{B}} \sim 6 \times 10^4$ cm/sec during the relaxation phase of the discharge. A diffusion coefficient can be estimated from the velocity,[18] $D_{\rm an} \sim v_{\vec{E}\times\vec{B}}\frac{n}{\nabla n}$. With a density scale length of 5 cm, this led to an estimate of $D_\perp \sim 3 \times 10^5\,\mathrm{cm}^2/\mathrm{s}$, comparable to the diffusion coefficients observed. The average value of the fluctuation-induced velocity during the decay phase of the plasma was $v_{\vec{E}\times\vec{B}} = 0.6 \pm 0.6 \times 10^4$ cm/sec. One possible origin of $v_{\vec{E}\times\vec{B}}$ was collisional drift waves.

There are pressure gradients across flux surfaces during the relaxation phase of the discharge. Collisional drift waves are unstable in inhomogeneous plasmas with high collisionality.[19] Their source of free energy is the density gradient, while the collisions affect the phase between the wave's electric field and density fluctuations, causing a positive correlation.[20] In the absence of collisions, or other dissipation, this mode, driven only by the density gradient, is stable.

The largest growth rate occurs at roughly $\gamma \sim \omega^*$, where

$$\omega^* \equiv \frac{k_\perp c T_e}{eB} \frac{1}{r_n}$$

is the diamagnetic drift frequency and

$$\frac{1}{r_n} \equiv \frac{1}{n} \frac{\partial n}{\partial r}$$

is the density gradient scale length. In the Proto S-1/C spheromak, $r_n \sim 5\,\mathrm{cm}$ during the relaxation phase. The perpendicular wave number, $k_\perp$, was estimated from $\delta \vec{E}_\perp \sim \vec{k}_\perp \delta\phi$, measured with the triple probe, to be $2\,\mathrm{cm}^{-1}$. The diamagnetic frequency was $\omega^* \sim 3 \times 10^5$ rad/sec, the same order of magnitude as the frequency of the electric field fluctuations observed.

For $\gamma \sim \omega^*$, D_{dr} can be estimated from the experimental parameters using Kadomtsev's mixing-length argument[19] as,

$$D_{\mathrm{dr}} = \frac{\rho_i v_i}{k_\perp r_n} \sim \frac{3}{16} \frac{cT}{eB}$$

in good agreement with the $\frac{5}{16}$ observed.

Thus, it appears that a combination of classical and Bohm diffusion is sufficient to explain the measured carbon diffusion coefficients. The lack of anomalous (i.e., nonclassical) diffusion on the closed flux surfaces is to be expected because of the large value of the classical diffusion coefficient, and because there was no pressure gradient across the closed flux surfaces within the errors of the measurement and, hence, there was no free energy to drive anomalous diffusion. During the relaxation phase of the discharge, there were pressure gradients throughout the plasma, and these provided the free energy necessary to drive instabilities which led to anomalous diffusion.

In the S-1 and CTX spheromaks, it was found that convective energy losses were important components of the plasma energy balance.[21,22] The values of the particle diffusion coefficients of $5D_{\mathrm{Bohm}}$ are sufficient to explain the particle confinement times observed in S-1[23] and CTX[21] during the periods when there were pressure gradients in the plasma.

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Figures

FIG. 1. Schematic of the Carbon injection scheme to measure the particle diffusion coefficient.

FIG. 2. Measured electron densities versus magnetic field strength during the decay phase of the discharge.

FIG. 3. Comparison of the measured $D_\perp$ to the classically predicted one during the decay phase($\geq 60\,\mu$sec) of the discharge. Also shown is the calculated value for $D_\perp = D_{cl} + 5D_{Bohm}$.

FIG. 4. Measured $D_\perp$ during the relaxation phase($t < 60\,\mu$sec) compared to $D_\perp = D_{cl} + 5D_{Bohm}$. In this case, D_{Bohm} includes the factor of 1/16. The classically predicted diffusion coefficient is also shown.

