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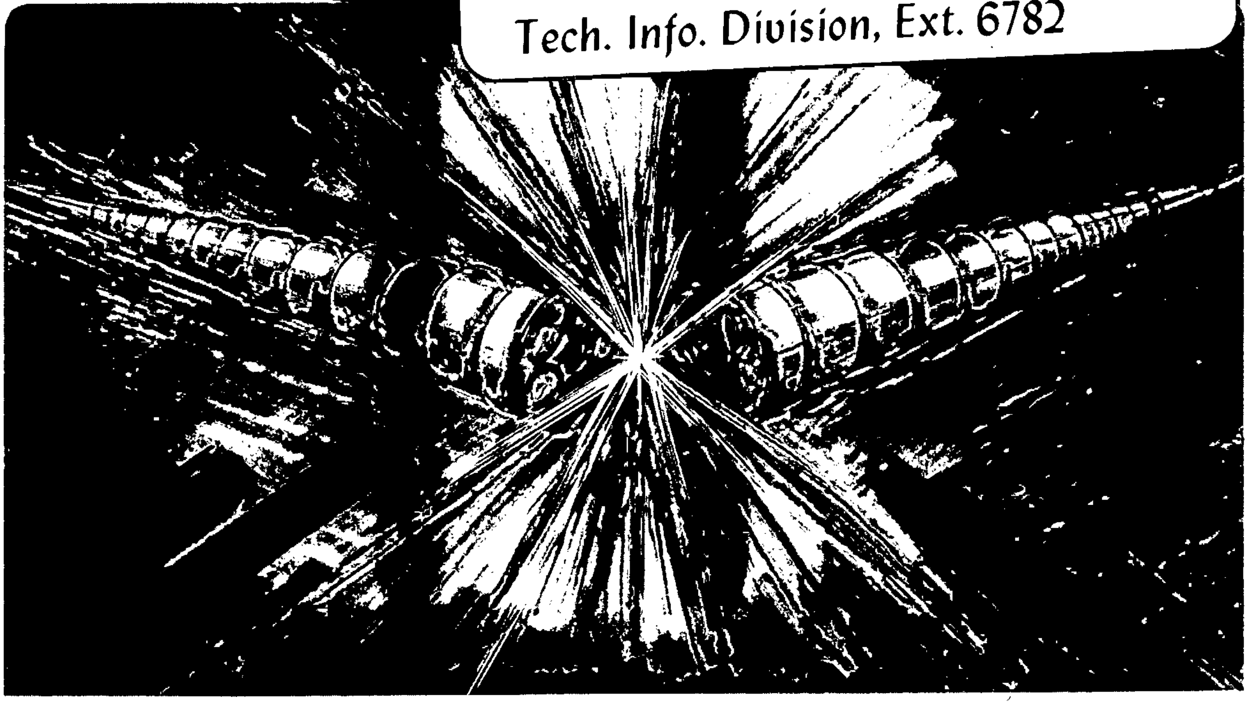

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Measurement of Ion-Acoustic Wave Velocity in a Pulsed Plasma*

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Abstract

A novel method for measuring the velocity of ion-acoustic waves is presented. The difference frequency between transmitted and received signals is observed as the transmitted frequency is swept linearly in time. This difference frequency is constant and proportional to the wave velocity. Temperatures inferred from the velocity agree with Langmuir probe measurements made on a hydrogen plasma.

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Measurements of the velocity of ion-acoustic waves in a plasma can be useful to determine the plasma ion flow velocity[1] and the electron temperature. We present a novel method for accomplishing this measurement that is particularly useful in pulsed plasmas of milleseconds duration.

THEORY

Ion-acoustic waves are normally stimulated by applying an electrical signal to a probe or grid immersed in a plasma. This signal may be a short pulse, in which case the ion-acoustic wave velocity is determined by the transit time of this pulse to a second probe (Ref. 1 for example), or it may be a cw oscillation, the velocity being determined by observing the wave length as the second probe is moved relative to the first (Ref. 2 for example). The first method suffers if the pulse is difficult to recognize because of high frequency attenuation or superimposed plasma noise, while the second method requires the plasma to be stable as the probe is moved.

In the method presented here waves are sent with a time varying frequency. The difference frequency between the transmitted and received signals resulting from the change in transmitted frequency during the transit time is observed. If the frequency is swept linearly in time, the difference frequency will be constant and proportional to the transit time. Let T(t) and R(t) be the transmitted and received signals respectively.

$$T(t) = \sin \phi(t) \qquad (1)$$

$$R(t) = \sin \phi(t - \delta t) \qquad (2)$$

Where $\phi(t)$ is the phase function of the transmitted wave and δt is the transit time. For probe separation s and wave velocity V, $\delta t = s/V$.

