INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

# RESEARCH REPORT

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# Experimental Technique to Measure Phase-Space Diagrams in Plasma Experiments.*

H. Ikezi and K. E. Lonngren**

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, JAPAN.

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** Permanent Address: Department of Electrical Engineering, University of Iowa, Iowa City, Iowa, U. S. A.

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## Abstract

An experimental technique is described which allows one to easily measure and rapidly display the particle distribution function in phase-space in nonlinear wave-plasma interaction experiments. An application to the study of Pseudowaves is also presented.

The numerical simulation of nonlinear interaction of waves in a plasma has recently received considerable attention. The results are frequently presented in terms of "phase-space" diagrams (position vs velocity or energy) at various times in the evolution of the interaction. The presentation of experimental data in similar "phase-space" diagrams would be helpful in order to understand the phenomena. This, however, has involved extensive and time-consuming manipulations of a large number of iterative measurements.

In this paper, we describe a technique using commercially available equipment that will perform these measurements at a preselected time in the evolution of the interaction, do the numerical manipulation, and produce a "phase-space" diagram on an oscilloscope in a time scale which is reasonable for many experiments. The time scale in our experiment was 20 seconds, but this is not, in any sense, a lower limit.

In many plasma experiments, it is relatively easy to measure the distribution function $f(\phi)$ of the plasma using an energy analyzer[(1)] ($f(\phi)$ vs the energy $\phi$). The measurement is made at a fixed position $x_0$. Repeating this measurement at different positions $x_1$, $x_2$, $x_3$, $\cdots$ , data can be obtained from which one could plot "phase-space". (See Fig.4 of Ref.2) However, in experiments, both $x$ and $\phi$ could be easily made to be continuously variable. The problem that remained was how to observe $f(\phi)$ as a function of $x$ and $\phi$, at least under conditions where signals are repetetive and sampling techniques are applicable.

The solution that we found to be quite satisfactory was to "digitize" a measurable voltage proportional to the distribution function $f(\phi)$ using a voltage controlled square wave generator, the frequency of which is proportional to the applied voltage, hence $f(\phi)$. The output of this generator was then used to modulate the intensity of an oscilloscope. The complete setup is shown in Figure 1.

In this system, there are five time scales of interest which are all synchronized with a master clock pulse and are indicated in Figure 1 at appropriate positions. Ramp voltages proportional to these time scales are also available as the need arises. The time scales are:

1) $T_{probe}$ = time scale of the probe movement. This could also be the time scale for studies of the temporal evolution of $f(\phi)$ as a function of energy $\phi$ and time.

2) $T_{selector}$ = time scale of the period of the periodic selector voltage in the energy analyzer.

3) $T_{signal}$ = time scale of the period of the repetition rate of the signal to be analyzed.

4) $T_{oscillator}$ = time scale of the period of the voltage controlled square wave generator.

5) $T_{delay}$ = time scale of delay between the excitation of a signal and its observation.

In our experiment, the time scales were

$T_{probe} \sim 20$ seconds

$T_{selector} \sim 0.1$ second

$T_{signal} \sim 0.3$ milliseconds

$T_{oscillator} \sim 0.05$ to 1 millisecond

$T_{delay} \sim 1$ to 10 microseconds

To explain the operation, we shall first look at a time scale when $\Delta T_{probe} \sim 0$ and $\Delta T_{selector} \sim 0$. Particles were launched from a source (in our case, an ion beam in a D-P machine[3] or a pseudo-wave[4] from a grid) into a plasma. All particles with energies greater than the repelling selector voltage $\phi$ are collected by the energy analyzer. The resulting current $I \propto \int_{\phi}^{\infty} f(\psi)d\psi$ is amplified. Since we wish to analyze only those particles which are collected at a time $T_{delay}$ after they were launched, we isolate them with either a sampling oscilloscope or boxcar integrator. Differentiating this signal, we obtain $f(\phi)|_{\phi \sim T_{selector}}$. This signal then controls the voltage-controlled square wave generator which in turn modulates the intensity of the scope. Larger valves of $f(\phi)|_{\phi \sim T_{selector}}$ produce a higher frequency square wave and more "dots" on the oscilloscope at a <u>fixed</u> point on the screen.