#86X0785

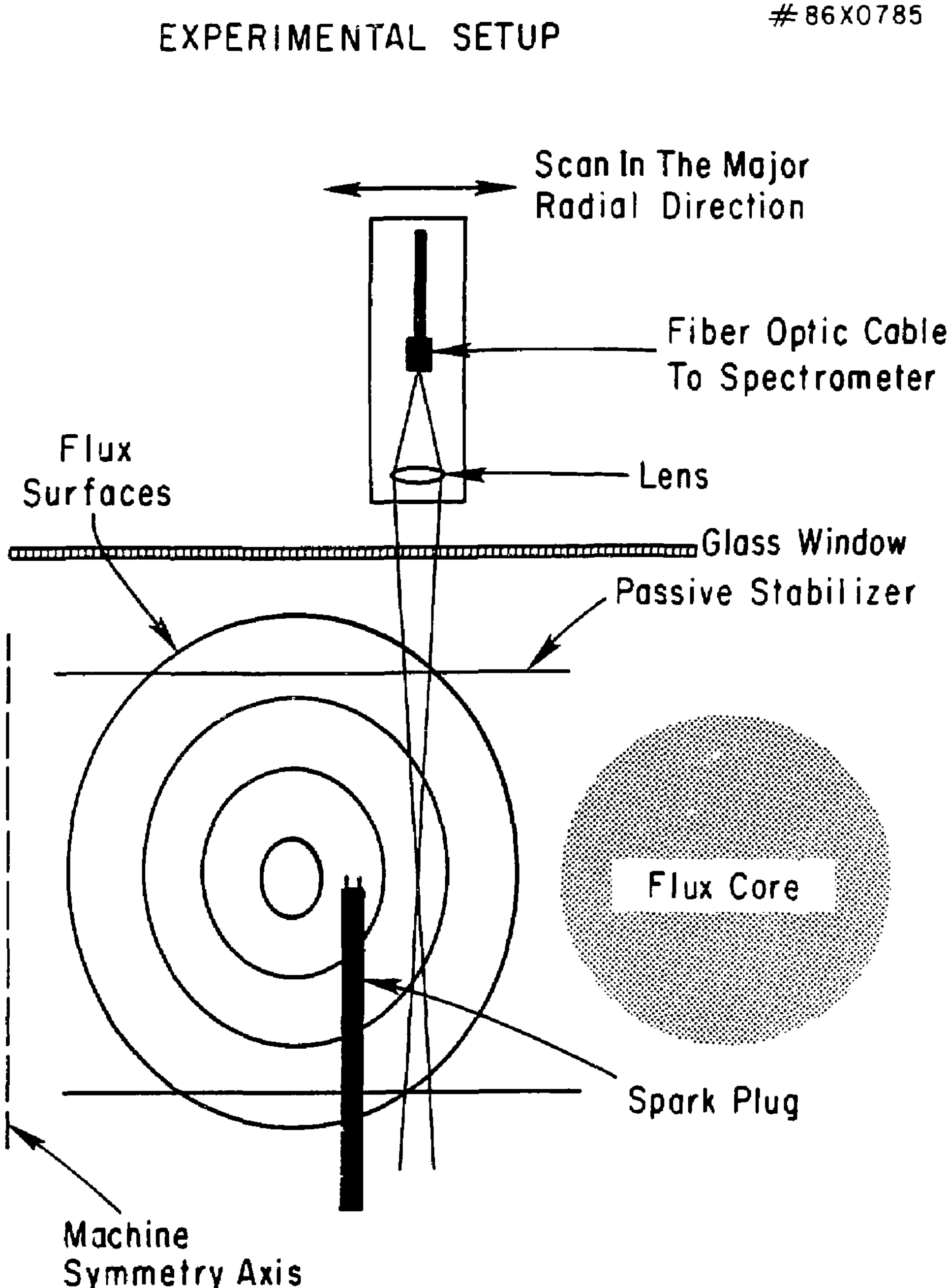