These signals are mixed electronically. The resulting signal, M(t) is;

$$M(t) = R(t) \cdot T(t) \tag{3}$$

$$= \sin \phi(t) \cdot \sin \phi(t - \delta t) \tag{4}$$

$$= 1/2 \cos \left[\phi(t) - \phi(t - \delta t)\right] - 1/2 \cos \left[\phi(t) + \phi(t - \delta t)\right] \tag{5}$$

The high frequency component is filtered out, and the signal

$$M'(t) = 1/2 \cos \left[\phi(t) - \phi(t - \delta t)\right] \text{ is recorded.} \tag{6}$$

For a linearly varing frequency ramp of the form

$$f(t) = f_o + \partial f/\partial t \cdot t \tag{7}$$

the phase function will be

$$\phi(t) = \phi_o + 2\pi f_o t + \pi \cdot df/dt \cdot t^2 \tag{8}$$

Now let

$$\Psi = 2\pi f_o \delta t - \pi \cdot \partial f/\partial t \cdot \delta t^2 \tag{9}$$

and

$$F_d = \partial f/\partial t \cdot \delta t \tag{10}$$

then $$M'(t) = 1/2 \cos (\Psi + 2\pi F_d t) \tag{11}$$

and the velocity $V = s/\delta t = \frac{s \;\partial f/\partial t}{F_d}$ † $\qquad (12)$

Note that noise of a fixed frequency will leave the mixer as a spread of frequencies, and direct (electromagnetic) coupling will produce a dc offset on the signal. The number of periods of the difference frequency, N, depends only on the range of frequency swept and not on the measurement time, t_m

$$N = F_d \cdot t_m = \frac{\delta F}{\delta t} \cdot \delta t \cdot t = \frac{F_2 - F_1}{t_m} \cdot \delta t \cdot t_m = (F_2 - F_1) \cdot \delta t \tag{13}$$

There are two constraints on the times involved. (1) Experimentally the frequency can be swept only to some maximum value (F_M) above which a linear wave no longer propagates. Thus to observe at least one period ($N = 1$) eq. (13) requires that $\delta t > 1/\delta F > 1/F_M$. (2) The change of driver frequency in its period must be small compared to the driver frequency. In particular $\delta f/\delta t \; 1/F_1 \ll F_1$ which implies $t_m \gg \delta t$. Neither of these is a severe restriction; the practical limit comes from the external circuit elements.

Since the number of periods does not depend on the sweep time, this technique can be conceptualized as analogous to the second method mentioned earlier by which the wavelength is varied instead of the probe separation.

EXPERIMENT

A schematic block diagram of the electronics is shown in Fig. 1. The grids were biased in the ion saturation region. R1 provides ground reference for the bias. C1 and the internal input resistance form a high pass filter to block the steady ion current. R2 and C2 are chosen to ensure that the phase delay around the two legs is identical.

The plasma in which we wished to measure the ion-acoustic wave velocity is produced in the neutralizer section a Lawrence Berkeley Laboratory 10-A neutral beam source.[3,4] It is a weakly ionized, cool plasma ($N_e = 0.4$ to 1.0×10^{11} cm^{-3}, $N_o \cong 3 \times 10^{13}$ cm^{-3} and $T_i < < T_e = 0.8$ to 3.0 eV) produced by a mixed beam of 25-keV H^+, H_2^+, and H_3^+ ions that neutralize by charge exchange on gas streaming from the ion source. The plasma parameters are fairly steady for 10 ms.

A consideration in determining the velocity is that the wave is not launched from the grid but from a pre-sheath around the grid.[5] Additional complications result if a wave is simultaneously launched from elements which are electromagnetically coupled to the antenna.[6] To test for these effects, measurements were made at several grid separations and the velocity was determined from the slope of a graph of transit time verses separation. Extrapolation to zero transit time showed that the waves came from the transmitter within the accuracy of the extrapolation ($\pm$ 2 mm), hence this source of error was neglected (Fig. 2).

To avoid disturbing the ion flow, fine mesh grids were used to excite the ion-acoustic waves. Such grids can also launch streams of ions known as pseudowaves.[7] Pseudowave speed is a function of the exciter amplitude and frequency. Because of this frequency dependence, the net output would have a changing period, as opposed to the constant period observed. Another check for pseudowaves was done by varying the amplitude by a factor of four. No change in the wave velocity was observable.

