ANNOTATION

An investigation of ion cyclotron resonance in a hydrogen plasma with a density of 10^{12} - 10^{14} cm^{-3} was carried out in a pulse regime. A direct discharge in a longitudinal magnetic field up to 10^{4} gauss served as a plasma source.

Dependencies of high frequency energy transmission to plasma from various parameters were taken.

INVESTIGATION OF ION CYCLOTRON RESONANCE IN A DENSE PLASMA

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Plasma heating in an ion cyclotron regime is undoubtedly an interesting and promising method of reaching high ion temperature. As ion velocities are in phase with an external accelerating field, heating of an ion plasma component must be a rather rapid process /I/. Screening of defense plasma from high frequency field penetration, which is due to radial ion currents, can in principle be depressed in a great measure by the method suggested by T. Stix [2]. He has produced a high frequency input system exciting an external electric field, which is periodic in an axial direction. At very large densities of 10^{14} cm^{-3} and more, the theory points out a possibility of generation of so called ion cyclotron waves with their subsequent thermalization.

A general view of a device used for ion cyclotron resonance researches is presented in a Figure I.

A direct current discharge excited in a glass tube of 60 cm length and 6 cm in diameter served as a plasma source. To excite the discharge the electrodes were supplied with a step function signal of 800 μ sec duration. The discharge current could thus reach the value of 500 A and be regulated by varying the ballast resistance R_1 (Fig. 2).

The discharge tube was placed coaxially to the solenoid 70 cm long and 20 cm in diameter. The magnetic field reached its maximum in $4.7 \cdot 10^{-3}$ sec.

The solenoid was fed by a capacitor battery which stored up to 40,000 Joules and was charged to 5 kV. The magnetic field was uniform at the length of 45 cm with an oxactitude of more than 1%.

To put high frequency power into plasma, induction coils were used consisting of four three-coil sections connected in opposite phases.

The axial period of the electromagnetic field was 11 cm.

The high frequency energy was led into the middle of the coil by means of a coaxial feeder.

The induction coil ($L = J\mu H$) together with capacitors C and C_o (Fig. 2) formed a resonance circuit with a quality factor of 270, which was connected to the 1 kwatt generator, operating in a continuous regime in a frequency range from 6 to 12 MHz.

The ion cyclotron resonance was detected by the voltage change of the resonance circuit, the voltage having been connected through the capicator C_1 to a germanium detector and then supplied to the vertical deflection amplifier of the oscillograph ЭНО - I.

One could observe on the oscillograph screen a voltage change due to the presence of plasma loading in a strong magnetic field.

A delay system permitted one to excite the discharge of all values of the magnetic field strength and therewith to observe an ion cyclotron resonance both with constant and varying magnetic fields during the impulse time.

Plasma density was measured by millimeter waves transmitted through its volume. These measurements were carried out by L. A. Dushin and V. I. Kononenko.

Resonance power absorption was investigated after discharge current termination i.e. in a decaying plasma.

Experiments showed that in an ion cyclotron resonance region the plasma absorbs 30-40% of the supplied high frequency power. A typical resonance absorption curve is presented in Fig. 3. The resonance peaks were found near the values $\omega_{ci} = \frac{eH}{mc}$, if plasma density did not exceed $n \simeq 10^{12}$ cm^{-3}.

The dependence of the resonance absorption of high frequency power upon hydrogen pressure and direct current intensity is shown in Figs. 4 and 5 respectively. As we see in these figures there are optimal conditions for high frequency power absorption by plasma, which are determined by neutral and charged particle density.

In Fig. 6 we see that the half-width of the resonance curve is continually increasing with the rise of gas pressure, which indicates a strong interaction between accelerated ions and neutral atoms. A similar result was obtained in our institute by other experimenters, who investigated the ion cyclotron resonance in a stationary regime of the PIG type plasma source with a high-frequency generator power of several hundreds milliwatts /4/. In this work the influence of the coulomb collision upon energy losses of resonance ions was proved to be small. The frequency dependence of high frequency power absorption is shown in Fig. 7.

