INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

RESEARCH REPORT

NAGOYA, JAPAN

Experiments of Plasma Confinement in JIPP Stellarator-I

Preliminary Results Using J × B Gun and ECRH Plasma

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Abstract

To investigate the dependence of plasma confinement on the properties of the magnetic field (rotational transform angle, shear, magnetic well, plasma radius etc.), a circular $\ell = 3$ stellarator with a vertical field is constructed with taking care of the accuracy. Several kinds of plasma sources (J × B type gun with a fast acting valve, titanium gun, ECRH, r.f. stochastic heating and ohmic heating by air coil) are prepared.

In this report, preliminary results of the experiments on the plasma confinement using J × B type gun and ECRH plasma are described. The diffusion coefficient estimated from the decays times and the plasma radius are inversely proportional to the square of the rotational transform angle ι. The profile of the density distribution is similar to $(r/a_s)^2 J_{-2/3}[1.25(r/a_s)^3]$ which corresponds to the relation $D \propto \iota^{-2} \propto r^{-4}$. The diffusion coefficients estimated from the Bessel distribution are down to 1/7 ~ 1/17 times of the Bohm one. If the foregoing distribution is adoped, the ratios become to 1/17 ~ 1/40. The confinement time does not depend appreciably on the property of the magnetic well (and antiwell). The dependence of the confinement time on the magnitude of the magnetic field is appearently linear. As the ion temperature of the plasma of J × B type gun depends on the magnitude also, the scaling law is not determined yet and more detailed investigation are being carried out.

§1. Introduction

Studies of the confinement of low β plasmas in a high shear circular stellarator field are being carried out using JIPP stellarator. To investigate the dependence of plasma confinement on the properties of the magnetic field (rotational transform angle, shear, magnetic well etc.) a circular $\ell = 3$ stellarator with a vertical field is constructed with taking care of the accuracy. The properties of the magnetic field can be changed flexibly by controlling the currents of toroidal coil, helical coil and the coil of the vertical field. The dependence of the properties on the current configuration was examined[1]. This device can be easily converted to the torsatron configuration.

The dependence of confinement on the plasma properties are very important problem and the several kind of plasma sources ($J \times B$ type gun with a fast acting valve, tianium gun, ECRH, r.f. stochastic heating, ohmic heating by air core coil) are prepared. In this report, the experiments on plasma confinement using $J \times B$ type gun and ECRH plasma are described. The experiments to study the diffusion processes of plasmas of r.f. stochastic heating and ohmic heating are being carried out.

§2. Experimental Arrangements

JIPP stellarator has a circular shape with major radius of 50cm and the inner radius of the vacuum vessel made of stainless steel is 8.4cm. The two halves of the vacuum vessel are insulated by ceramic spacers with thickness of 1cm, so that the r.f. stochastic heating and the ohmic heating can be applied (Fig. 1 and Fig. 2). The magnitude of the toroidal field is up to 4kG in quasi-stational operation (5sec in each minute). The helical field is $\ell = 3$ with the number of field period $m = 8$ and the minor radius of helical coil is 10.6cm. The current of up to 22kamp.-turn (= 2.5 kamp × 9turn) is fed through coaxial current feeders. The helical coils are wound by using helical grooves which are machined by numerically controlled method. The geometrical accuracy of helical coil is better than 0.5mm. The magnetic surfaces are checked with the pulsed electron beam method[2], and measured ones agree with the results of computation very well (Fig.3). The rotational transform angle, shear and plasma radius of the typical current parameters are given in Table I and Fig. 4. A configuration of torsatron type[3] is also realized in this device.

Table I. Parameters of Magnetic Configuration

$B_T \leq 4.1$ KG $(I_T < 1.6$ KA)

$R = 50$ cm $I_H < 2.5$ KA

I_H/I_T	2		3.2	
I_V/I_T	0	0.02	0	0.02
R/a	9.5	11.5	14	16
ι(outside)	1.5π	π	1.7π	1.1π
ι(axis)	0	0.4π	0	0.5π
shear	0.15	0.05	0.12	0.03
well depth	3%	10%	3%	7%

We adopt different kinds of plasma sources to study the diffusion processes of plasmas with wide range of the parameters. The first one is so-called J × B type gun with a fast acting valve[4]. (Fig. 5) The gas is fed by the fast acting valve and the current is fed during about 0.5 msec by condenser discharge with relatively low voltage (300v). The second one is titatium gun[5]. The third one is ECRH plasma production by using a magnetron with the frequency of $2.45GH_z$ ($B_{ec} \doteq 875G$) with the maximum power of 0.8kW. The forth one is r.f. stochastic heating[6]. The fifth one is ohmic heating method by using air core coil. The winding of air core coil is arranged so that the leakage flux in the confinement region is negligiblly small (less than 1 gauss) (Fig. 6).

Movable probes which can scan inside the vessel are arranged. The sensitive microwave interferometer of 8mm is used. The multigrid type energy analysers are being prepared.

§3. Experimental Results of J × B Type Gun Plasma

§3.1. Helium Plasma Experiment

The properties of the plasma was studied in the linear field[7], before applying J × B type gun plasma to the toroidal field. The J × B type plasma source operates as a quasi D.C. source of about 0.5ms ~ 1ms with the operation of fast acting valve. The electron temperature is in the range of 0.2 ~ 2eV and the ion energy of the directional motion across the magnetic field at the injecting stage is proportional to the square of the field (measured by an electrostatic ion energy analyser within the region of 0.4 ~ 1.5 kGauss). The ion energy of the directional motion is about 100 eV when B is 1 kGauss and hydrogen plasma is used. The degree of ionization is around 1%.

This gun is mounted in the vaccum vessel of the stellarator at 2cm inside the wall. Just after the gun is switched off, the density distribution extends outside of the calculated separatrix. But 1msec later, the falling position of density profile coincides with the separatrix position. The ion saturation current of single probe is shown in Fig. 7. The density decreases with the decay constant of 1 $\sim$ 5msec from an initial value of 10^9/cc. The electron temperature T_e measured by probe characteristics is 1.5eV and changes only slightly during the confinement time. The electron temperature does not depend appreciably on the magnitude and the configuration of the confining field. The density n_o of neutral helium is 1.4×10^{12}/cc. The cooling time of T_e by helium gas is 0.1sec. The cooling time of ion temperature T_i by charge exchange with helium atom is estimated to be 0.4ms when T_i > 1eV, so that T_i becomes low during the decay time. The effect of the ionization and the recombination can be negligible.

