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PLASMA FORMATION AND SUSTAINMENT BY A MULTIJUNCTION GRILL ON THE CASTOR TOKAMAK

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RESEARCH REPORT

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Abstract

Radiofrequency power up to 40 kW, injected into the vacuum chamber of the CASTOR tokamak by a multijunction grill, was used for plasma formation during the rampup phase of the toroidal magnetic field. When electron cyclotron resonance (ECR) appears inside the tokamak chamber for given pumping frequency ($f = 1.25$ GHz) a plasma with density greater than $2\times10^{18}m^{-3}$ and temperature $T_e = 10\div40$ eV is produced. Plasma is sustained at some lower value of the density during the whole RF pulse. Simultaneously, a toroidal current up to $\simeq 0.2$ kA is generated. The energy confinement time is estimated to be about 30 μs during the ECR breakdown.

1. INTRODUCTION

The noninductive current drive in tokamaks is promising way to establish a steady-state operation in a future tokamak-reactor. Usually the target plasma for noninductive current drive is produced by an ohmical heating (OH) transformer. Then, lower hybrid wave (LHW) are injected into the plasma to maintain or to rampup the toroidal current. Recently, experiments on current drive by LHW have been tried in a target plasma produced by a noninductive discharge. It offers the possibility of the complete omission of the OH transformer in future. In the WT-2 and JIPP T-IIU tokamak an additional ECR source (gyrotron) has been used for the initiation of the discharge [1, 2] . PLT group has been successful in the plasma startup by the same power source, which was then used for noninductive current drive [3] . The LHW launcher was phased in this case first at 0^{o} and after the plasma formation the phasing was changed to a value appropriate for effective current drive. Moreover, a careful programming of the vertical field B_{vert} was highly necessary.

We report here preliminary results of a simple method of the noninductive plasma formation and sustainment in a tokamak by LHW, launched via 4-waveguide multijunction grill with fixed phase shift ($\Delta\varphi = 120^{o}$), used previously for LH current drive experiment in targed OH plasma [4] .

2. EXPERIMENTAL ARRANGEMENT

The experiment was carried out on CASTOR tokamak in IPP Prague ($R = 0.4$ m, $a = 85$ mm, $r_o = 100$ mm, $B_T \lesssim 2$ T, hydrogen working pressure $p_{H_2} \gtrsim 30$ mPa). The same preionization source (electron gun) was used as for standard inductive breakdown. The RF power was launched into vacuum chamber using 4-waveguide multijunction grill with dimensions of waveguides 10x160 mm (see Fig. 1). It should be noted, that about 30 % of the RF power is reflected when plasma has been created and that the RF power of generator decreases approximately to 50 % at the end of the pulse. The orientation of the grill is such, that according to the numerical computation [4] , about 50 % of incident power propagates in the direction of the electron drift velocity during the standard OH discharge in CASTOR (antiparallel to the toroidal magnetic field $\vec{B_T}$, i.e. $\vec{k} \uparrow\downarrow \vec{B_T}$), see Fig. 2. In the opposite direction ("parasitic" branch of the spectral density distribution, parallel to $\vec{B_T}$) about 20 % od incident power propagates. While the calculated spectrum of the main branch has a peak at $N_{\parallel} = 5.5$ (it corresponds to the electron energy about 9 - 10 keV), the "parasitic" spectrum is substantially extented to the higher $N_{\parallel}$

During the experiment the primary coil of the OH transformer was short-circuited. Moreover, we didn't employ neither static (vertical and horizontal), nor dynamic magnetic compensating fields ($B^{stat}_{vert} = B^{stat}_{hor} = B^{dyn}_{vert} = 0$) in this experiment.

Plasma parameters (n_e, T_e) were monitored by a movable Langmuir probe, lacated in the same cross-section as the grill. The radial profiles of n_e and T_e between the liner and the radius $r/a = 0.45$ can be measured by this probe. The probe consists of a molybdenum wire (0.8 mm diameter by 3 mm long).

