TOROIDAL OHMIC HEATING IN THE WISCONSIN SUPPORTED OCTUPOLE

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ABSTRACT

An experiment is described in which a toroidal magnetic field $B_{To} \leq 1.5$ kG is added to the supported octupole. The decay of the octupole poloidal field induces a toroidal plasma current $I_p \lesssim 200$ A, resulting in a field configuration near axis similar to a Tokamak with a four mode poloidal divertor and $q \approx 10$ on axis.

Ohmic heating causes a hundred-fold increase in n_e to about $10^{12}/cm^3$ with $T_e \sim 10$ eV. Time evolution of typical spatial profiles of n_e and j_T are shown and discussed. Measured plasma electrical conductivity is dominated by neutral collisions at high H_2 filling pressure and by electron runaways at low pressure. Conductivity is proportional to B_T^2 and is close to Spitzer in magnitude.

In this experiment we have added a toroidal field to the Wisconsin supported octupole. Fig. 1 shows the cross-section in the constant θ plane of the surfaces of constant magnetic flux for the pure octupole field.

Four solid copper hoops act as secondaries of an iron core transformer. The hoops carry a total current of up to 300 kA, providing the source of the octupole field. The aluminum toroidal tank has major radius 43 cm and a square minor cross-section with sides 35 cm.

Application of the toroidal magnetic field allows current with a strong toroidal component to flow in the plasma near the center of the toroid. The driving electric field is provided essentially by the decay of the octupole field. In our experiment, the plasma current is opposite in direction to the hoop current, thus inducing a poloidal magnetic field opposite in direction to the octupole field. New closed flux surfaces are created at the center of the machine, changing the octupole null into four nulls a few centimeters from the center, as shown schematically in Fig. 2. The magnetic configuration thus becomes similar to a Tokamak of large aspect ratio (10-20) with a four node poloidal field divertor.

The parallel electric field is affected very little by the plasma current since the flux linked by the plasma is determined by the approximately 200 kA flowing in the hoops as compared with only a few hundred amperes in the plasma.

The field timing and operating parameters are shown in Fig. 3. The octupole field B_8 is a half sine wave lasting 5 ms. By triggering the toroidal field B_T at 3.5 ms the peak of B_T will coincide with the maximum toroidal E_T, which is proportional to $\dot{B}_8$. In this way we maximize the toroidal current density j_T and the resulting ohmic heating. The duration of B_T may be chosen to be 1.1 or 2.2 ms, with correspoinding peaking times of .45 or .8 ms.

The toroidal electric field on axis E_{To}, which is induced by the decay of B_8, is adjustable from .6 to 3 V/m at the time of the B_T trigger, rising to .84 - 4.2 V/m one millescond later. The toroidal field on axis B_{To} may be varied up to 1.5 kG.

The resulting discharge achieves electron density n_e about 10^{11} to $10^{12}/cm^3$ and electron temperature T_e roughly on the order of 10 eV. These low values for n_e and T_e allow the use of material probes for investigation of plasma properties, with particular advantage in determining spatial profiles.

Fig. 4 shows the development in time of a typical midcylinder n_e profile as measured with a double-tipped Langmuir probe. The times shown are measured from the B_T trigger. The case shown is for E_{To} = 2.3 V/m, B_{To} = 1.0 kG (peak at .8 ms), and H_2 filling pressure 2.5 x 10^{-5} torr. The peak $j_T \approx 3.5$ A/cm^2 and lowest q on axis is about 10.

Just before the trigger, n_e is a few times $10^{10}/cm^{-3}$ and has a flat profile. Very soon after the B_T trigger, the profile develops a double peak located 6-8 cm above and below the midplane. The n_e peaks occur inside the channel of poloidal current which flows in the region of common flux between hoops and walls and is driven by the poloidal E which is proportional to $\dot{B}_T$. This poloidal current limits itself on the midcylinder to the region outside of 12 cm from the midplane. The toroidal current, on the other hand, occupies a channel within about 2-4 cm of the midplane and reaches its peak at the same time as B_T does. The maximum n_e attained for the case shown is 1.2 x $10^{12}/cm^3$.

The lack of symmetry in peak height upon reflection through the midplane is due to the disturbance of the toroidal discharge by the probe. As another monitor of this effect we observe the decrease in visible light emitted from the plasma as the probe is inserted deeper and deeper into the plasma, as shown in Fig. 5. The light diagnostic is a photo diode in the lid at midcylinder which has a 14° viewing angle with the probe well out of its line of sight. The decrease in light signal is nearly linear as the probe crosses the main region of plasma, with a 40% decrease at 12 cm below the midplane as compared with 12 cm above.