Figure 8 shows the dependence of the observed confinement time τ on the helical coil current I_H, while the toroidal field is kept constant to be 2 kGauss (Current of toroidal coil I_T = 772A). The dependence of the rotational transform angle, the shear parameter and the plasma radius on the helical current I_H are given in Fig. 4 and Table I. As the plasma boundaries estimated from the density profiles in the cases of I_H/I_T = 0.5, 1, 2 coincide with the position of calculated separatrix, the inverse of the diffusion coefficient defined by $1/D = \tau\ (2.4/a_s)^2$ are also plotted (a_s is the average radius of separatrix and τ is the observed confinement time). When the dependences of the rotational transform angle l and the shear parameter $(dl/d\rho)a_s^2/(2\pi R) \doteq (\Delta l)a_s/\pi R$ on the helical current are taken into acount of, the diffusion coefficient is related to the rotational transform angle rather than shear parameter. The relation $1/D \propto l^2$ is most probable (although it is not hold in the region $l/2\pi$ < 0.4). The inverce of Bohm diffusion coefficient corresponding B = 2kGauss and T_e = 1.5eV are $1/D_B = 2.2\ s/m^2$. The ratio of D_B/D increases up to 7 with the increace of ι.

To examine the relation of confinement time and the magnetic well depth, the current I_V of the coil of the vertical field is adjusted and the magnetic well depth is changed from -4% (antiwell) to 10% (well). The relation of τ and well depth are shown in Fig. 9. The confinement time does not depend appreciably on the well property. In this case, the stability condition of drift wave by shear is satisfied[8] even without average min.B property. When the stellarator field has the properties of well or antiwell, the radius of separatrix decreases and the rotational transform angle at the most outside magnetic surface decreases also. But the rotational transform angle on the magnetic axis of the surface increases from 0 to the finite value ($\iota/2\pi \sim 1/4$). These effects may cancell with each other. Further investigation is necessary to understand these results.

Figure 10 shows the dependence of the confinement on the magnitude B of the magnetic field when the ratio of helical coil current I_H and the toroidal coil current I_T is constant. The radial distribution of the density and the floating potential are shown in Fig. 11 and 12. The confinement time depends on B linearly. The electron temperature does not depend on B. Although the ion temperature T_i is being cooled by the helium atom with decay time $\sim$0.4ms, the possibilities that T_i depends on B can not be excluded during the observing period (1 ~ 4ms), as the ion energy at the injection stage is strongly dependent on B and high energy ($\sim$100eV). The multigrid energy analyser are being prepared to estimate the ion temperature.

§3.2. Argon Plasma Experiment

The similar experiments are carried out using A plasma. The initial density of plasma is 10^9/cc with the decay constant of 1 ~ 5ms. The electron temperature is about 1.5eV. The neutral gas density is 3×10^{11}/cc. The cooling times of electron and ion temperature by A gas are the order of 5sec and 2.5×10^{-3}sec respectively. The dependence of the confinement time on the helical current and the property of the magnetic well are shown in Fig. 11 and Fig. 12. The relations are similar to those of the helium plasma. The ratio of observed confinement time to Bohm one is up to 10 in this case when B is 2kGauss.

The dependence of τ on B is shown in Fig. 13. In this case, the confinement time is saturated at B = 1.5kGauss. The radial distributions of the density and the floating potential are shown in Fig. 16 and 17. In this case the density gradient is steepen as B increases $[(dn/dr)/n \propto B]$. As the cooling time of T_i is comparable with the decay time, the ion temperature depends on B. This is confirmed by measuring the transit time of plasma after the plasma injection.

§4. Experimental Results of ECRH Plasma

ECRH plasma of helium is produced using a magnetron of 2.45GHz (B_{ec} = 875Gauss). The typical signal is shown in Fig. 18. The power of about 100W is applied during 1.5msec. After the power is turned off, the density decreases with two different time constants. During about 0.5ms after switching off the power, the density decays from 10^{10}/cc to 3×10^9/cc with decay time of $\sim$ 0.7ms. Then the density decreases with $\tau \simeq 2$ ~ 3ms. The time variation of T_e is shown in

Fig. 19. The density of neutral helium gas is 1.3×10^{13}/cc. As the collision time of electron and the atom is 1.8μs and the e-e collision time is ∿30μs, the velocity distribution of the afterglow plasma is considered to be maxwellian. The cooling time of electron by helium atom is 6.5×10^{-3}sec. With this range of density of neutral atom and the applied power of ∿100W, the hot electron is not produced and x-rays is not be observed by a scintillator and photomultiplier combination. It is observed from the density profile that the plasma density during the heating has peaks near the magnetic surfaces which intersect the resonance zone. The rapid decay of after glow at the first stage is probably connected with the convective phenomena. The dependence of the longer one of the decay times is considered here.

The dependence of the confinement time on the helical current and the property of magnetic well are shown in Fig. 20 and Fig. 21. The density profiles of the different ratios of I_H/I_T are shown in Fig. 22. The distribution of the floating potential is shown in Fig. 23 which indicates the plasma being ion rich. The falling points of the density profiles coincide with the positions of separatrises. The relation of the diffusion coefficient D with the rotational transform angle is $D \propto \iota^{-2}$. The ratio of τ to Bohm time τ_B becomes up to 17. The dependence of τ on the property of magnetic well is also weak.

§5. Conclusion

The dependences of plasma confinement on the properties of the magnetic field of $\ell = 3$ stellarator are examined using $J \times B$ type gun (He, Ar) and ECRH plasma (He). The preliminary results are following.

The diffusion coefficient estimated from the decay times of ion saturation current of the probe and the plasma radius are inversely proportional to the square of the rotational transform angle. The profile of density distribution is similar to $(r/a_s)^2 J_{-2/3}[1.25(r/a_s)^3]$ which corresponds to the relation $D \propto \iota^{-2} \propto r^{-4}$. The diffusion coefficients which are estimated from Bessel distribution are down to 1/7 ~ 1/17 times the Bohm coefficient, but if the foregoing distribution is adopted, the ratios become 1/17 ~ 1/40 times the Bohm coefficient.

The confinement time does not depend appreciably on the property of the magnetic well (and antiwell) in the experimental conditions.

The scaling law of the confinement time on the magnitude of the magnetic field is not determined at the present time. The relation is linear in the experimental conditions of $J \times B$ type gun of helium plasma. But in other experimental condition of argon plasma, τ is saturated at B = 1.5Kgauss. As the ion temperature strongly depends on the magnitude of the magnetic field, more investigations are necessary and are being carried out.