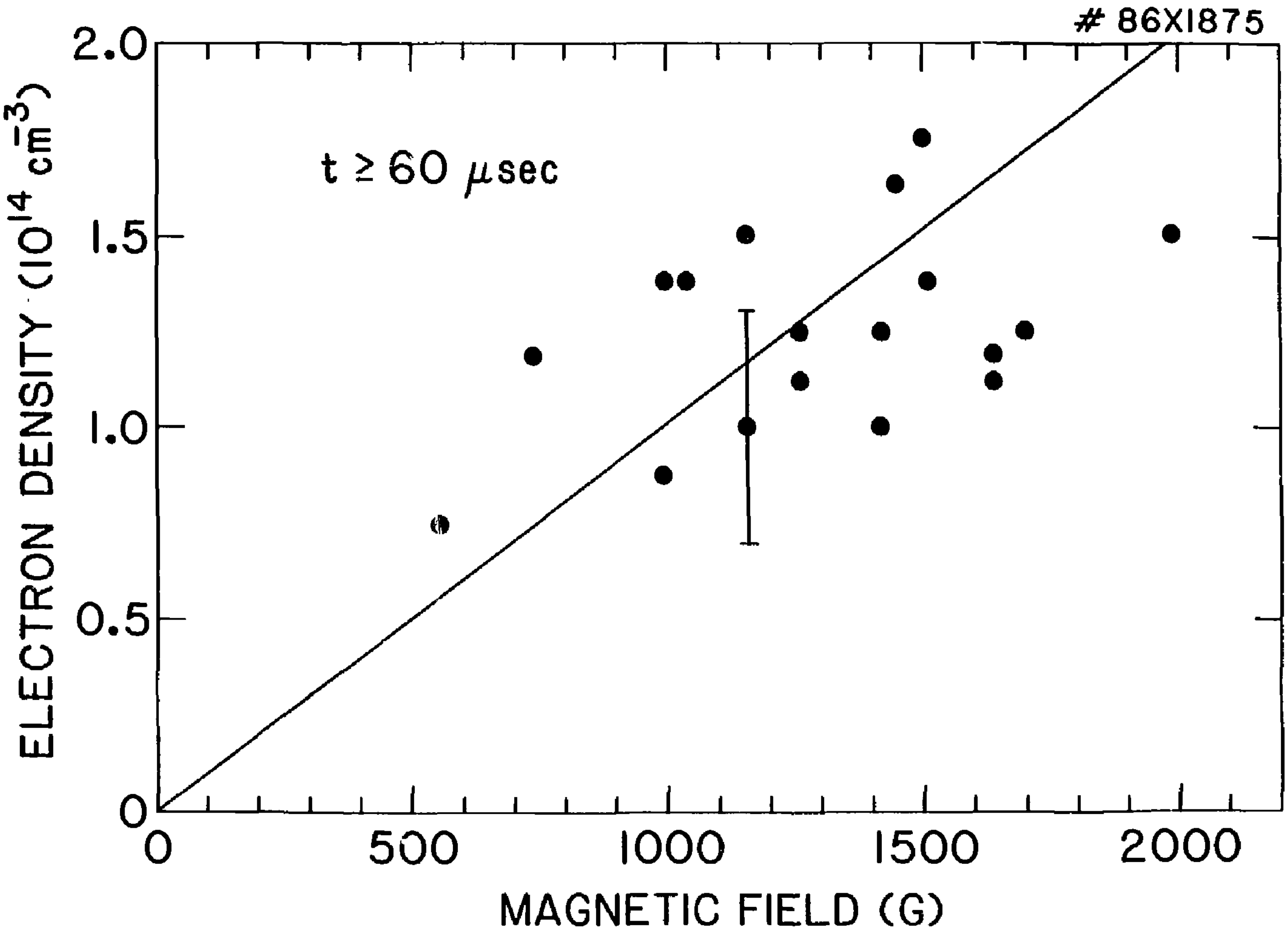