Fig. 6 continues the time evolution of the n_e profile. By the time of the B_T peak (.8 ms after trigger) the n_e profile is flattening out and decreasing.

The time evolution of a typical j_T profile is displayed in Fig. 7. The operating parameters for the case shown are E_{T0} = 3 V/m, B_{T0} = 1.0 kG (peak at .45 ms), and H_2 filling pressure 3 x 10^{-5} torr. The main current channel extends from 3 cm below to 3 cm above the midplane. The measurements were made with a two-sided Langmuir probe, and consequently the absolute magnitude of j_T is somewhat uncertain since saturation is not good. The maximum current density along with its profile in Fig. 7 is consistent with the poloidal magnetic field due to the plasma current being equal and opposite to the octupole field at the edge of the current channel at ± 3 cm from the midplane. Thus the toroidal current is strongly peaked within the separatrix, as expected.

The maximum j_T occurs at about the time of maximum B_T. It corresponds to an on axis $q \approx 8$ and total current within the channel $I_p \approx 180$ A. The decay of j_T shows a strong hollowing out of the profile, with on-axis current decreasing to zero while current on the perimeter is still large.

This effect may be a manifestation of lack of equilibrium for the position of the current channel at late times.

The electrical conductivity σ has been investigated as a function of some of the operating parameters. The conductivity is here defined as the peak measured j_T divided by the toroidal electric field E_{To} on axis. Fig. 8 is a log-log plot of σ versus H_2 filling pressure p for two typical cases with different E_T, B_T and B_T rise times. For high pressure, the slopes of the curves are consistent with an n_e/p dependence for σ, indicating dominance of classical electron-neutral collisions.

For low pressure, the σ decrease coincides with a decrease in n_e and may be due to the presence of electron runaways.

In Fig. 9 is plotted σ versus B_T on log-log scales for several runs with different operating conditions. The triangles and squares in the graph represent runs with filling pressures different by a factor of 2. The open and closed circles represent rises times for B_T differing by a factor of 2. A wide range of B_θ, or E_{To} on axis, is represented. Each data run shows σ proportional to $B_T{}^2$, with possible lesser dependence for $B_T > 1$ kG. The $B_T{}^2$ dependence suggests a conductivity limited by magnetic mirror trapped particle orbits.

On the right hand side of the graph in Fig. 9 is indicated the "conductivity temperature," or T_e calculated with Spitzer's formula from the measured σ. The range of T_e thus obtained seems reasonable for the plasma conditions of this experiment. For some of the operating conditions used, T_e as measured with a Langmuir probe was 3 - 8 eV.

In summary, we have produced an ohmically heated plasma in a magnetic field topology similar to a Tokamak with a four node poloidal field divertor.

One advantageous feature of doing this experiment in an octupole is being able to adjust plasma parameters independently of each other over a wider range than Tokamaks can. In addition, the lower n_e and T_e allow the use of simple material probes to readily obtain spatial profiles of plasma parameters.