Reference

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2) E. Berkl, G.V. Gierke and G. Grieger: IPP 2/69 Garching Juni 1968.

3) C. Gourdn et al. Plasma Physics and Controlled Nuclear Fusion Research, Conference Proc. Novosibirsk, International Atomic Energy Agency, Vienna 1969 Vol. 1 p847.

4) J.H. Adlam et al. ibid Vol. 1 p573.

5) D.K. Akulma et al., Plasma Physics and Controlled Nuclear Fusion Research, Conference Proc. Calham, IAEA Vienna 1966 Vol. 2., p733. N. Inoue, Y. Kawasumi and K. Miyamoto, to be submitted to Plasma Physics.

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7) N. Inoue, Y. Kawasumi and K. Miyamoto: to be submitted to Plasma Physics.

8) N.A. Krall and M.N. Rosenbluth: Phys. of Fluids 8 1488 (1965).

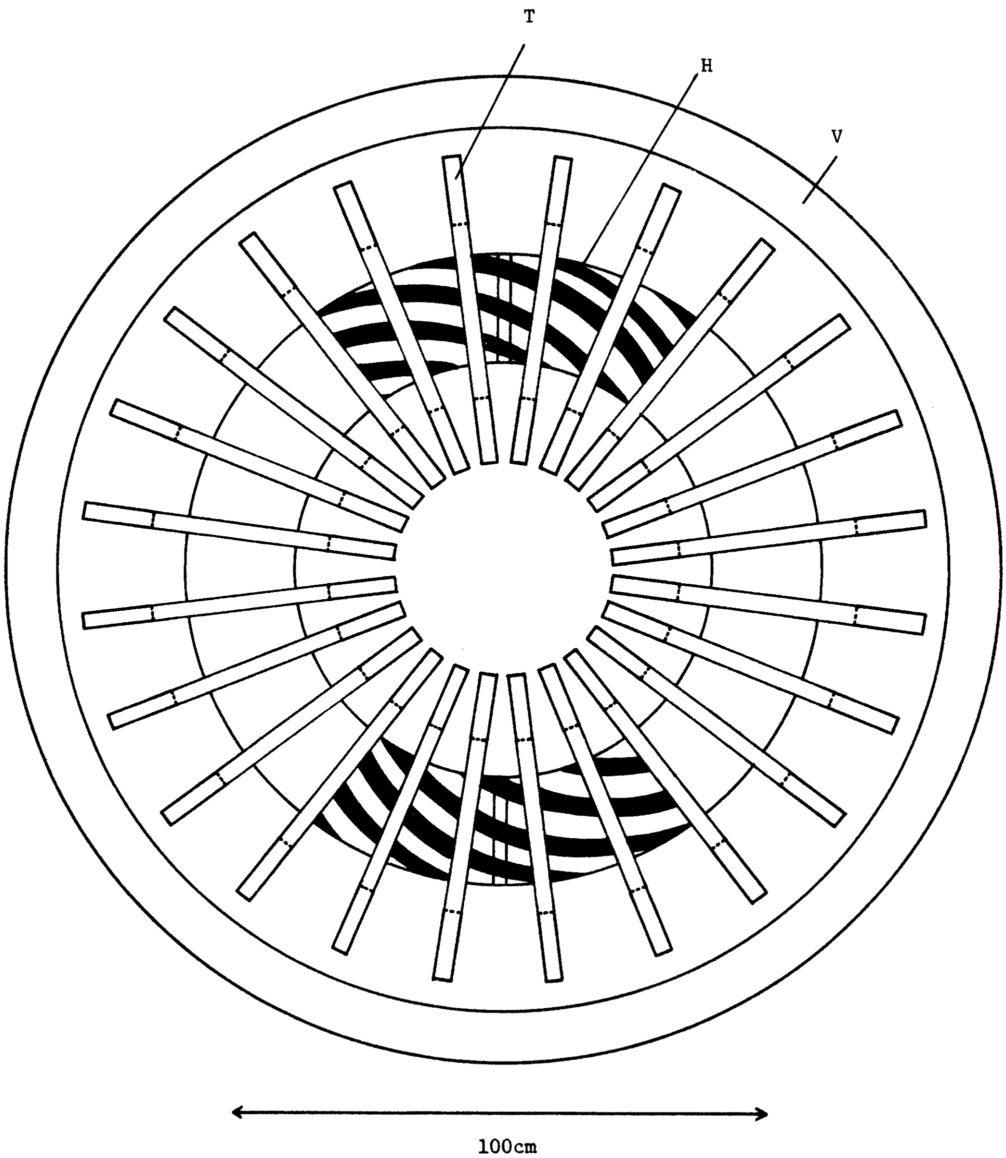


Fig. 1 Schematic diagram of JIPP stellarator.