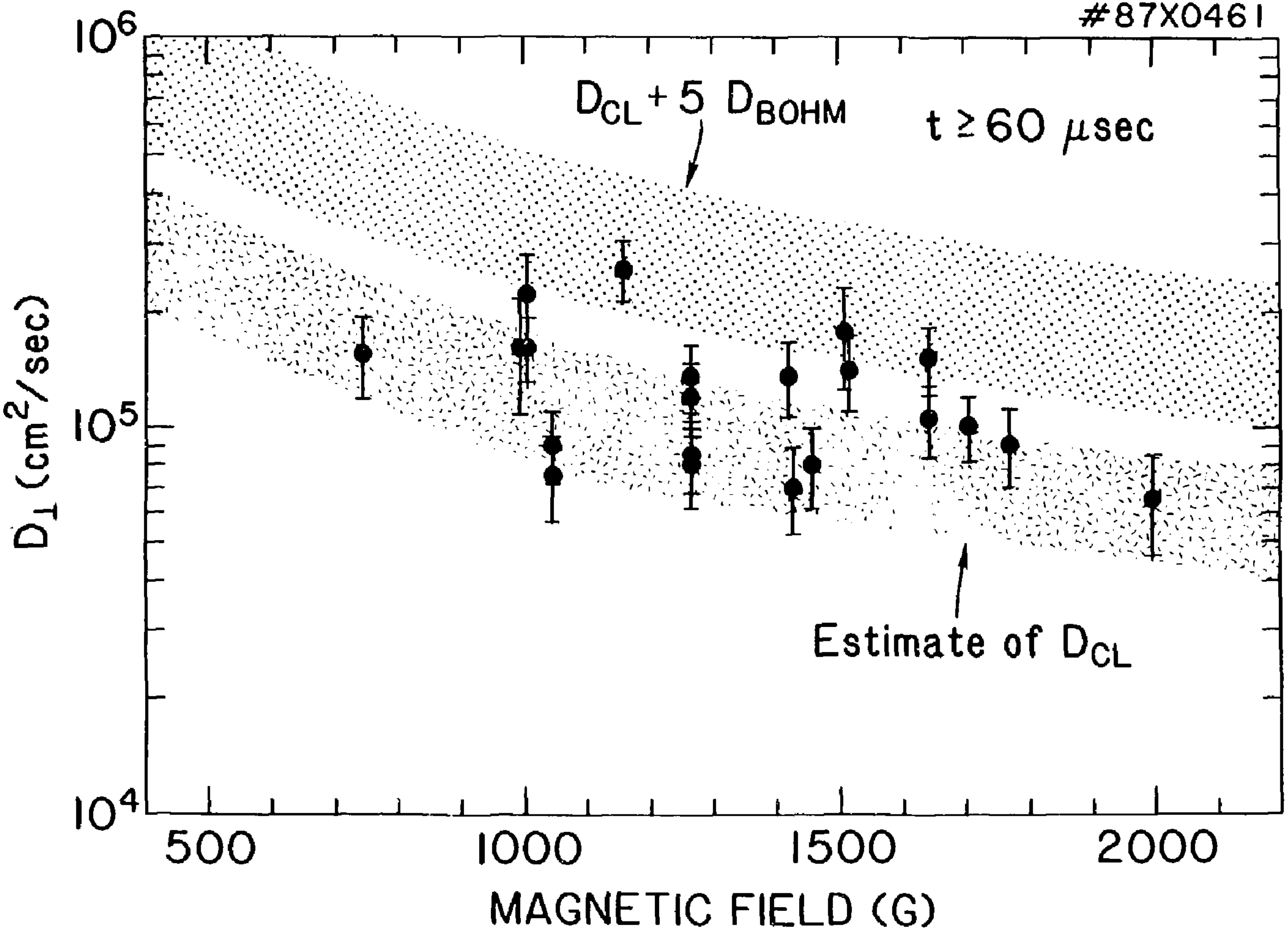