A comparison of T_e as measured by a langmuir probe and as determined by V_{IA} is shown in Fig. 3. The wave was launched in a direction where the effect of flow is minimal and under conditions where T_i and the flow are expected to be small but not zero. The least squares fit for the slope is 1.0 ± 0.3. Given the uncertainties introduced by variations in T_i, flow, and the launch point and the increased signal damping observed for larger T_e, we feel the agreement is reasonable.

We have described here a novel technique for measuring the speed of ion-acoustic waves that has several advantages compared to other methods. It is independent of fast waves or direct coupling; the period of the launched wave can be greater than the transit time (subject to the limitations discussed following Eq. (13)), allowing the inclusion of low frequencies where the attenuation is small; and it can be done quickly. This method may not improve results over simpler methods in some cases, but for a plasma of short duration and fairly high wave velocity, we have found it quite useful.

We wish to thank Charles Arthur for his assistance in designing the electronics for this experiment.

FOOTNOTES AND REFERENCES

[*] This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

[†] Measurement of V in several directions will give the plasma flow, which is our goal in making this measurement (preliminary results have been obtained). The velocity can also be used as a rapid nondisturbing measurement of temperature. Though we are in no position to try it, one should be able, with the same electronics and using a fixed driving frequency, to make a time-dependent measurement of temperature by observing the phase shift of the output. $M(t)=1/2 \cos(2\pi F \cdot \delta t(t) + \phi_0)$.

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Figure Captions

Figure 1. Schematic diagram of the frequency swept ion-acoustic velocity measurement experiment.

Figure 2. Plot of transit time verses grid separation. Extrapolation by least squares fit to zero time shows the wave to originate at the transmiter to the accuracy of this measurement (± 2 mm). Error bars are determined from uncertainty in reading period of F_d.

Figure 3. Comparison of T_e from Langmuir probe and T inferred from $V = T/m_i$ (m_i assumed to be the mass of H_2). Slope from least squares fit is 1.0 ± 0.3. Error bars are rough estimates of standard error determined from sources of error mentioned in the text.