The discharge current growth accompanied by the ion density increase in the discharge volume /5/, causes the shift of the resonance peaks in the direction of magnetic fields smaller than the resonance value (Fig. 8).

The frequency probe measurements ($\lambda \simeq 4$ mm) showed then in decaying hydrogen plasma the density was $6 \cdot 10^{13}$ ion/^{3}cm 150 μ sec after the current 300 was cut off.

In Figs. 9 and 10 a function of resonance power absorption is presented at different moments after the discharge current was stopped, i.e. the function of the plasma density. The upper curve of the oscillogram (Fig. 9) is the discharge current impulse, the lower one is the voltage change on the resonance circuit. We see that at the start there is a non-resonance power absorption due to the discharge current flow, and then - a high frequency power absorption peak produced by an ion cyclotron resonance.

The form of the curve in Fig. 10 indicates that there exists an optimum plasma density for high frequency power absorption and this is proof of the absorption dependence upon the discharge current intensity (see Fig. 5).

Examining the Figures 8 and 9 we notice that at plasma density increase, the resonance absorption peak becomes assymmetric at the side of stronger magnetic fields. This assymmetry may probably be explained by the generation of the ion cyclotron waves, which were discussed in [2] and [3].

The observed character of the resonance high-frequency power absorption indicates the existence of the optimum density value. It is possible that at greater densities, a screening of plasma from high frequency fields becomes appreciable.

A quantitative check of the obtained data with an available theory [3] is impossible as a number of theoretical conditions are not fulfilled in the experiment (conditions of high ionization degree, larger conductivity, no density gradient along plasma radius and of no collisions in plasma). But qualitative comparison of some experimental data with theoretical data brings us to interesting conclusions.

According to theory a maximum high frequency power absorption W takes place in ion cyclotron resonance

of $\gamma = 1$, as $W \sim \frac{\gamma}{1+\gamma^2}$

Here $\gamma \sim \frac{n\lambda^3}{T_i^{1/2}}$, where n is an ion density, λ is the length of the exciting coil period, Ti - ion temperature.

In our experimental conditions when a direct discharge served as a plasma source and we had λ = [illegible] cm, Ti ~ [illegible] ev, a theoretical condition of γ = [illegible] (and therefore of $W = W_{max}$) was fulfilled for n = 2 4.10^{12} 1/cm^3.

Experimental dependence of W upon n has the same character but the maximum of this curve corresponds to the density of $n \sim 4.10^{13}$ ion/cm^3, measured in a main discharge column. This discrepancy of density values may be explained if we assume that the ion cyclotron resonance takes place only at the boundary of the plasma column "choosing" the region where $\gamma = 1$.

Plasma density determination by resonance peak's asymmetry points out that calculated density value is less than that, measured by an independent method.

Similar results were obtained in examining the work of the B-65 stellarator, where resonance peak's asymmetry or even it's splitting in two, corresponded to lower density values than the measured ones.

Thus checking the theory with our experimental data and with those obtained on the stellarator, one may conclude that the high frequency penetration into plasma in weak if the density of the latter is above 5.10^{12} ion/cm^3.

In this connection we have an actuate necessity of an unambigious confirmation of the existence of ion cyclotron waves and their subsequent thermalization. This would enable us, in case of success, to heat plasma with a density exceeding 10^{13} cm^{-3}.

But we should like to note more possibilities of plasma heating in the pure resonance regime of higher density values, which nevertheless fulfilling the condition of $\gamma \approx 1$. Hence it follows that the critical density may be increased by means of a temperature rise, but this dependence is a weak one.

A period λ of the high frequency input system is a far more substantial factor. Diminuation of λ is very promising from theoretical point of view: reducing λ by half for example we get an almost tenfold density increase.

Moreover, according to the theory, a diminuation of λ value results in an increase of high frequency power absorption W at the ion cyclotron resonance, as $W \sim \frac{1}{\lambda^2}$.

We think a more thorough investigation of this point would be advisable.