Θ = CONST. PLANE PROJECTION FLUX PLOT

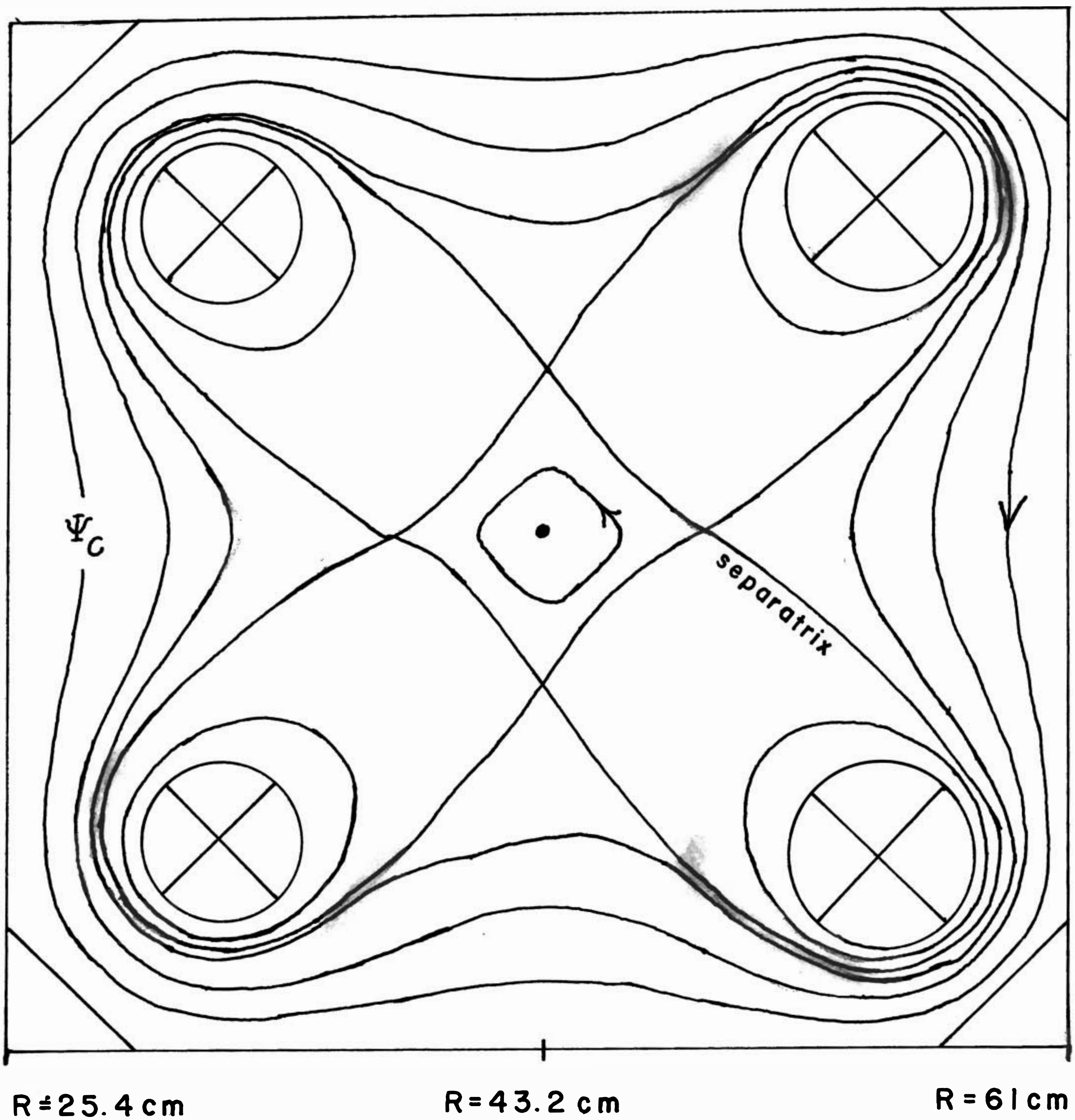


figure 2

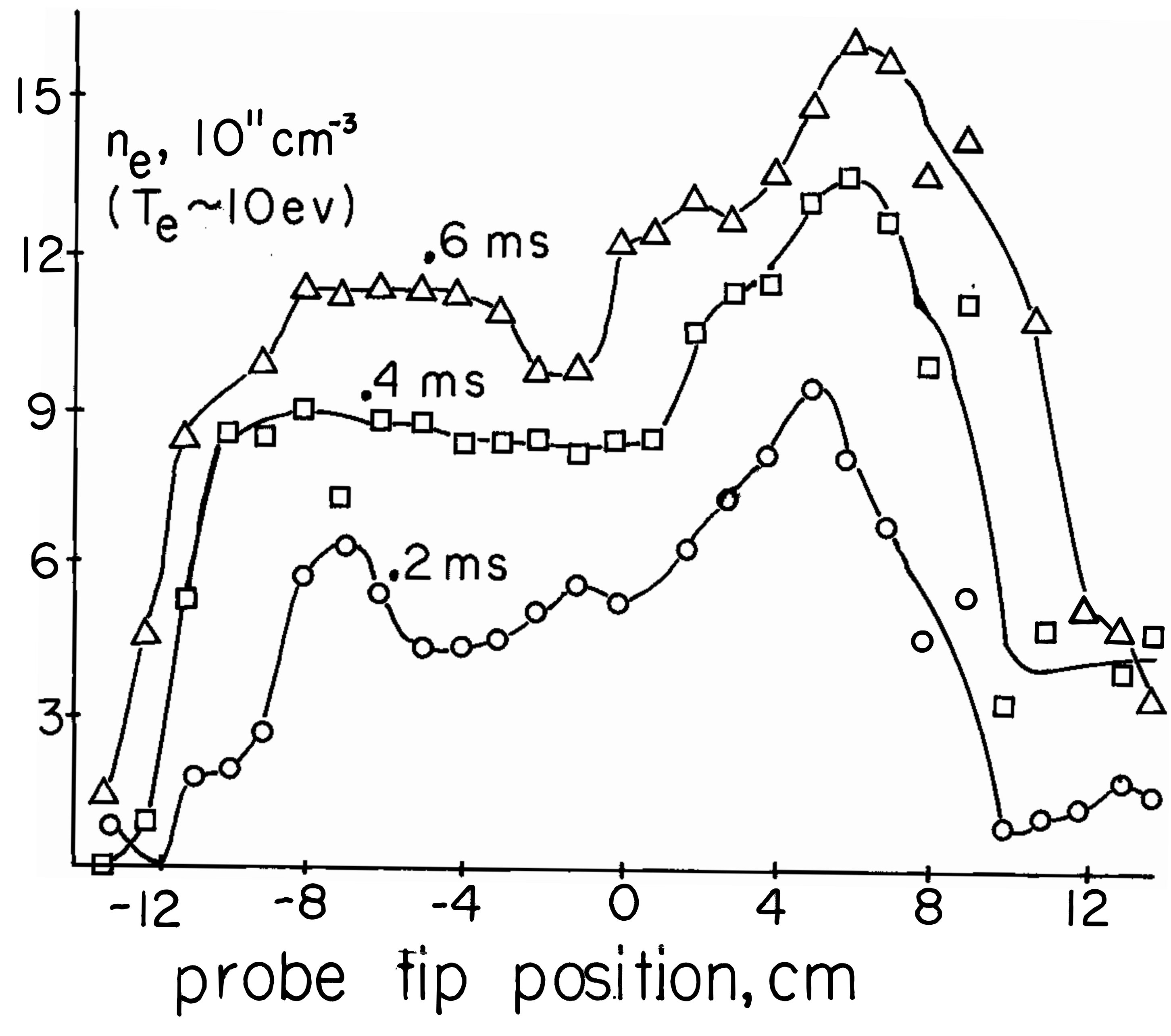
figure 4

TIME EVOLUTION MIDCYLINDER n_e PROFILE

E_o = 2.3 V/m

B_{T_o} = 1 kG (.8 ms peak)