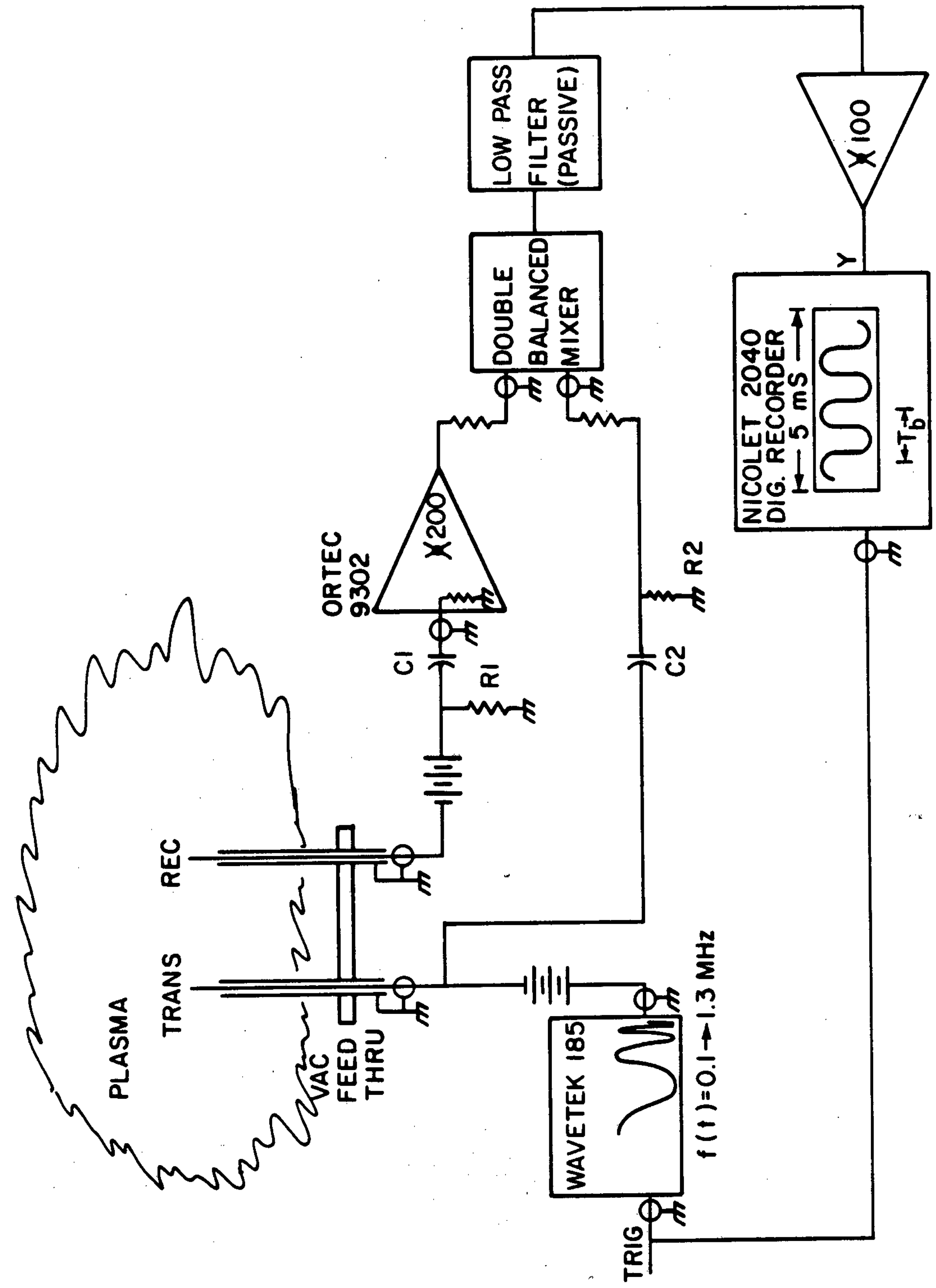

FIG. 1

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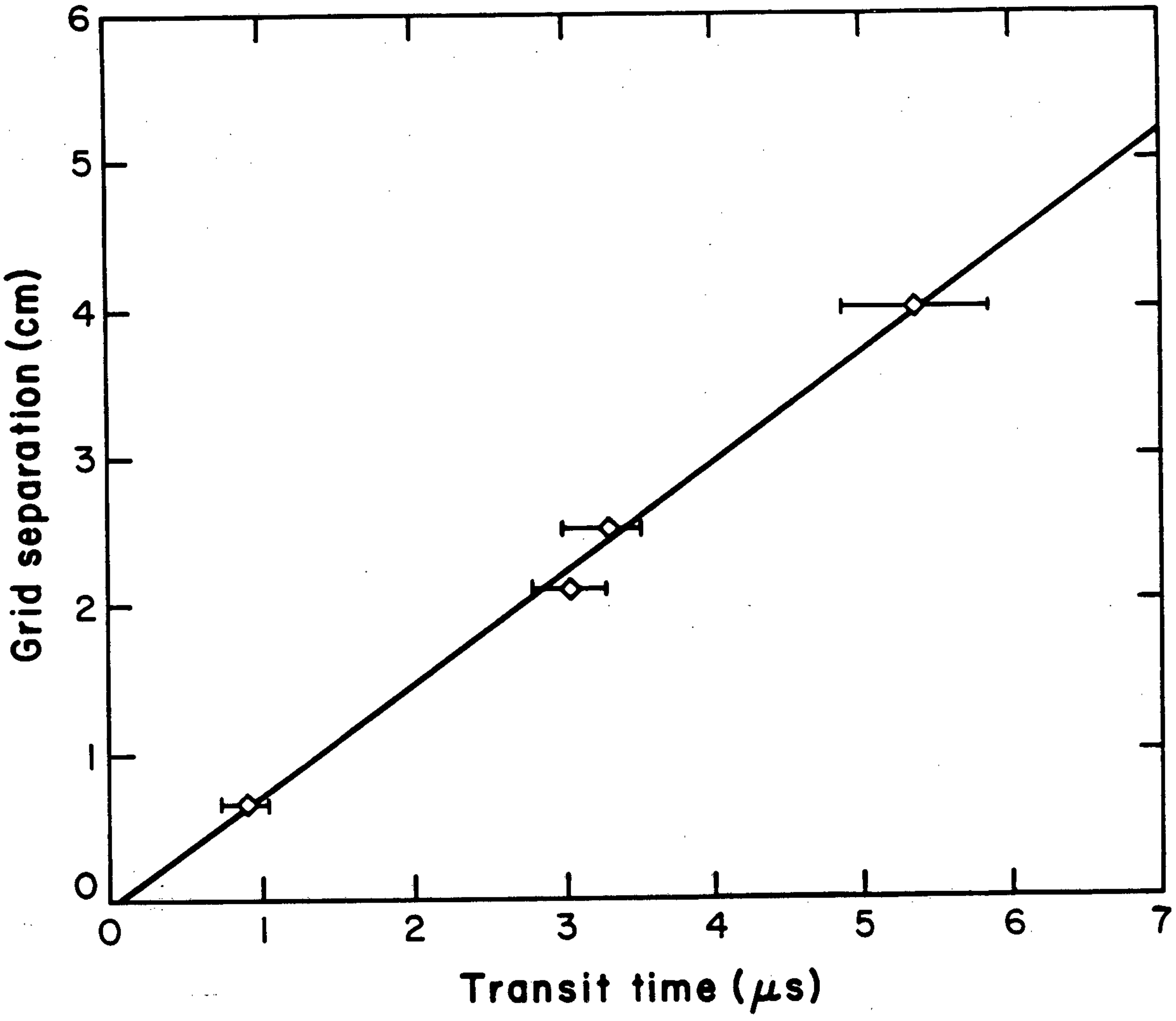