Fig. 1



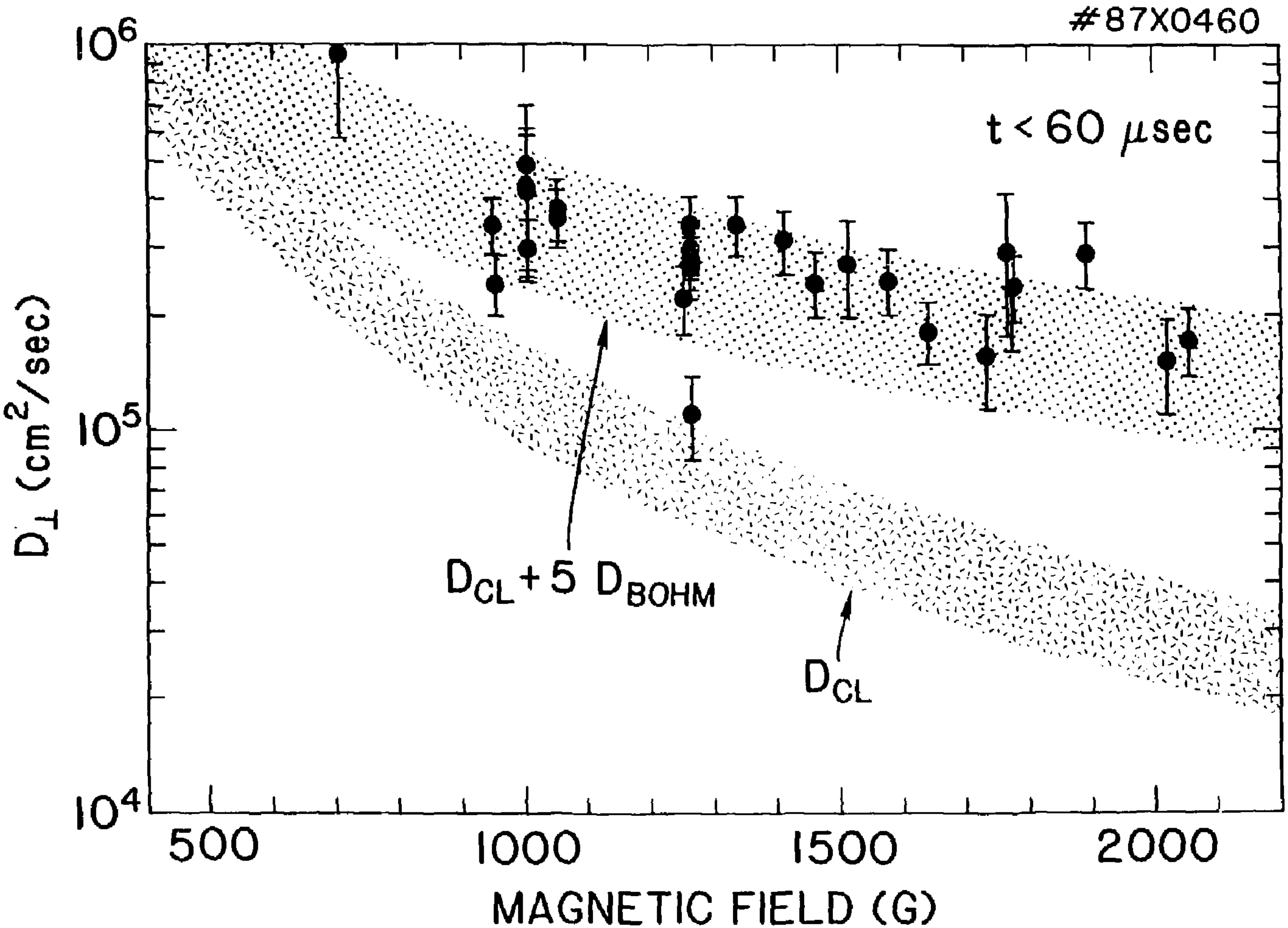
86X1875
t ≥ 60 μsec
ELECTRON DENSITY (10^14 cm^-3)
2.0
1.5
1.0
0.5
0
0
500
1000
1500
2000
MAGNETIC FIELD (G)

Fig. 2



#87X0461
D_{CL} + 5 D_{BOHM}
t ≥ 60 μsec
Estimate of D_{CL}
$D_{\perp}$ (cm^2/sec)
MAGNETIC FIELD (G)

Fig. 3



#87X0460
t < 60 μsec
D⊥ (cm²/sec)
10⁶
10⁵
10⁴
500
1000
1500
2000
MAGNETIC FIELD (G)
D_CL + 5 D_BOHM
D_CL

Fig. 4

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