In addition to the standard plasma parameters (plasma current, the loop voltage, the line average density $\bar{n}_e$ measured by the 4 mm interferometer and visible line intensities), the integral electron cyclotron radiation in the range of 36 GHz and HXR emission ($E \gtrsim 0.2$ MeV) were monitored during the experiment.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Plasma is generated by RF power, launched into the toroidal chamber by the grill. The RF pulse is applied simultaneously with the startup of the toroidal magnetic field B_T, which reaches its maximum value ($B_T^{max} = 1.3$ T) after 30 ms. As B_T increases, ECR zone arises at the inner side of the vacuum chamber at about $t \simeq 0.5$ ms (according to Fig. 3) and ECR plasma is created. Due to the mechamism of waves transformation [5] , this plasma is then sustained during the whole RF pulse, despite of the fact, that in consequence of the increasing magnetic field the ECR zone is already outside of the chamber.

The temporal evolution of plasma parameters during the RF pulse is demonstrated in Figs. 4a-h. After reaching its maximum value at $t \simeq 1.3$ ms, the line average density decreases, at first rapidly, then slowly until the end of the RF pulse is reached. Similar character exhibits the ion saturated current I_s^+ (see Fig. 4b) corresponding in some sense to a local electron density at the radius $r = 40$ mm.

A toroidal plasma current I_p appears during the ECR breakdown. It rises with a rate about 40 kA/s and approaches the maximum value $I_p^{max} \simeq 0.2$ kA at $t \doteq 5$ ms. At this time the toroidal magnetic field is about one order of magnitude higher than the cyclotron value for the pumping wave. Therefore, the resonant (ECR) mechanismus of the wave energy absorption is absent during the current rise. One possible mechanism of this current generation is an interaction of the lower hybrid wave ($2f_{LH} \leqslant f \ll f_{ce}$ in our case), launched by the multijunction grill, with the already existing target plasma. It is necessary to note, however, that the direction of the electron drift is opposite to the direction of the $\vec{k}$-vector of the main branch of the calculated RF spectrum. It seems to be probable [6], that the observed toroidal current is driven in this case by the "parasitic" branch of the spectrum due to the enhanced population of the higher $N_{\parallel}$ (see Fig. 2). Such assumption is justified by the relatively low velocities of the primary plasma electrons. Due to this fact, an efficient interaction between the target plasma and RF wave can be expected just at high $N_{\parallel}$ only [7].

The total efficiency of the noninductive current drive is rather low in our case. This fact may be connected with the low value of the RF power in this high $N_{\parallel}$ part of the "parasitic" branch of the spectrum (only a few % of the total power). At the second, plasma equilibrium has been performed only passively by the conducting copper shell of the tokamak. As we have mentioned above, we didn´t employ the dynamic vertical magnetic field required for the successful long-term equlibrium of the current channel. The value of the toroidal current **should be limited by this fact as well.**

Moreover, it has been shown recently [8] that even such low values of toroidal electric field E_T as ± 0.1 V/m change the electron distribution function and consequently the efficiency of the RF current drive. Such toroidal electric field is created in our noninductive experiment mainly due to the inductance of the plasma loop ($E_T = \frac{U_{loop}}{2\pi R} = \frac{L_p}{2\pi R} \cdot \frac{dI_p}{dt} \simeq 0.1$ V/m), see Fig. 4d. Especially during the I_p rampup phase ($t \lesssim 5$ ms) acts this electric field against the RF current drive and the counter-current caused by this field can achieve several tens of amperes. This fact should have negative influence of the LHCD efficiency as well.

While the ECR radiation is not measurable during the initial phase of the discharge (limited bandwidth of the 8 mm waveguide receiver), a quite noticable level of the signal is observed after that phase until the end of the RF pulse. It indicates presence of an overthermal component in the electron distribution function. However, no hard X-ray emission ($E \gtrsim 150$ keV) was registered. It shows, that no electrons with corresponding energy are produced. This is an additional argument for the above mentioned statement, that the current is driven by the high $N_{//}$ part of "parasitic" branch of the spectrum only.