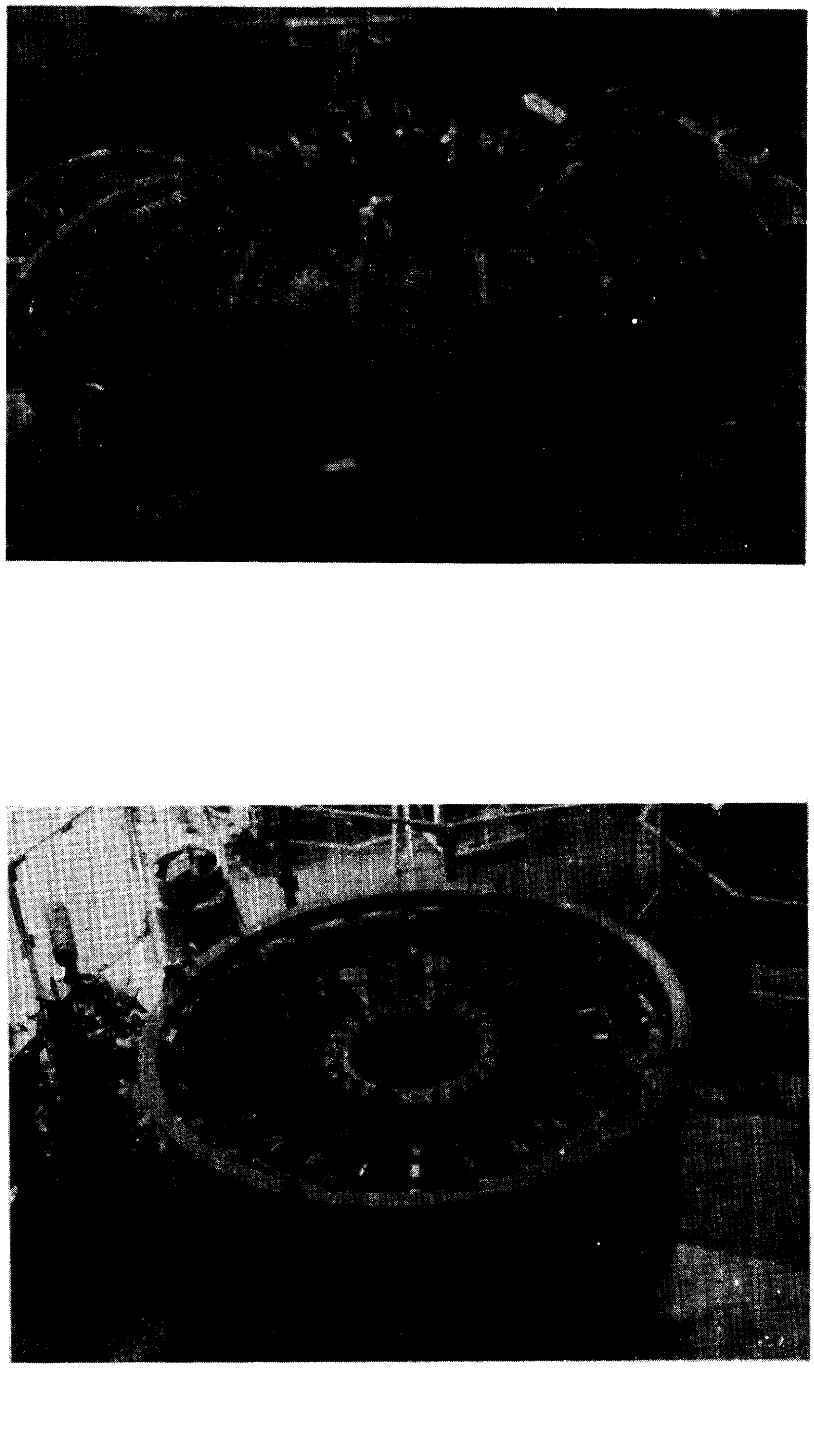
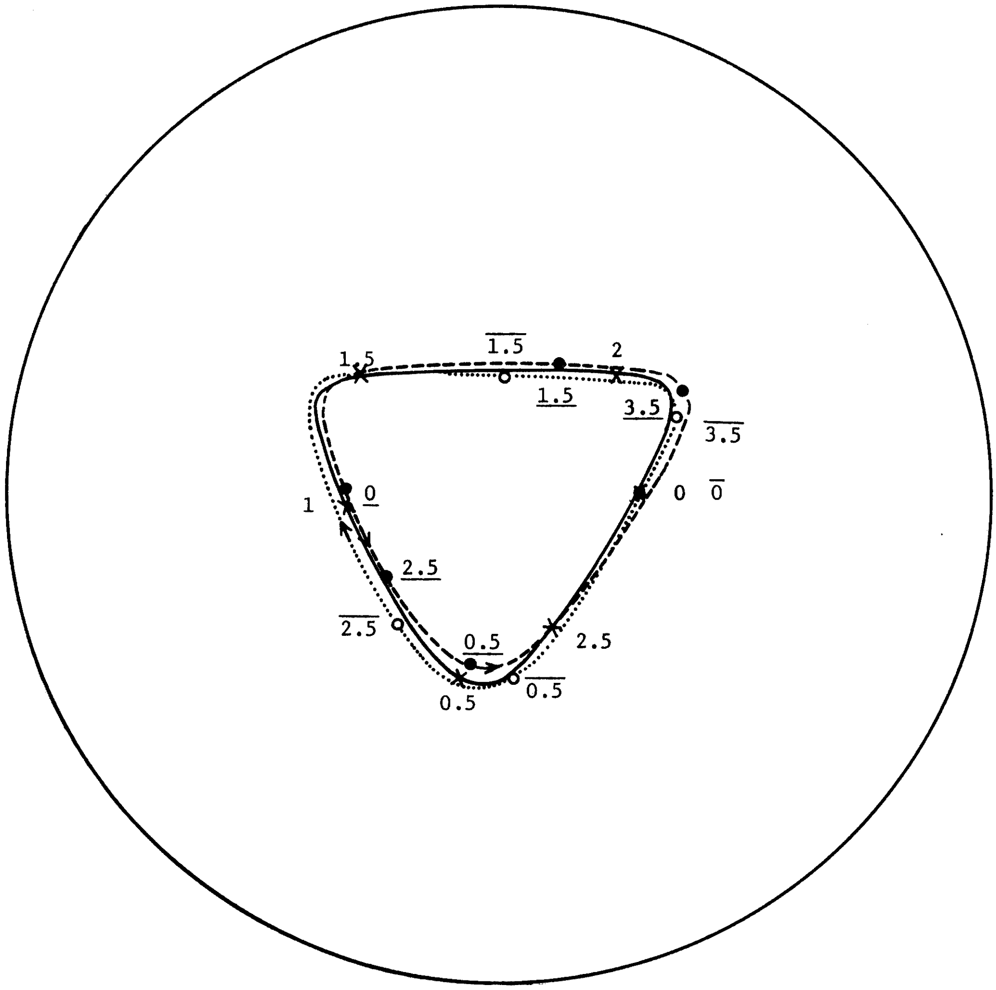


Fig. 2 Photograph of JIPP stellarator and its helical coil.