LITERATURE

1. K. D. Sinelnikov and others - Proc. of 1958 Geneva Conference, No. 2211.

2. T. H. Stix and R. W. Palladine. - Proc. of 1958 Geneva Conference, A/CONF.15/360.

3. T. N. Stix - Proc. of 1958 Geneva Confernece, A/CONF.15/P/361.

4. L. Dubovey, O. Shvets, C. Ovchinnikov "Atomnaya Energiya" (in print)

5. K. S. W. Champion - Pfos. Phys. Soc. 70,4468,212 (1957)

Figure Subscripts

Fig. 1. General view of the experimental device

Fig. 2. Scheme of the experimental device.

Fig. 3. Ion cyclotron resonance oscillogram: a quantity reciprocal to the circuit voltage against the increasing magnetic field.

Fig. 4. Hydrogen pressure dependence of the resonance high frequency power absorption at the constant discharge current.

Fig. 5. Discharge current dependence of the resonance high frequency power absorption.

Fig. 6. Hydrogen pressure dependence of the half-width of the resonance high frequency power absorption at the constant discharge current.

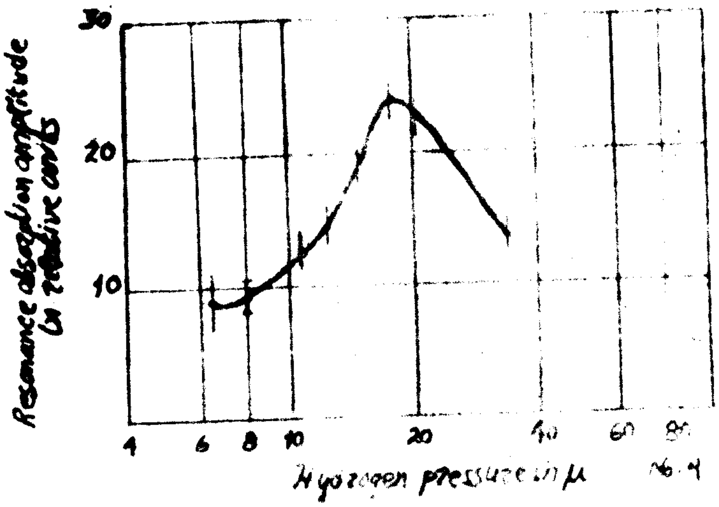
Fig. 7. Generator frequency dependence of the resonance high frequency power absorption.

Fig. 8. Discharge current dependence of the resonance absorption peak shift.

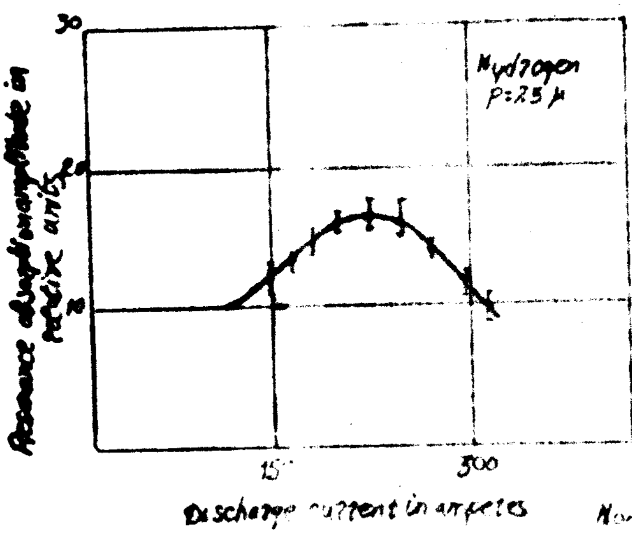
Fig. 9. Oscillograms of the resonance high prequency power absorption at different moments after the discharge current termination.

1. Resonance observed 100 μ sec after the discharge current is cut off.
2. The same after 250 μ sec.
3. The same after 500 μ sec.
4. The same after 620 μ sec.
5. The same after 930 μ sec.
6. The same after 1100 μ sec.