Temporal evolution of spectral line intensities exhibit a sharp peak at the moment of maximum plasma density. It should be noted, that the line CV with a high value of the excitation potential reaches its peak value at the same time as the lines H_β and

CIII (see Fig. 4f, g, h).

According to the probe measurements, the electron temperature T_e increases smoothly from T_e = 4÷5 eV until the maximum value of the plasma current ($t \simeq 5$ ms), when it reaches value about 40 eV (see Fig. 5). The radial profiles of the ion saturated current (see Fig. 6) are rather flat or sometimes even hollow. It is necessary to note, that the local electron density evaluated from probe measurement at r = 40 mm is 2-3 times greater than the line average density $\bar{n}_e$ measured along the central chord by 4 mm interferometer.

According to the probe measurements the energy confinement time $\tau_E = Q/P_{inc}$ (Q-total energy in the plasma column) has been estimated as 30÷40 µs at the beginning of the discharge. Such low value of τ_E is not surprising as, due to the low value of the generated toroidal current (unsufficient to establish the rotational transform), there is no real confinement in the given toroidal configuration.

The plasma density as well as driven toroidal current depend only weakly on a initial pressure of the working gas. An effective breakdown has been achieved, however, only for hydrogen pressures greater than $p_{H_2} \simeq 34$ mPa.

As we have mentioned above, the experiment was performed at a zero level of the external compensating magnetic fields $B_\perp$. We have found that any other value of $B_\perp$ makes the RF breakdown difficult. It can be explained by a substantial elimination of the stray magnetic fields in comparison with the standard inductive breakdown as a consequence of the transformer short-circuiting and due to the very low toroidal magnetic field during the breakdown. Therefore, any external perpendicular field increases vertical helicity of the toroidal field lines and consequently enhances the plasma losses.

4. SUMMARY AND CONCLUSIONS

Preliminary results of RF plasma formation in a tokamak during rampup of the toroidal magnetic field are reported. When ECR condition for given pumping frequency is fulfilled inside the vacuum chamber, a plasma with density about $n_e = 2x10^{18} m^{-3}$ and temperature a few tens electronvolts is formed. After that the plasma is sustained during the whole RF pulse, even when ECR zone is already outside the plasma (we have observed such effective absorption of RF power for frequencies much lower than f_{ce} earlier in linear[5] and toroidal devices [9] for B_T = const.). Moreover, the toroidal current generated by a RF wave is also observed. RF-sustained plasma has an overthermal character. However, after a few milliseconds the plasma density and current fall down as consequence of a poor confinement. To reach a tokamak regime on the CASTOR, it is necessary to rumpup the plasma current substantially. There are two possibilities how to do it:

(i) According to our opinion it is necessary to use a controlled or at least a preprogrammed power source for vertical compensating field just after the ECR breakdown. In that case more suitable conditions for confinement of current carrying electrons will exist and it should be possible to rampup the plasma current by the same or maybe an additional waveguide grill.

(ii) To use the RF breakdown for generation of the sufficiently dense target plasma for the inductive-driven discharge (i.e. RF preionization). In that case we will be able to control the temporal evolution of the loop voltage and ramping-up of the inductive plasma current. Furthermore, such experimental arrangement enables us to study simultaneous rampup of I_p and B_T (to keep the safety factor q_a alose to constant). It has been found recently on JET that higher values of I_p can be reached under such conditions without any increase of MHD activity [9] .

In both cases an effective prolongation of the tokamak pulse can be achieved (up to about 50 ms in our case) without any additional demands on the toroidal field capacitor bank.

Acknowledgement.