Now let $\phi \propto T_{selector}$ be incremented by one unit. The process described above is repeated except that the resulting "dots" on the scope are displaced on the y axis of the scope by an increment proportional to the increment in $\phi$. Eventually a vertical line of varying intensity is formed. The probe is now moved an increment $\Delta x \propto \Delta T_{probe}$ and the above process is repeated. Finally the probe is moved through its entire length of travel and the entire phase-space is covered. This procedure has divided the phase-space into a very large number of subspaces, say N where

$$N = (N_x)(N_\phi) = \left( \frac{T_{probe}}{T_{selector}} \right) \times \left( \frac{T_{selector}}{T_{signal}} \right)$$

which for our case is more than 60,000. We found it convenient to use a storage oscilloscope although a camera and time-exposure with a conventional oscilloscope would yield equivalent results.

To check and calibrate the system, we launched "pseudo-waves" from an additional grid inserted in one-half of a D-P machine(5). Pseudowaves are freely-streaming charged particles that leave the grid with a maximum kinetic energy equal to that of the energy acquired at the grid. Their velocity in the plasma is $v \sim (\phi_{ex})^{1/2}$. The position of any particle x will be equal to $(v)(T_{delay})$. Therefore, a phase-space diagram of energy ($\propto v^2 \sim x^2/T^2_{delay}$) with $T_{delay}$ fixed vs position x should be parabolic in shape and have its maximum value of energy equal to $\phi \sim \phi_{ex}$. In Figure 2, we present typical phase-space diagrams and signals from a Langmuir Probe at various values of $T_{delay}$. The shape of the curves is parabolic and the curves have their maximum value of energy approximately equal to $\phi_{ex}$.

As a further check, we set up conditions in which "Multiple Pseudowaves" could be excited(6). In this case, we can excite more than one pseudowave by carefully tailoring the potential well about the grid. The fastest pseudowave will have energy approximately equal to $\phi_{ex}$ and the rest will have less. In Figure 3, we present typical probe and phase-space diagrams when two were launched. We note the discrete nature of these "Multiple Pseudowaves".

In conclusion, we have found this technique to be very helpful in differentiating true wave propagation from pseudo-wave propagation in plasmas[5] and in ion-beam generated shock experiments[7]. The time scales were chosen to match those of our experiment, their choice does not appear to be a fundamental limitation to the technique. Limitations would more probably be imposed by the user's application or electronic equipment in hand.

## References

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## Figure Captions

Figure 1. Experimental Setup to measure "Phase Space". The various time scales in the device are indicated in parantheses at the appropriate locations. In our experiment, we used a Princeton Applied Research Model 160 Boxcar Integrator; a Microdot Model F 240 A Voltage Controlled Square Wave Generator and a Tektronix Model 549 Storage Oscilloscope.