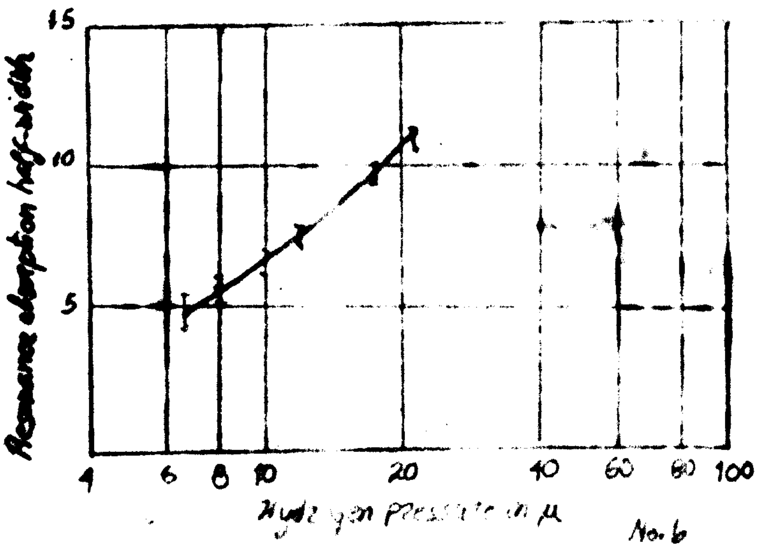
Fig. 10. Time dependence of the resonance high frequency power absorption after the discharge current is cut off.


Resonance absorption amplitude in relative units
30
20
10
4
6
8
10
20
40
60
80
Hydrogen pressure in μ

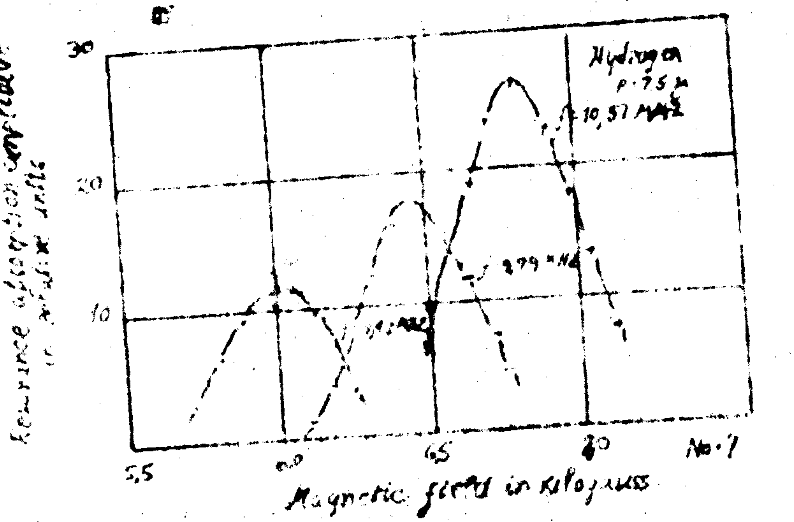
No. 4


Hydrogen
P=25 μ
Resonance absorption amplitude in relative units
30
20
10
150
300
Discharge current in amperes

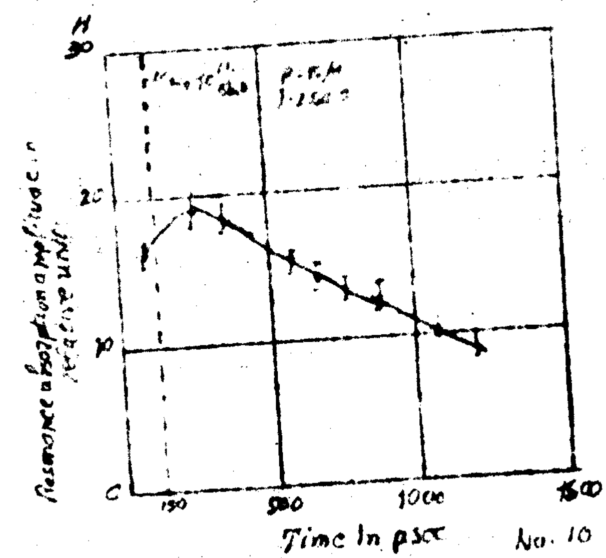
No. 5


Resonance absorption half-width
15
10
5
4
6
8
10
20
40
60
80
100
Hydrogen pressure in μ