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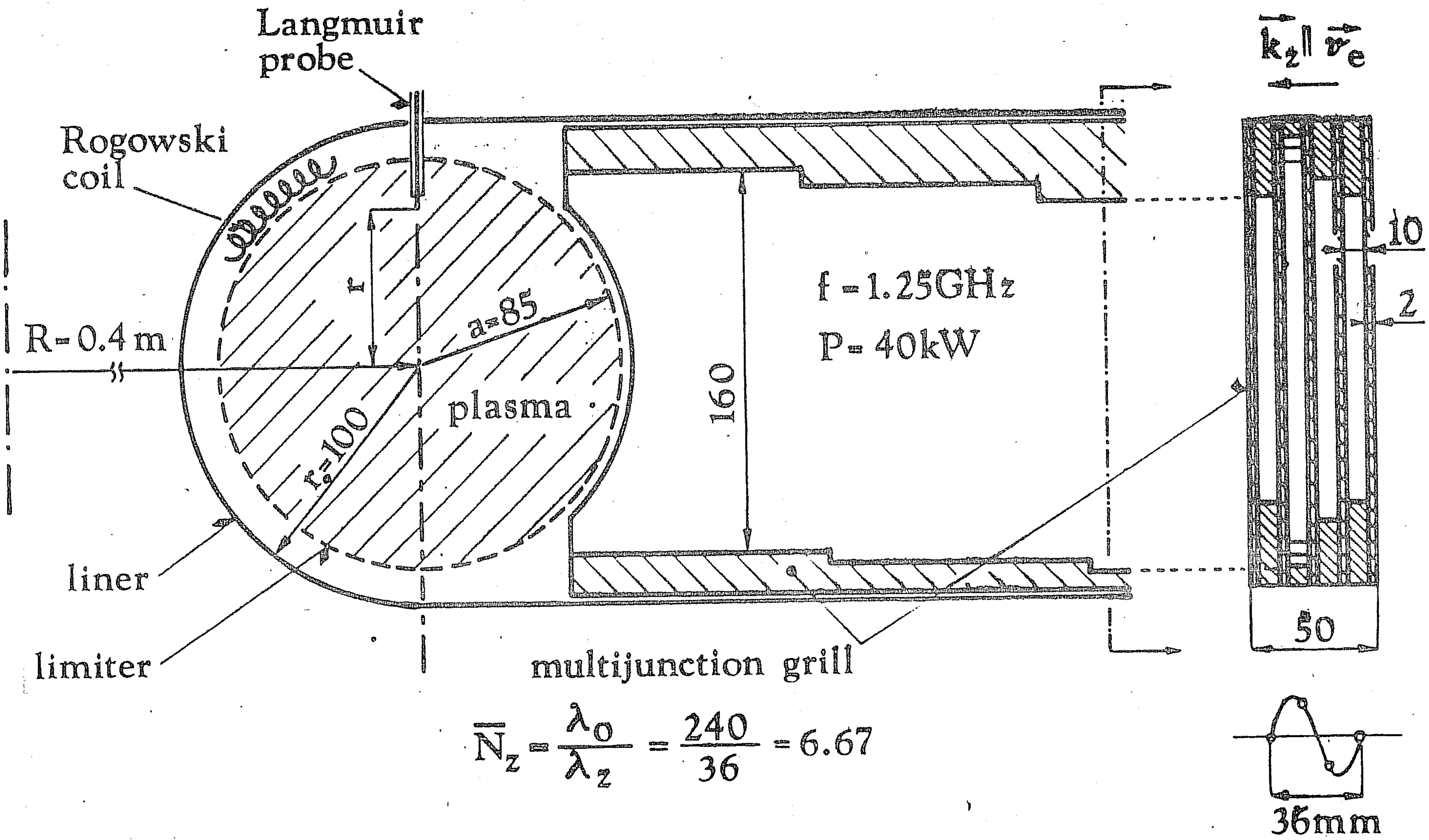
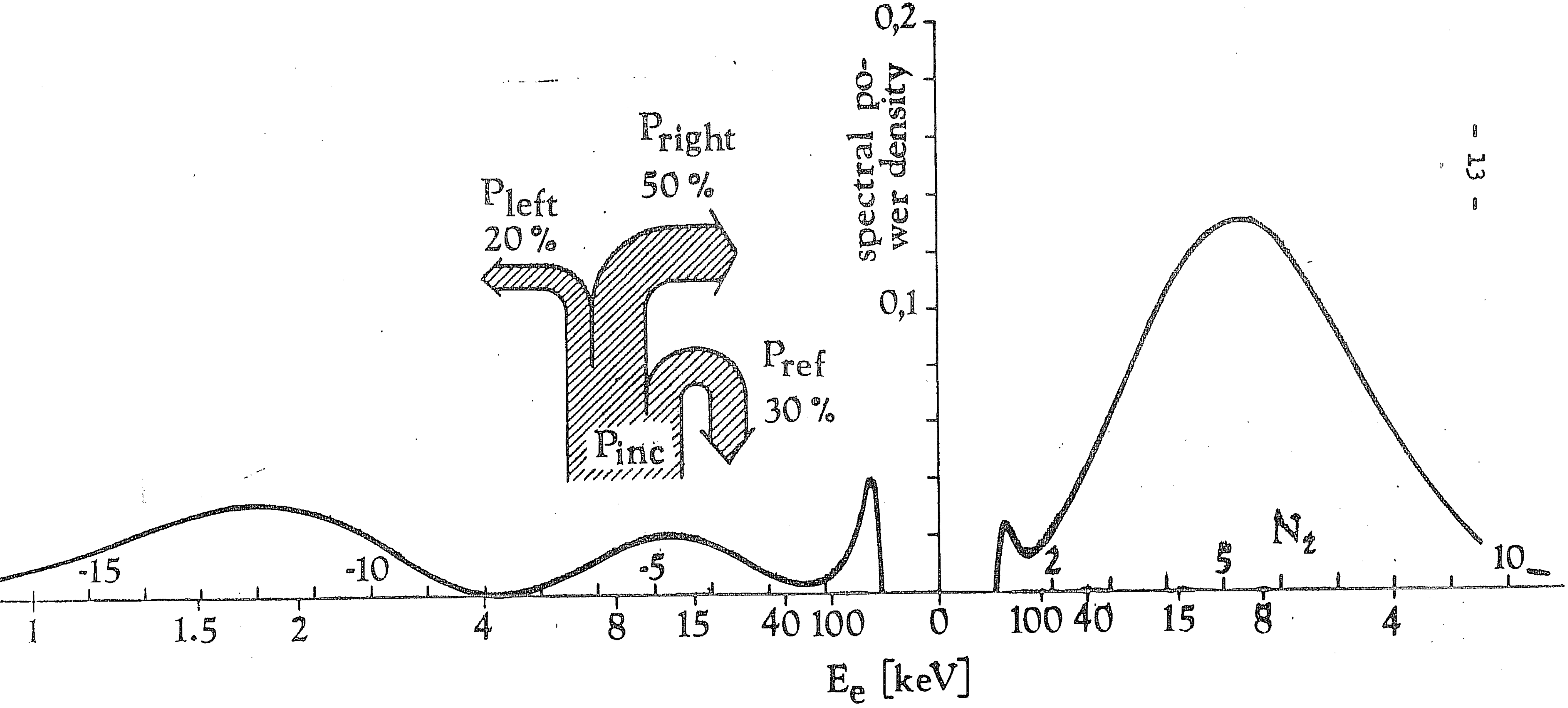