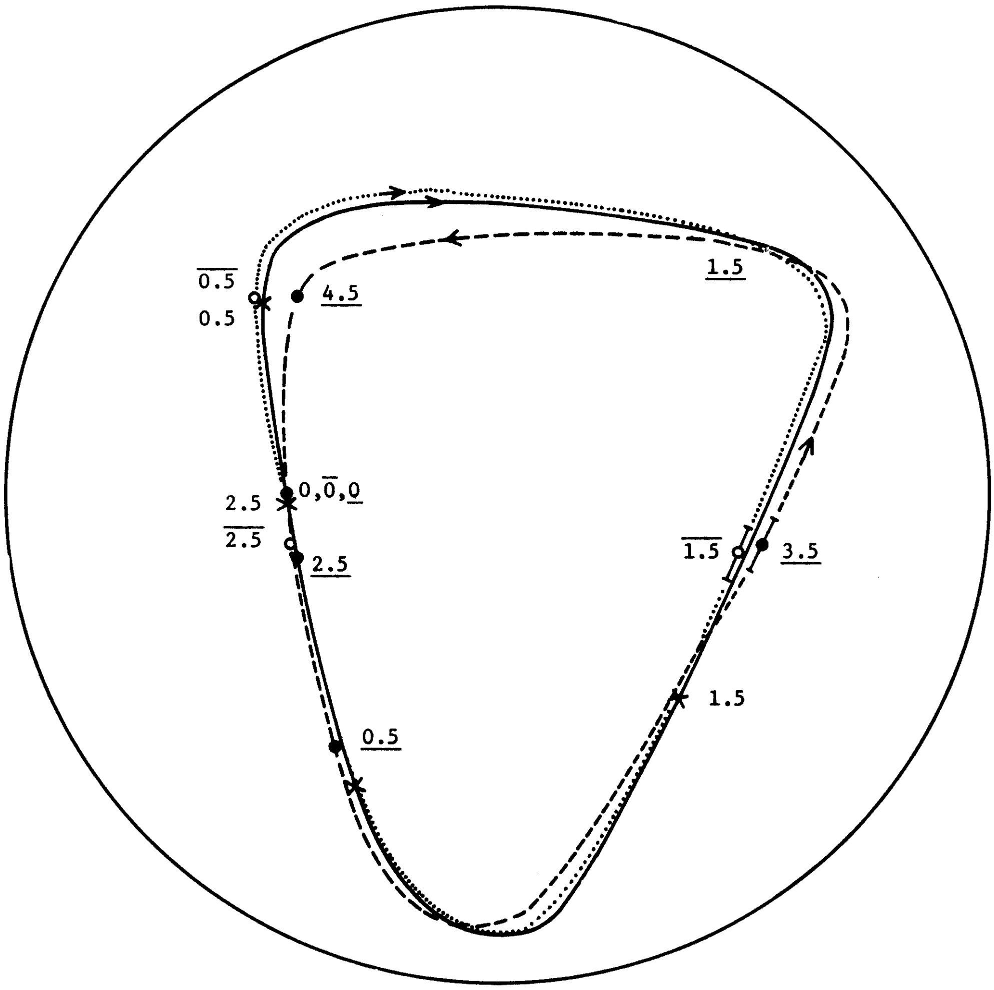
Magnetic Surface of Stellarator Field

Fig. 3 a) drift surfaces measured by pulsed electron beams in the case of stellarator configuration. The ratio of currents of helical coil and toroidal coil is $I_H/I_T = 3.4$ and B = 260 Gauss. The energy of electron beam is 90 eV.

——X—— : calculated magnetic surface

··· ○ ··· : drift surfaces of electrons beam running parallel to the magnetic lines of force.

- - ● - - : drift surfaces of electrons beam running antiparallel to the magnetic lines of force.



Magnetic Surface of Torsatron Field

Fig. 3 b) drift surfaces measured by pulsed electron beams in the case of torsatron configuration I_H/I_T = 4.9, I_r/I_T = -0.98 (I_v in the current of the coil for vertical field), B = 260 Gauss, energy of electron beam is 90 eV.

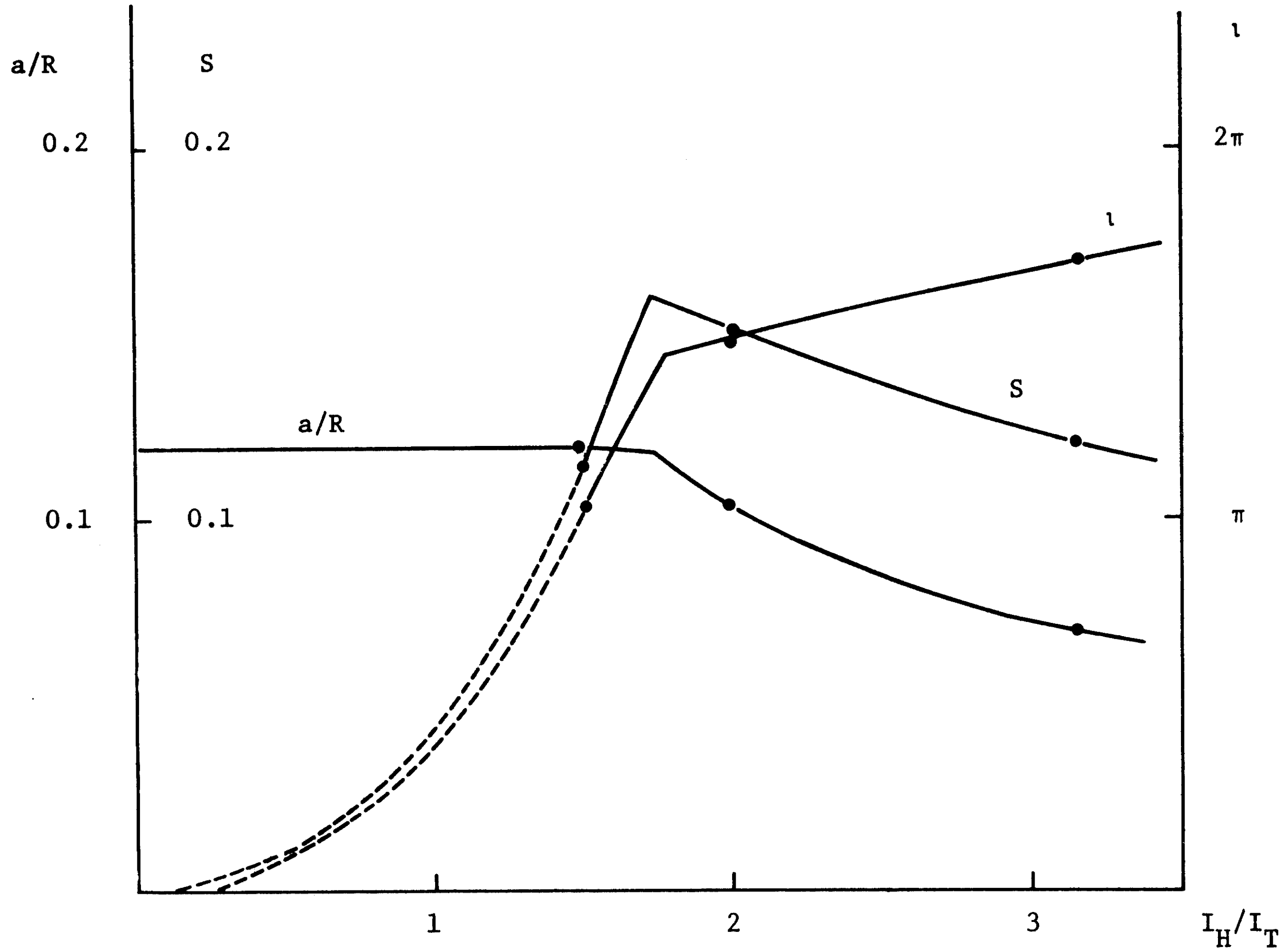


Fig. 4 The dependence of the inverse of aspect ratio a_s/R, the rotational transform angle ι and the shear parameter $S \equiv d\iota/d\rho \; a_s^2/(2\pi R)$ on the helical current.