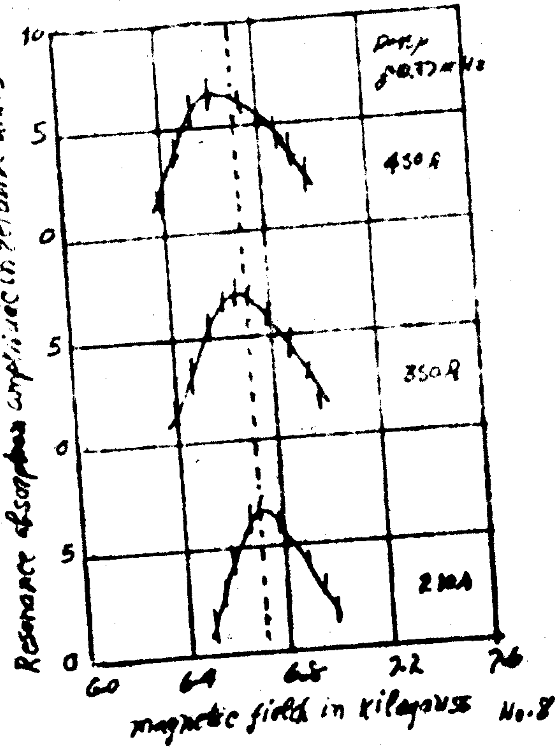
No. 6



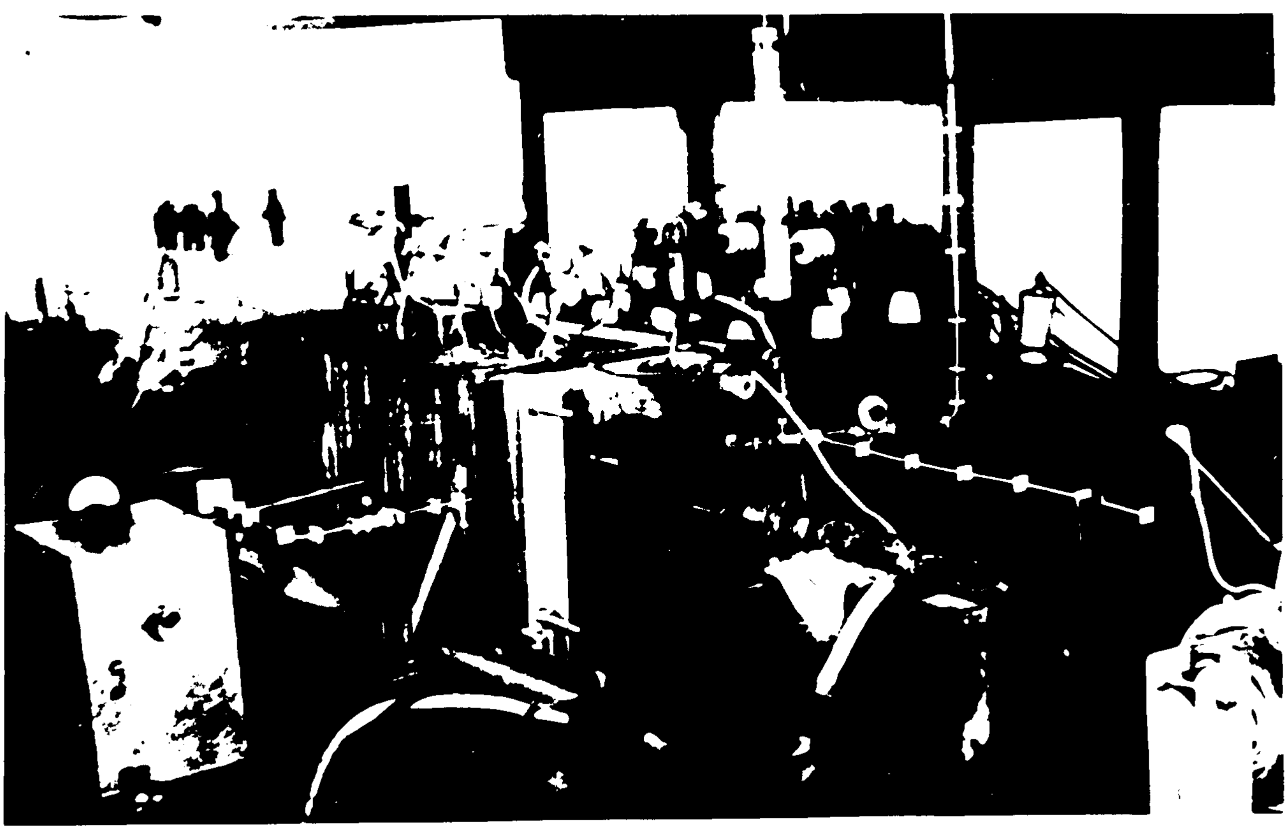
Hydrogen
p·7.5 μ
f·10,57 MHz
30
20
10
55
60
65
70
No. 7
Magnetic fields in kilogauss