$$\overline{N}_z = \frac{\lambda_o}{\lambda_z} = \frac{240}{36} = 6.67$$

FIG. 1

FIG. 2


0,2
spectral power density
0,1
P_{left} 20 %
P_{right} 50 %
P_{ref} 30 %
P_{inc}
-15
-10
-5
2
5
N_2
10
1
1.5
2
4
8
15
40
100
0
100
40
15
8
4
E_e [keV]

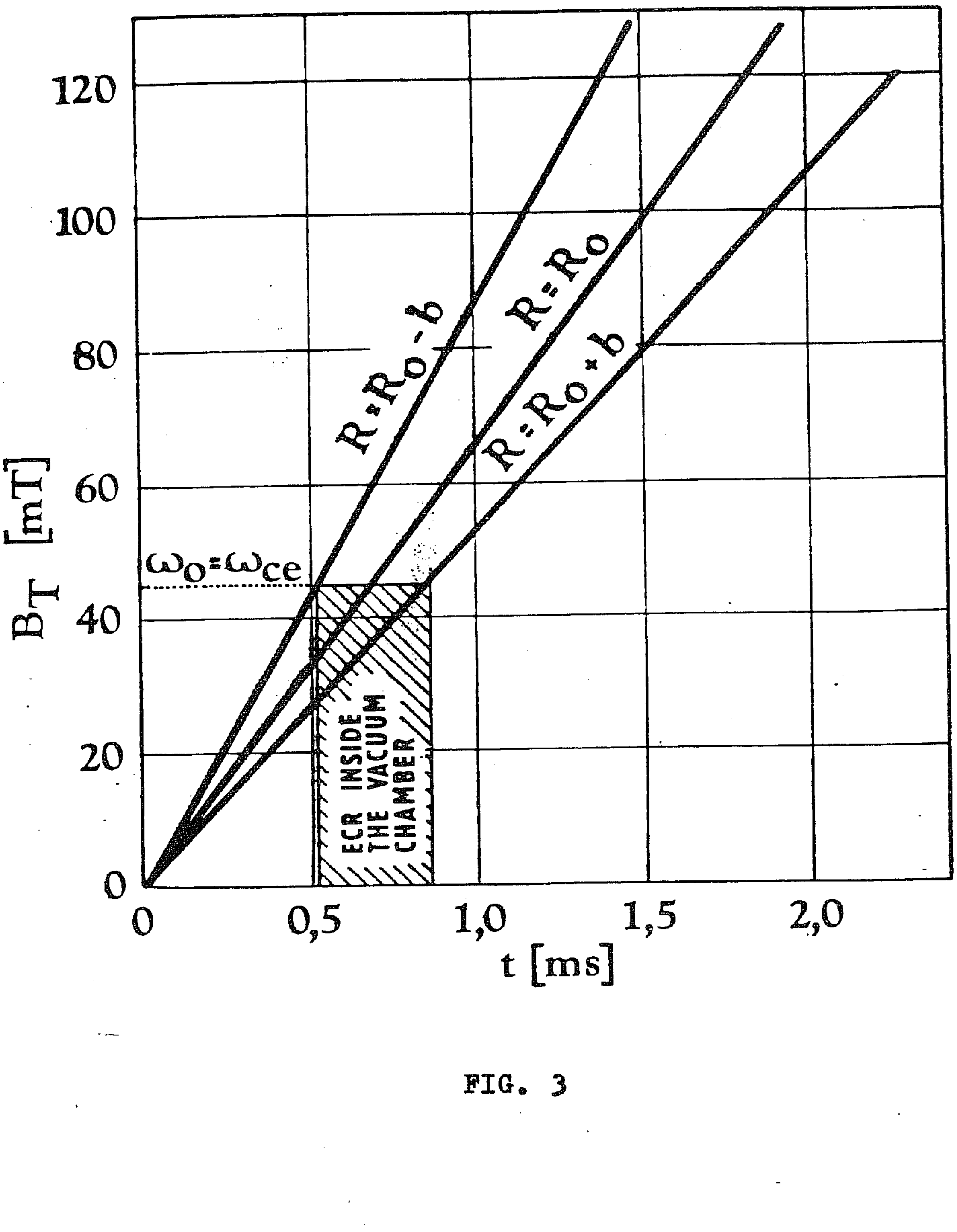

120
100
80
60
40
20
0
B_T [mT]
0
0,5
1,0
1,5
2,0
t [ms]
$R = R_o - b$
$R = R_o$
$R = R_o + b$
$\omega_o = \omega_{ce}$
ECR INSIDE THE VACUUM CHAMBER