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FIG. 2

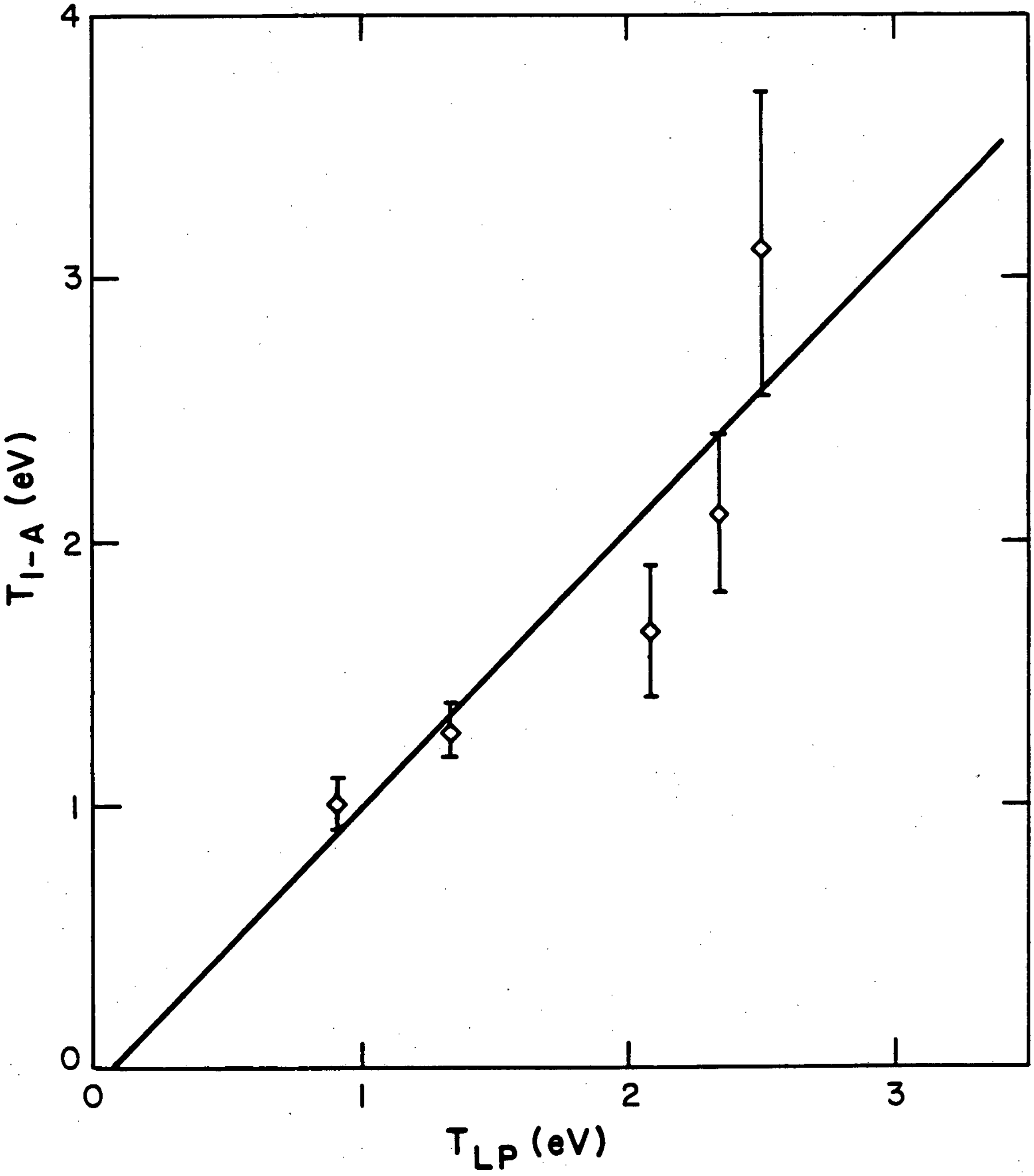

FIG. 3

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