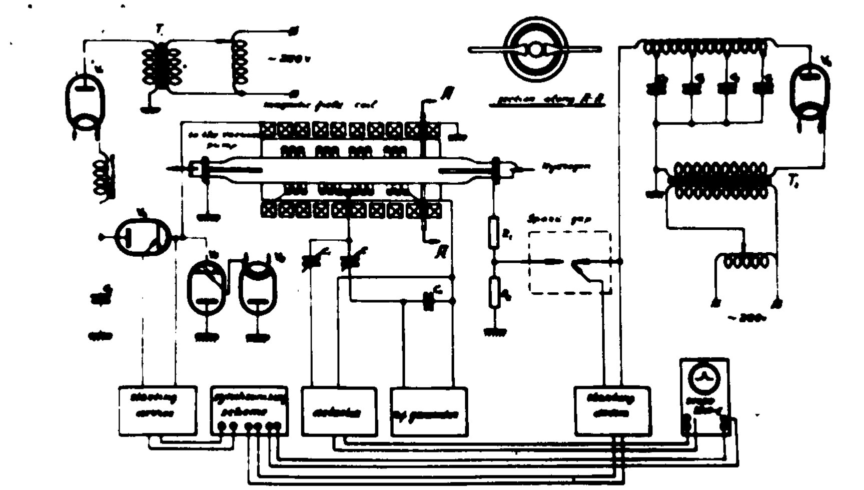
30
20
10
C
150
500
1000
1500
Time in μsec
No. 10



10
5
0
5
0
5
0
450 A
350 A
60
64
68
72
76
magnetic field in kilogauss
No. 8



1.



Block diagram of the experimental system

2.

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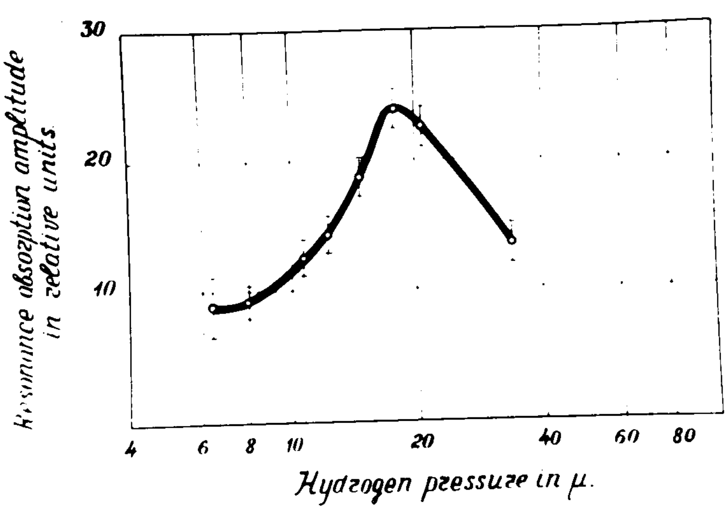