FIG. 3

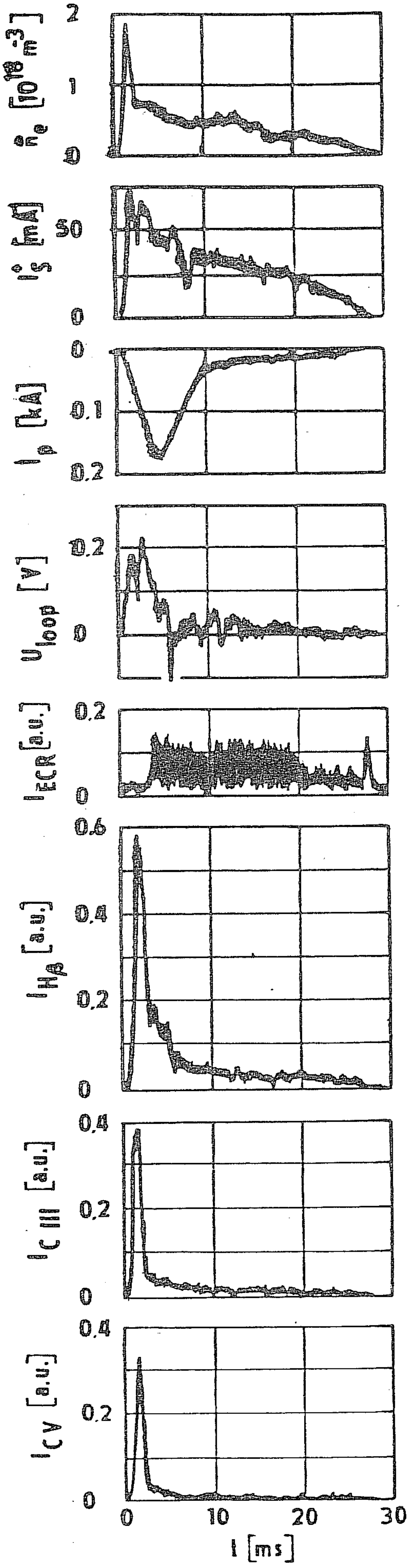

n_e [10^18 m^-3]
2
1
0
I_s^0 [mA]
50
0
I_p [kA]
0
0.1
0.2
U_loop [V]
0.2
0
I_ECR [a.u.]
0.2
0
I_Hβ [a.u.]
0.6
0.4
0.2
0
I_C III [a.u.]
0.4
0.2
0
I_C V [a.u.]
0.4
0.2
0
0
10
20
30
t [ms]