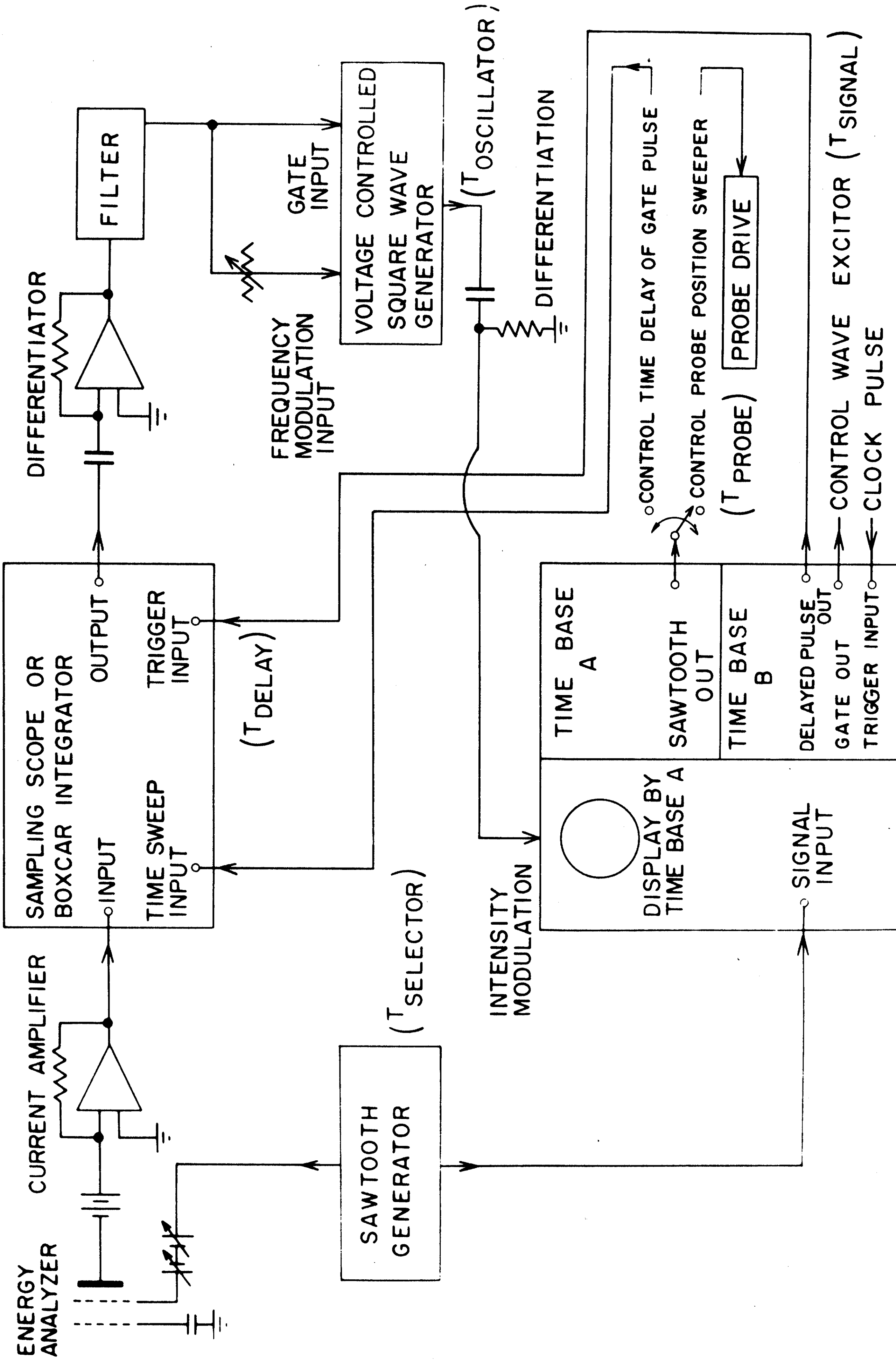
Figure 2. Study of Pseudowaves (a) Signal from Langmuir Probe as a function of position for $\phi_{ex} = 30$ volts. The three traces correspond to $T_{DELAY}$ = 2, 3 and 4 μseconds respectively. The horizontal scale is $\Delta x = 0.5$ cm/div.

(b) Phase-Space diagrams corresponding to the pseudowave signals. Vertical scale is $\Delta\phi$ = 20 volts/div.