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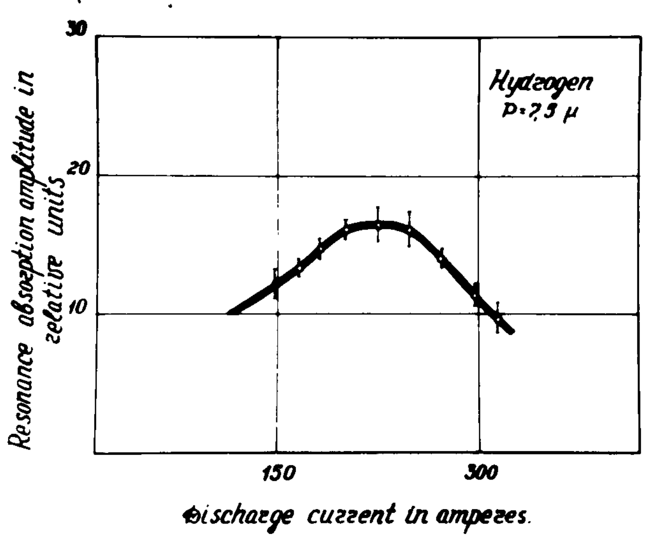
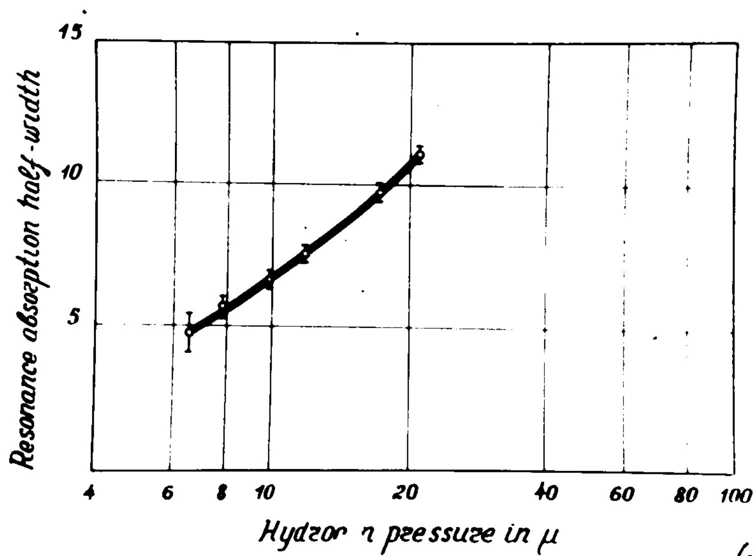

30
20
10
Hydrogen
p=7,5 μ
Resonance absorption amplitude in relative units
150
300
discharge current in amperes.

5.


Resonance absorption half-width
15
10
5
4
6
8
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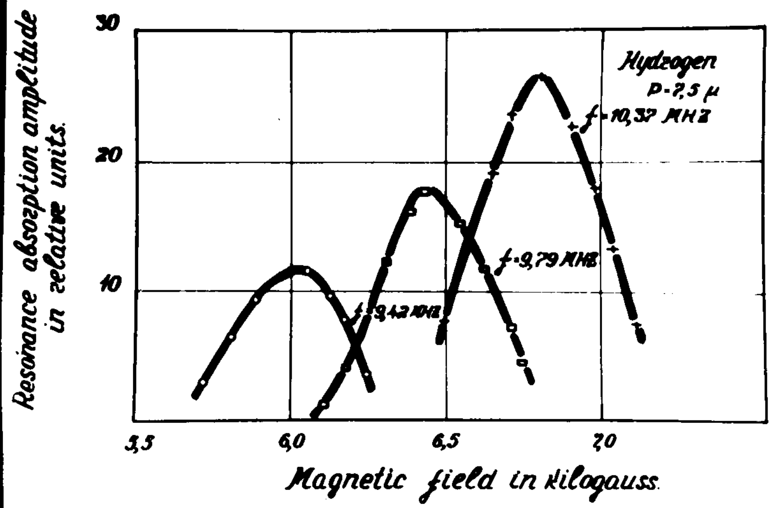
20
40
60
80
100
Hydrogen pressure in μ

6.



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