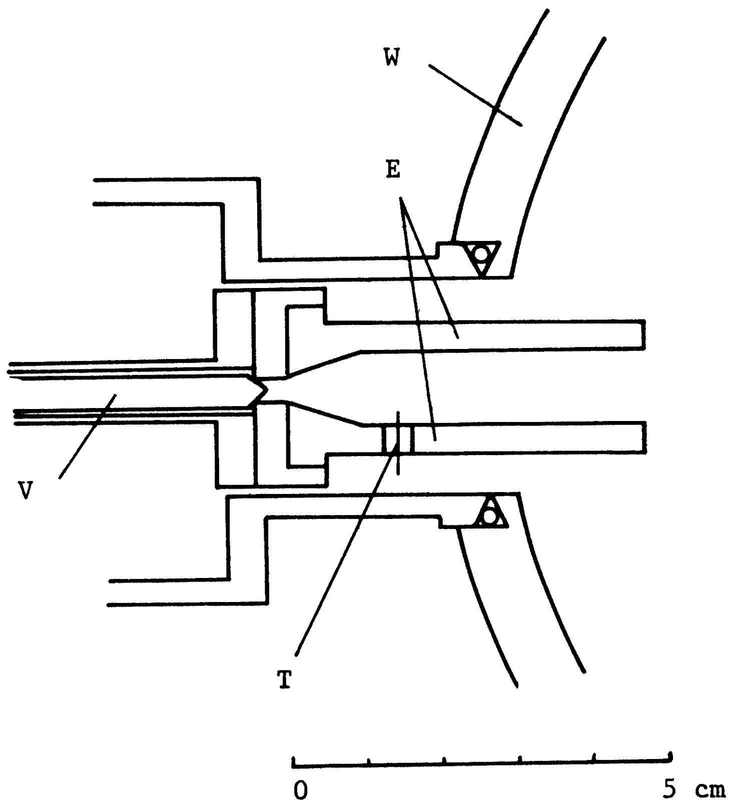


Fig. 5 Schematic drawing of J × B gun. V : the fast acting valve, T : Trigger pin, E : electrodes, W : wall of vacuum vessel.

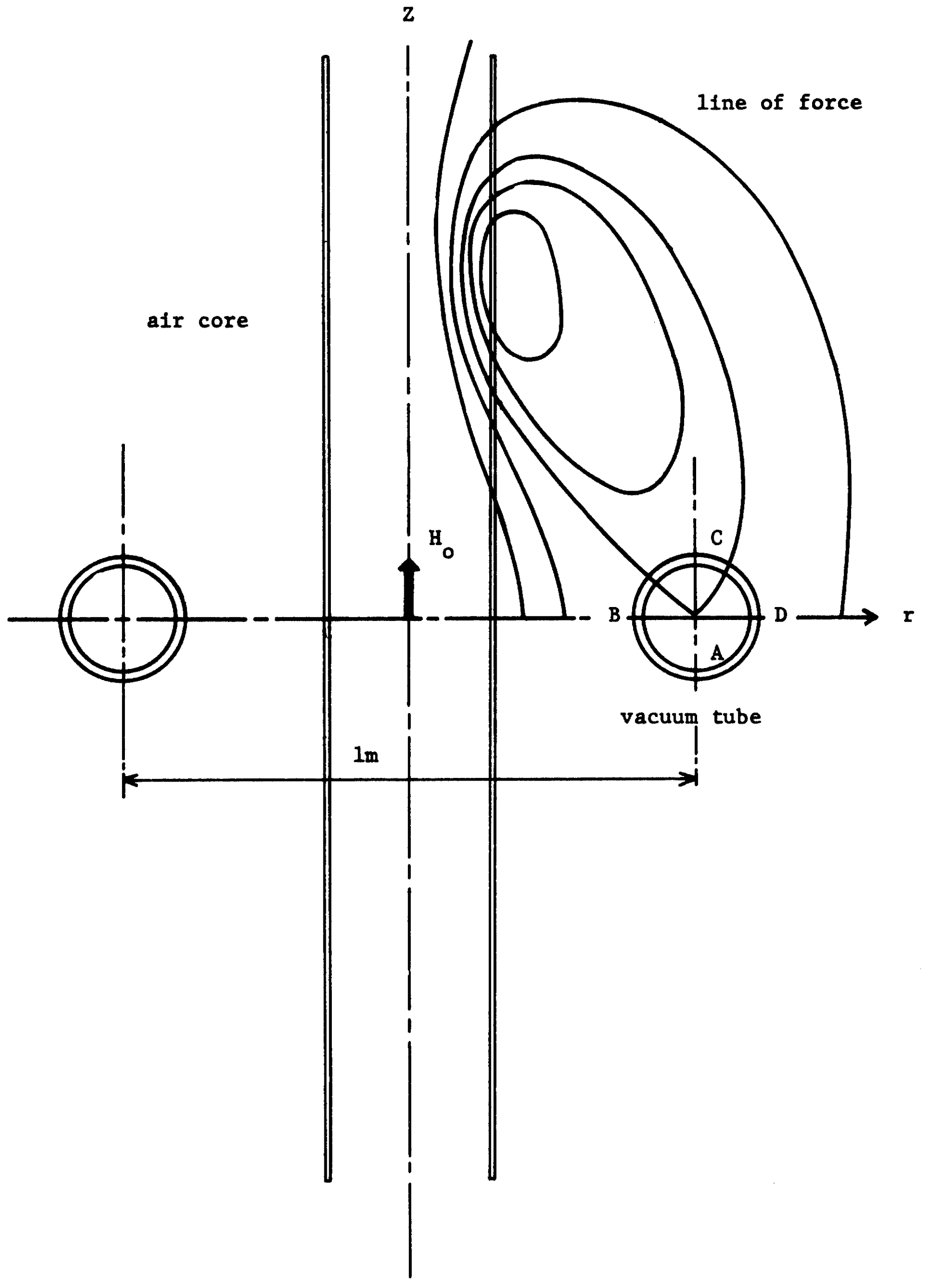


Fig. 6 Air core coil of ohmic heating.