Figure 3. Study of Multiple Pseudowaves

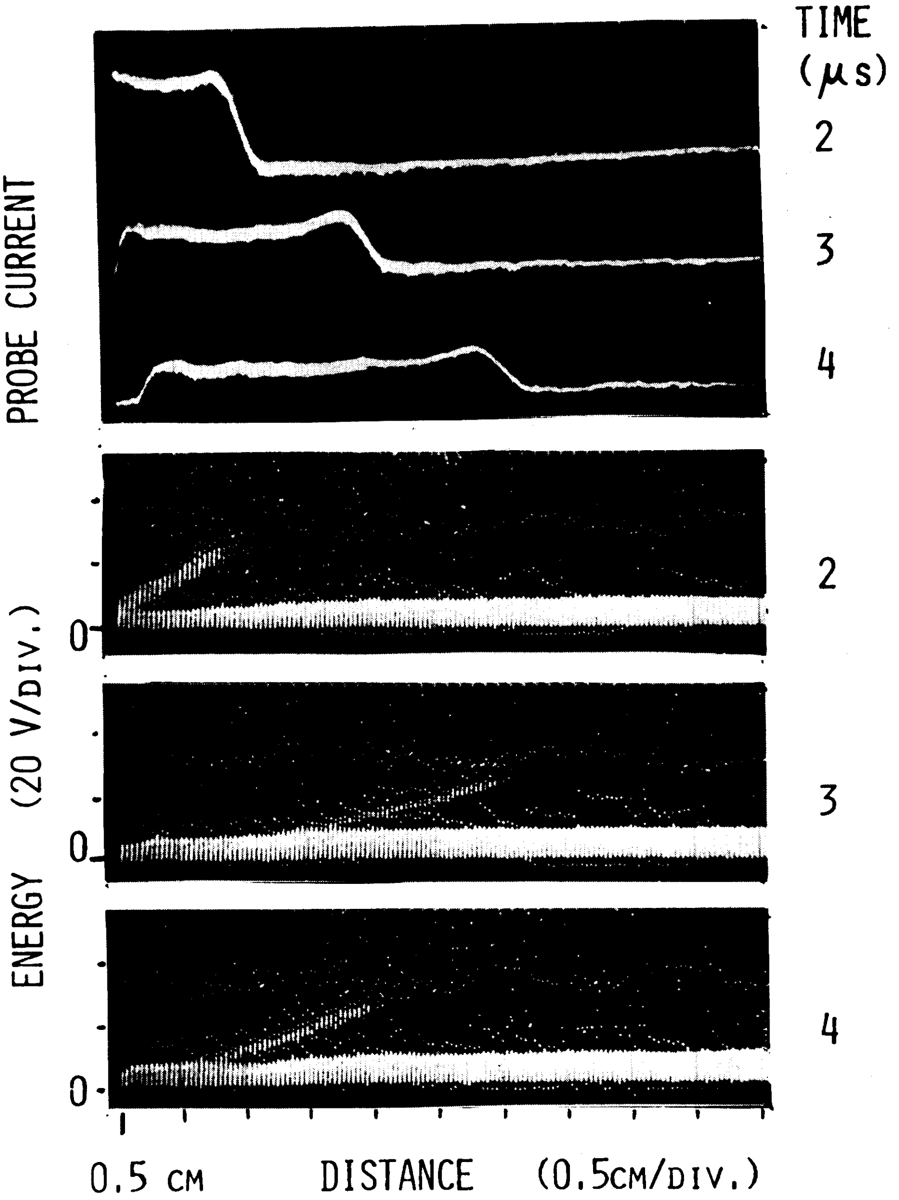
(a) Signal from Langmuir Probe as a function of position for $\phi_{ex} = 55$ volts. The three traces correspond to $T_{DELAY}$ = 2, 3 and 4 μseconds respectively. The horizontal scale is $\Delta x = 0.5$ cm/div.

(b) Phase-Space diagrams corresponding to the multiple pseudowave signals. Vertical scale is $\Delta\phi$ = 20 volts/div.



DIFFERENTIATOR
FILTER
GATE INPUT
VOLTAGE CONTROLLED SQUARE WAVE GENERATOR
FREQUENCY MODULATION INPUT
(T OSCILLATOR)
DIFFERENTIATION
CONTROL TIME DELAY OF GATE PULSE
CONTROL PROBE POSITION SWEEPER
PROBE DRIVE
(T PROBE)
CONTROL WAVE EXCITOR
(T SIGNAL)
CLOCK PULSE
SAMPLING SCOPE OR BOXCAR INTEGRATOR
OUTPUT
TRIGGER INPUT
INPUT
TIME SWEEP INPUT
(T DELAY)
TIME BASE A
SAWTOOTH OUT
TIME BASE B
DELAYED PULSE OUT
GATE OUT
TRIGGER INPUT
DISPLAY BY TIME BASE A
SIGNAL INPUT
INTENSITY MODULATION
CURRENT AMPLIFIER
ENERGY ANALYZER
SAWTOOTH GENERATOR
(T SELECTOR)


FIG.1



TIME
(μs)
2
3
4
PROBE CURRENT
2
3
4
ENERGY (20 V/DIV.)
0
0
0
0.5 CM
DISTANCE (0.5CM/DIV.)