p = 2.5×10^{-5} torr H_2



EFFECT OF PROBE ON PLASMA DISCHARGE

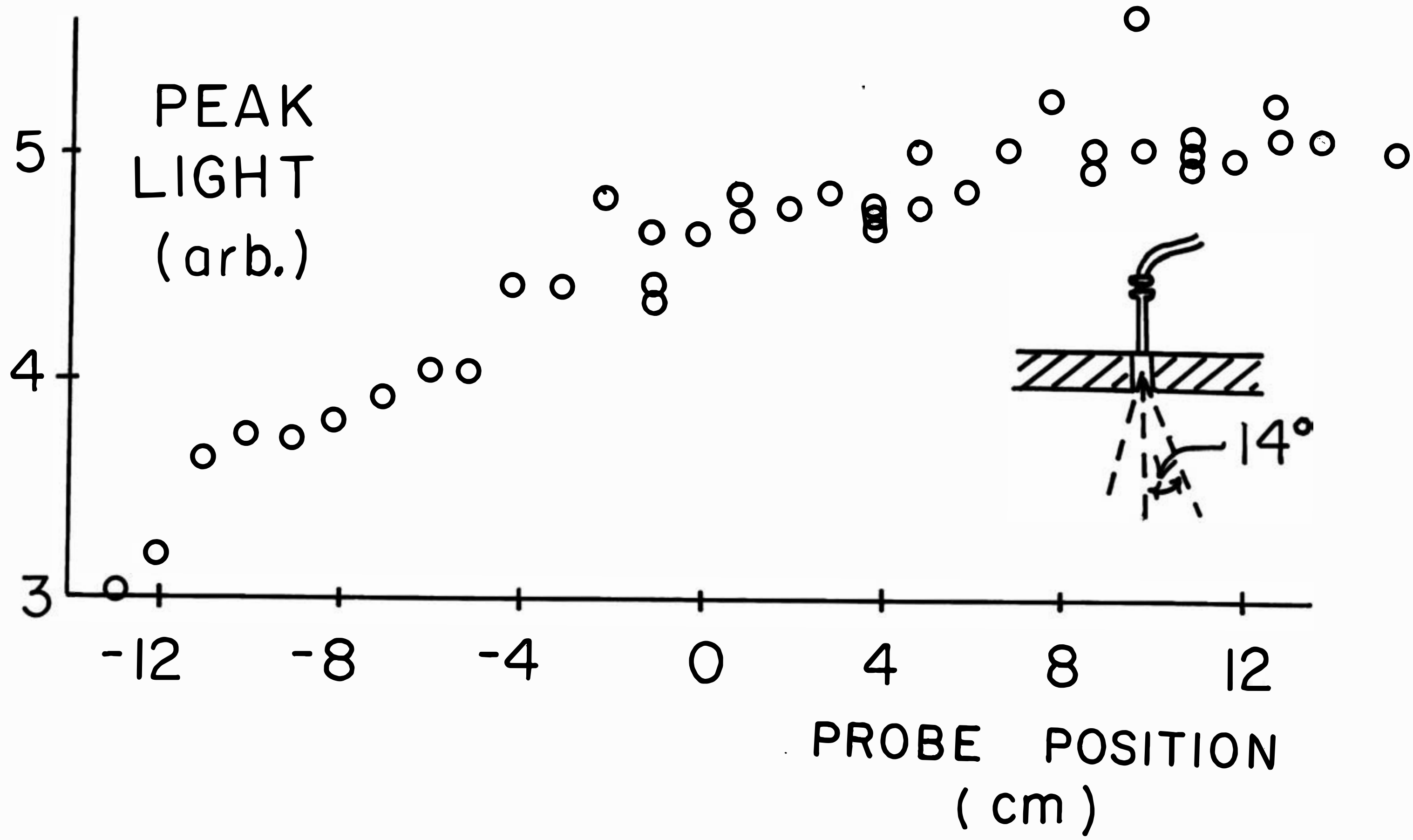


figure 5

Time Evolution: Midcylinder n_e Profile

E_{To} = 2.3 V/m
B_{To} = 1 kG (.8 ms peak)
p = 2.5×10^{-5} torr H_2

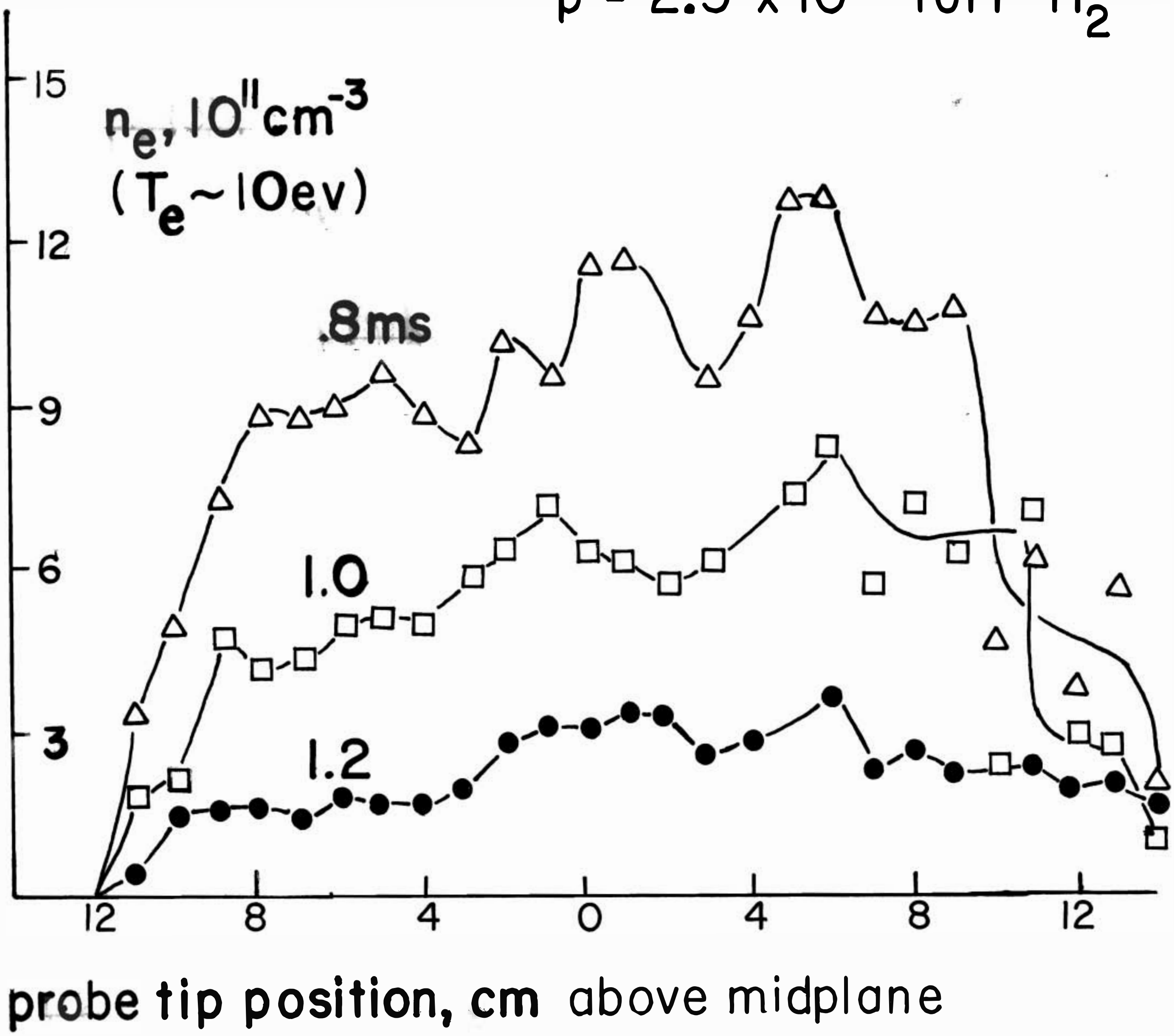