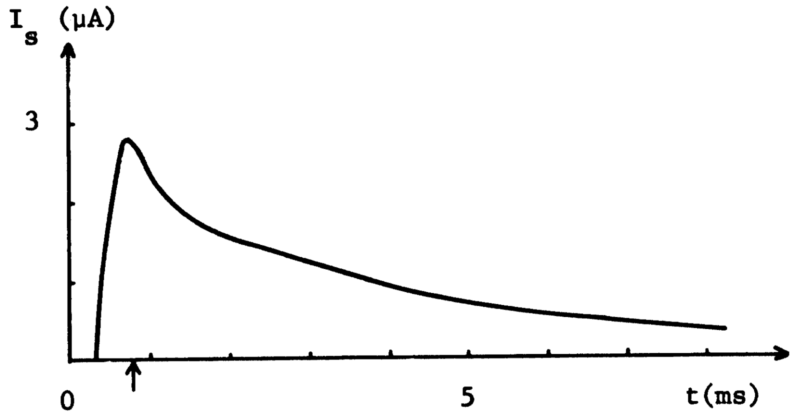


Fig. 7 The typical signal of ion saturation current of $J \times B$ gun plasma (He).

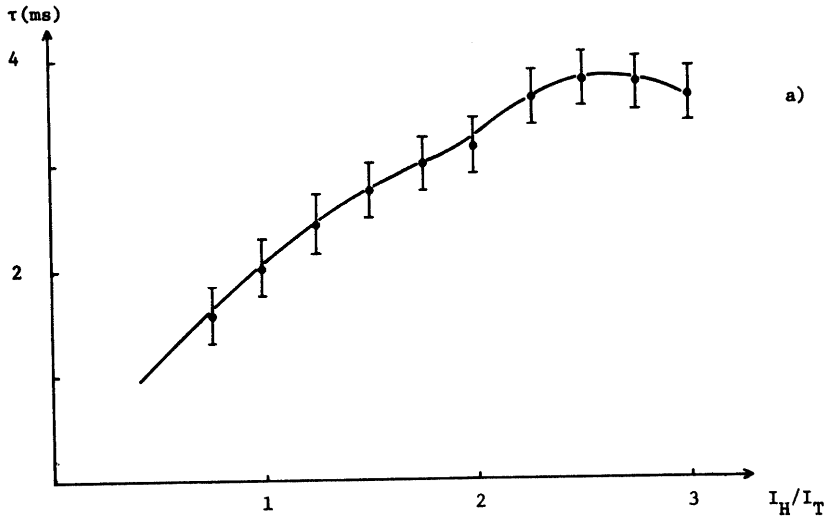


Fig. 8 a) The dependence of the confinement time τ of the He plasma of J × B gun on the ratio of the helical current I_H to the current of toroidal coil I_T, when the toroidal field B_t = 2kgauss.

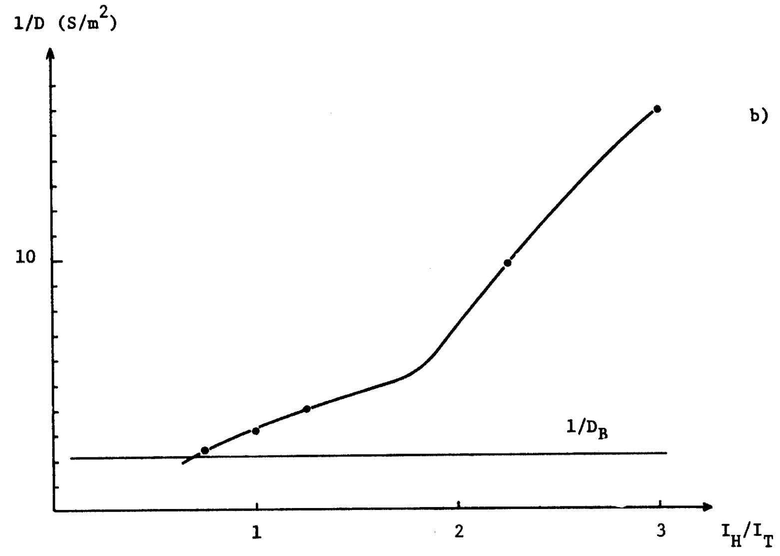


Fig. 8 b) The dependence of the inverse of the diffusion coefficient calculated by $1/D = \tau(2.4/a_s)^2$ on the ratio I_H/I_T where a_s is the average radius of the separatrix. $1/D_B$ corresponds to the Bohm diffusion of B = 2kgauss, T_e = 1.5eV.

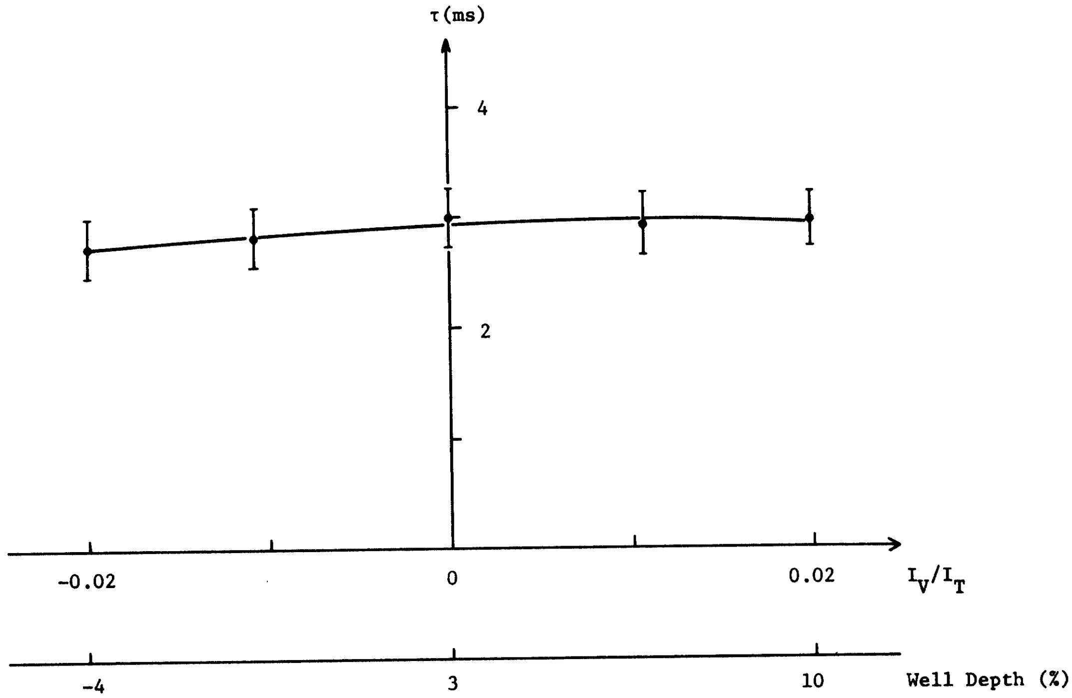


Fig. 9 The dependence of the confinement time τ of the He plasma of J × B gun on the well depth, when I_H/I_T = 2, B_t = 2kgauss. I_v is the current of the coil for the vertical field.