FIG. 4

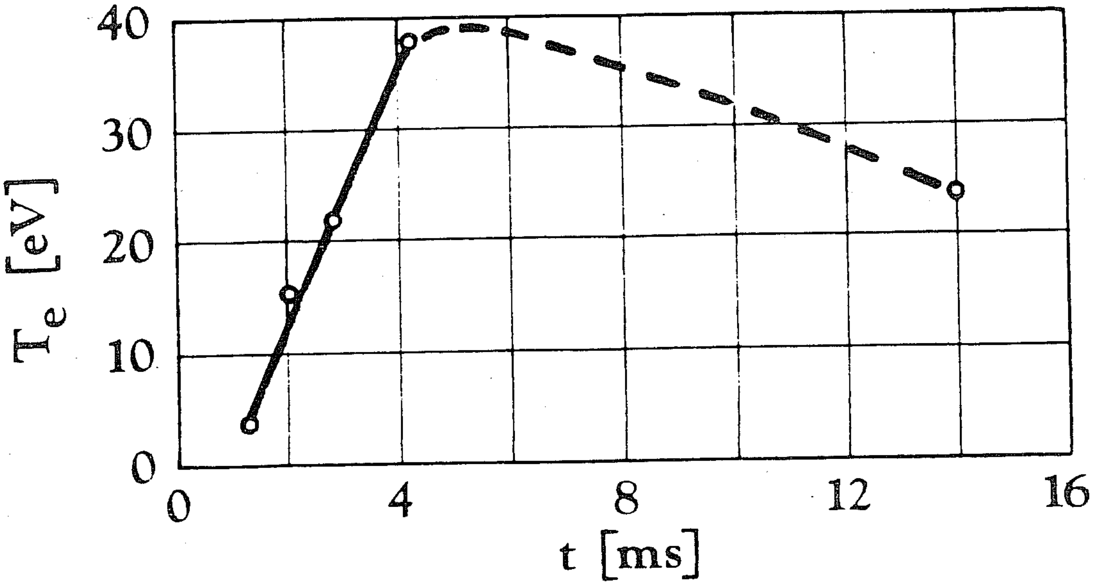


FIG. 5

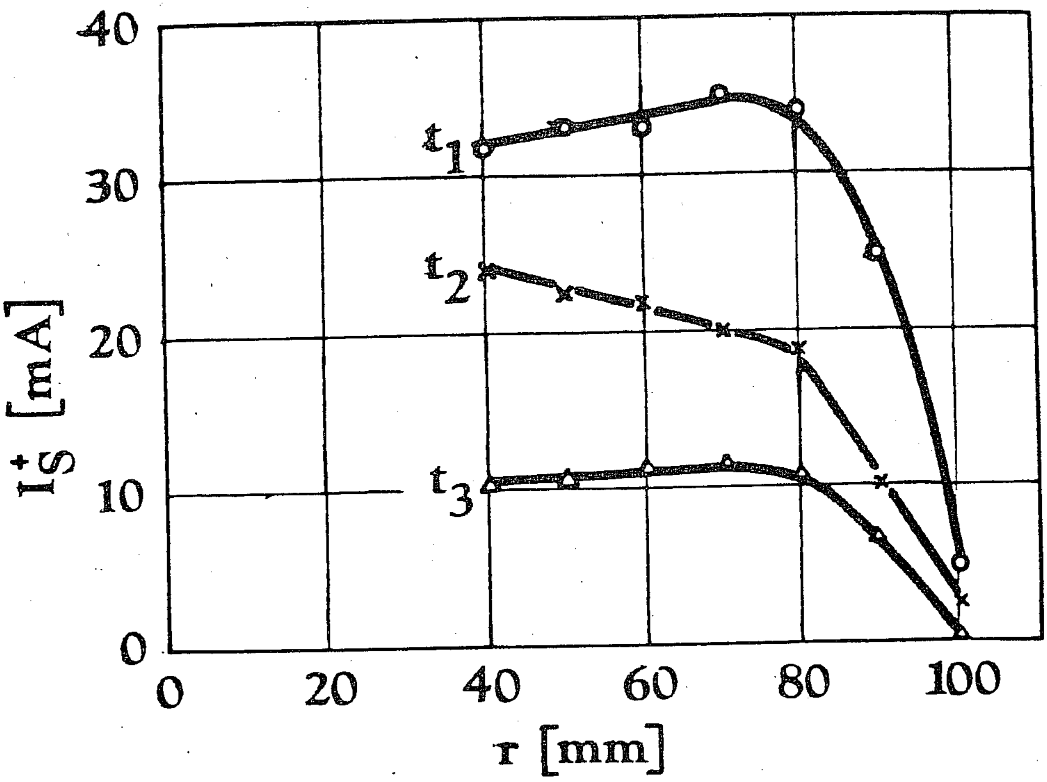


FIG. 6