figure 6

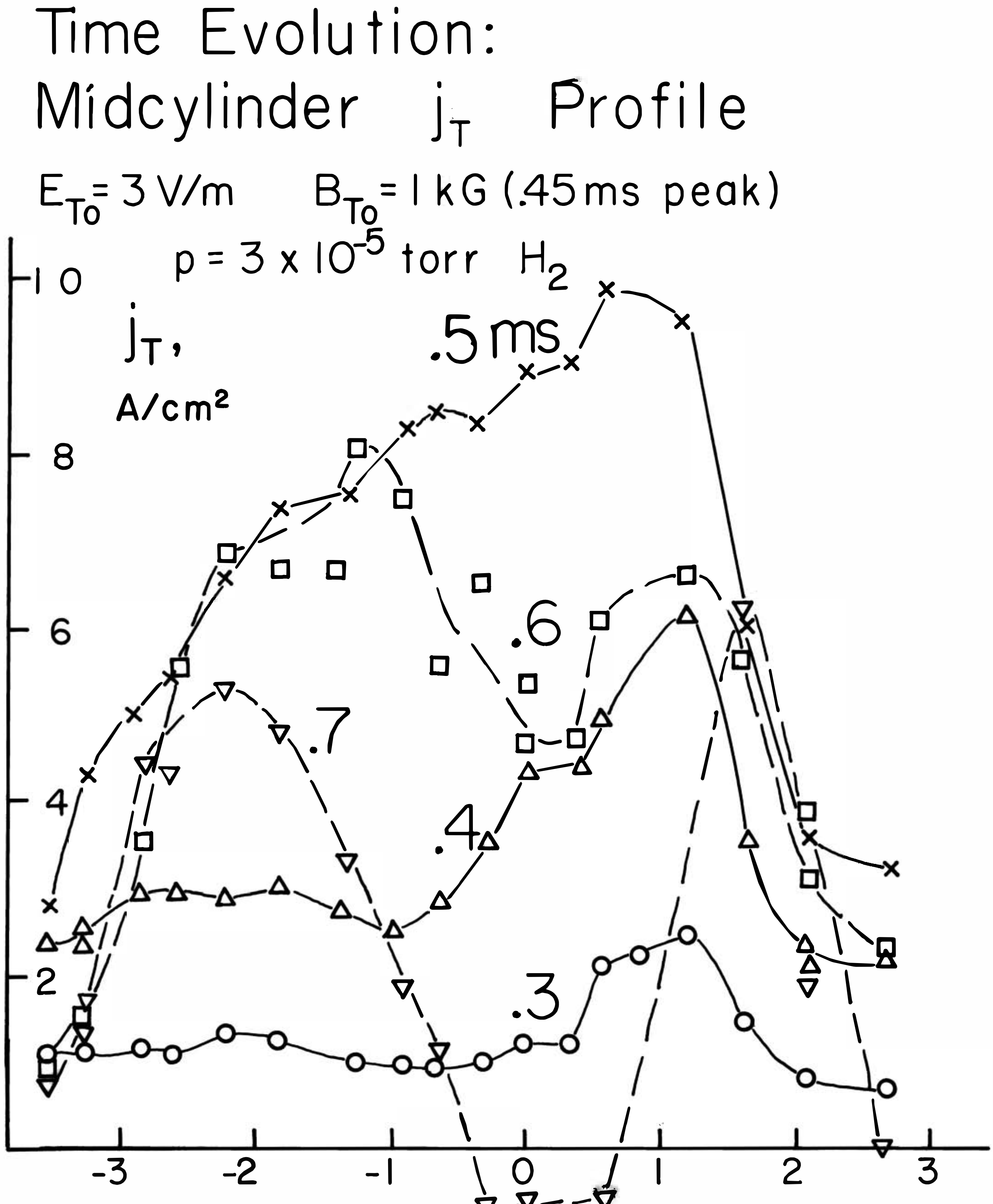

Time Evolution:
Midcylinder j_T Profile
E_{T_0} = 3 V/m B_{T_0} = 1 kG (.45 ms peak)
p = 3 x 10^{-5} torr H_2
j_T, A/cm²
10
8
6
4
2
.5 ms
.6
.7
.4
.3
-3
-2
-1
0
1
2
3
probe tip position, cm above midplane