FIG.2

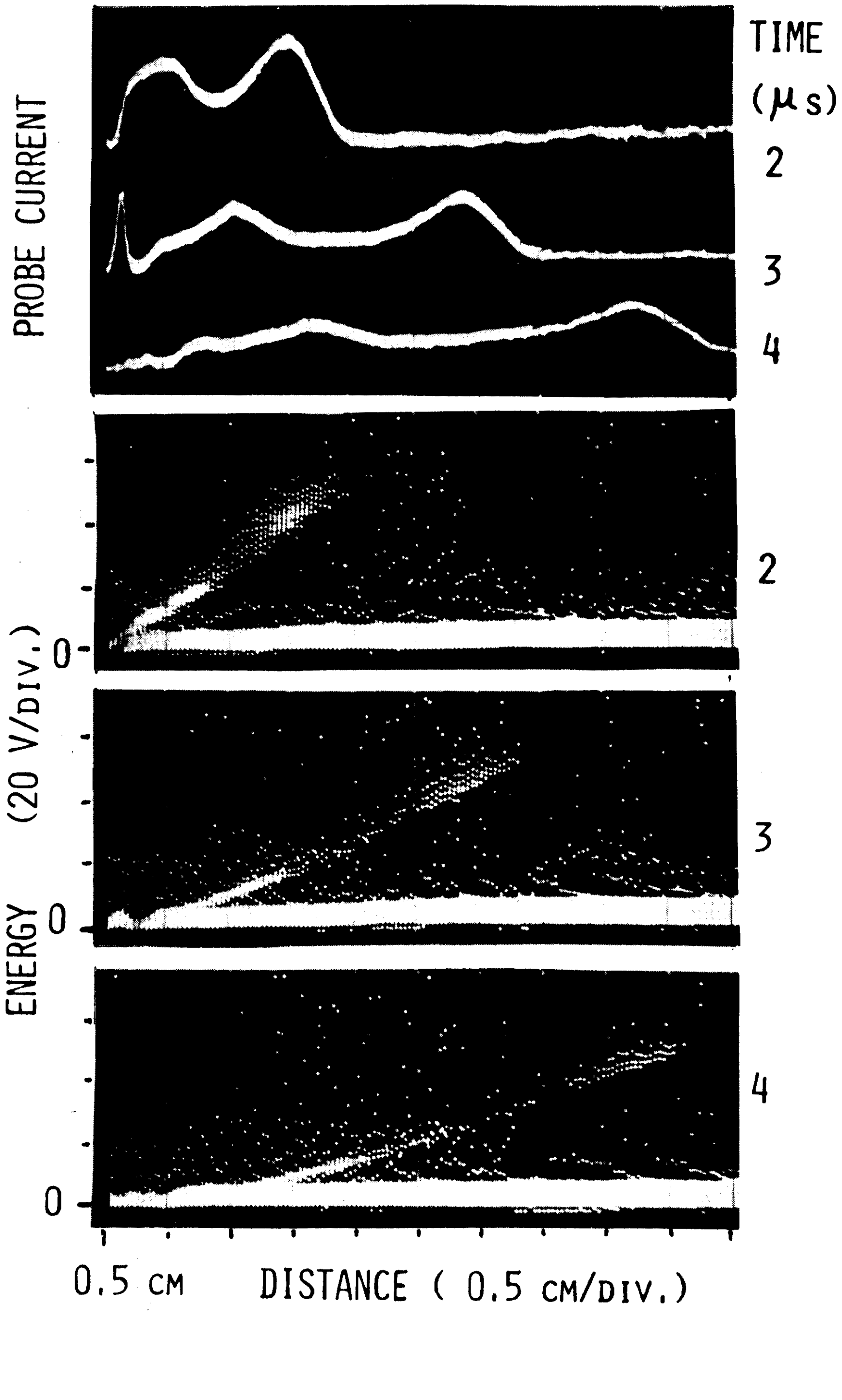

TIME
(μs)
2
3
4
2
3
4
PROBE CURRENT
ENERGY (20 V/DIV.)
0
0
0
0.5 CM
DISTANCE ( 0.5 CM/DIV.)

FIG.3