figure 7

σ vs Pressure

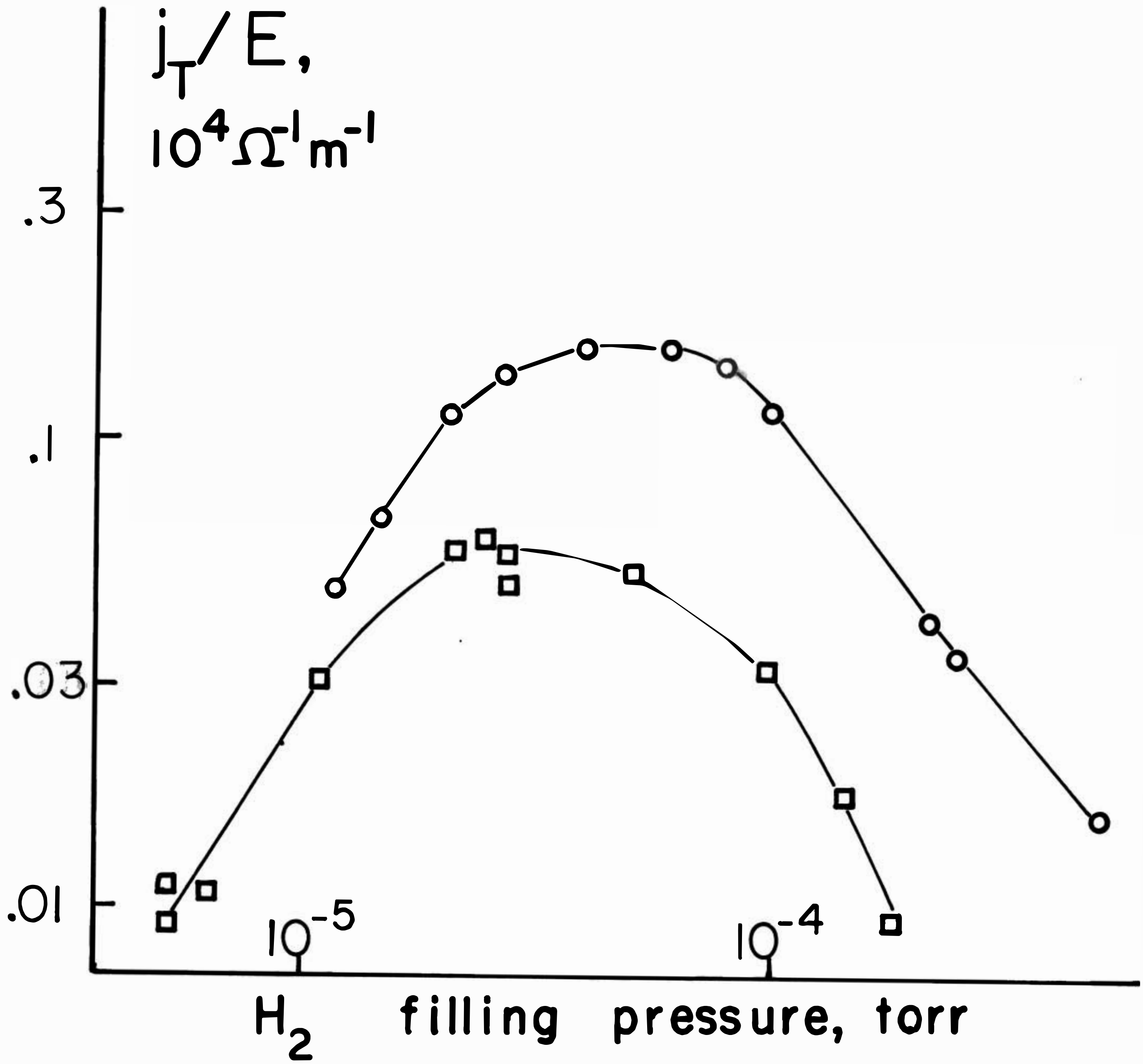


figure 8

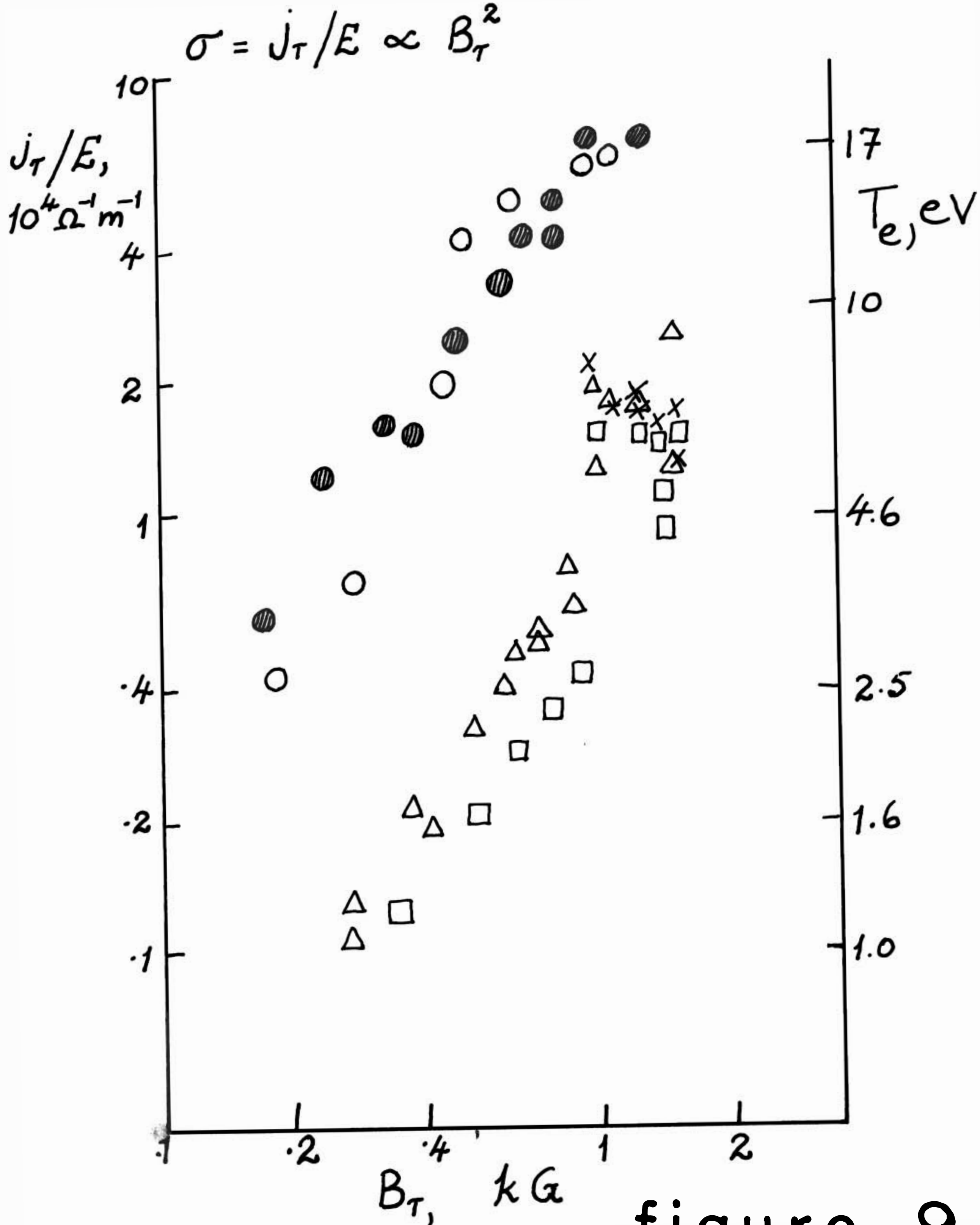

$\sigma = j_T / E \propto B_T^2$
j_T/E, $10^4 \Omega^{-1} m^{-1}$
10
4
2
1
·4
·2
·1
T_e, eV
17
10
4.6
2.5
1.6
1.0
·1
·2
·4
1
2
B_T, kG

figure 9