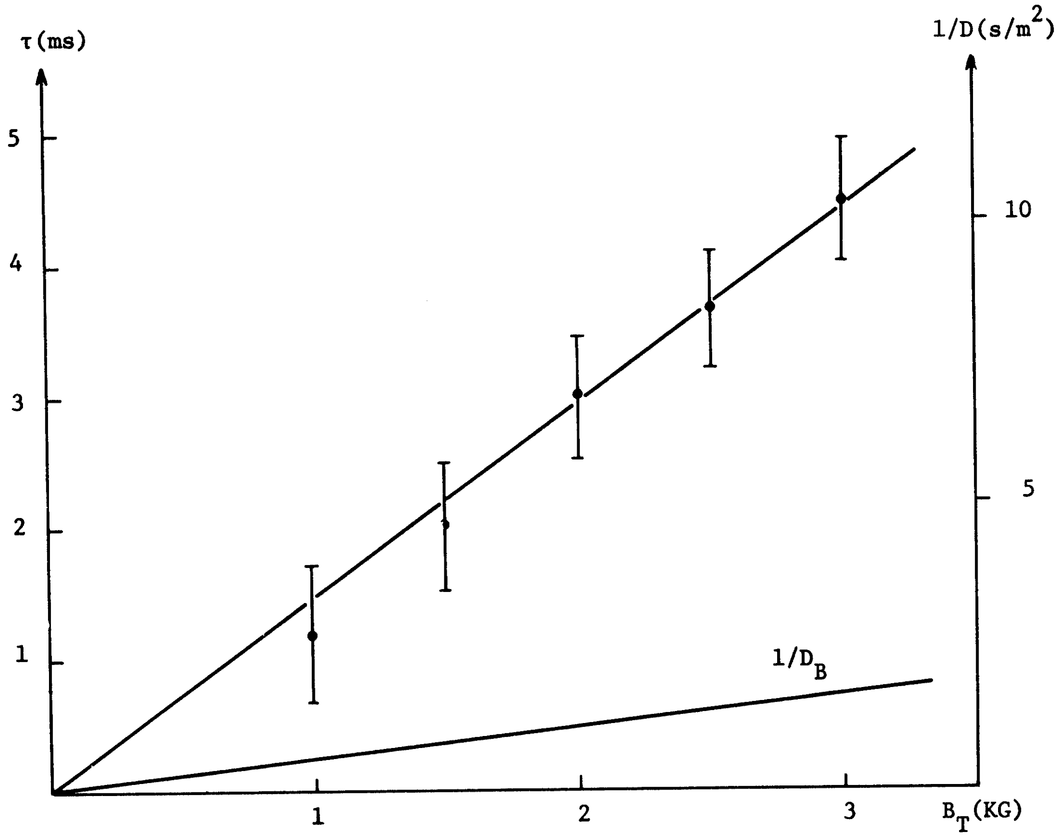


Fig. 10 The dependence of the confinement time τ of the He plasma of J × B gun on the magnitude of the toroidal field, when $I_H/I_T = 2$, $I_V = 0$.

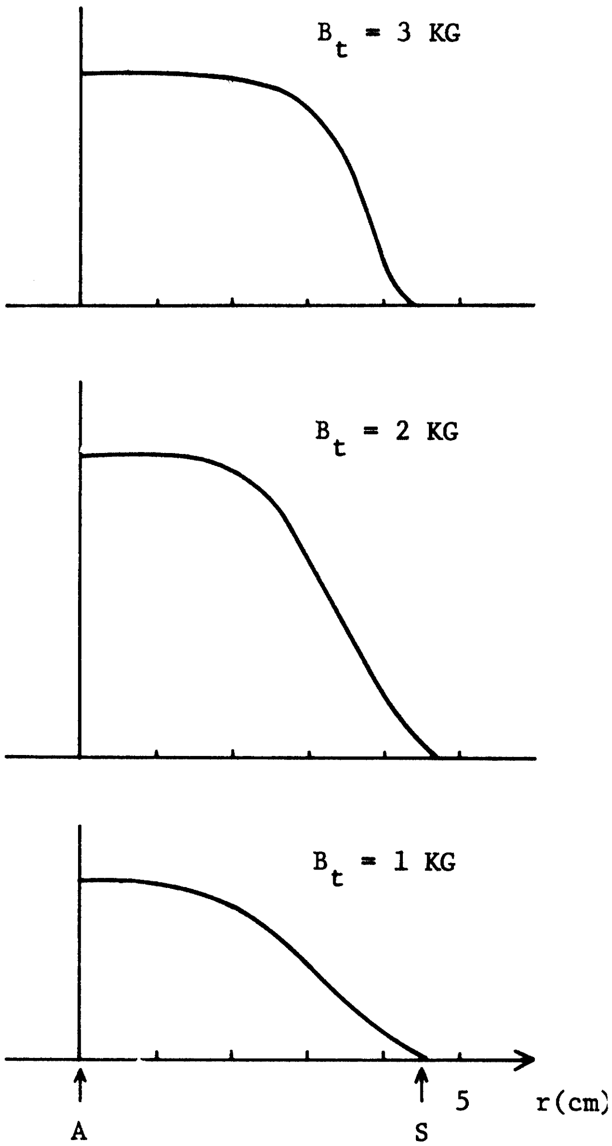


Fig. 11 The radial distribution of the density of the He plasma of J × B gun at 1.2ms after switching off the gun for the different magnitude of the toroidal field, when $I_H/I_T = 2$. A and S indicate the positions of the magnetic axis and the separatrix.

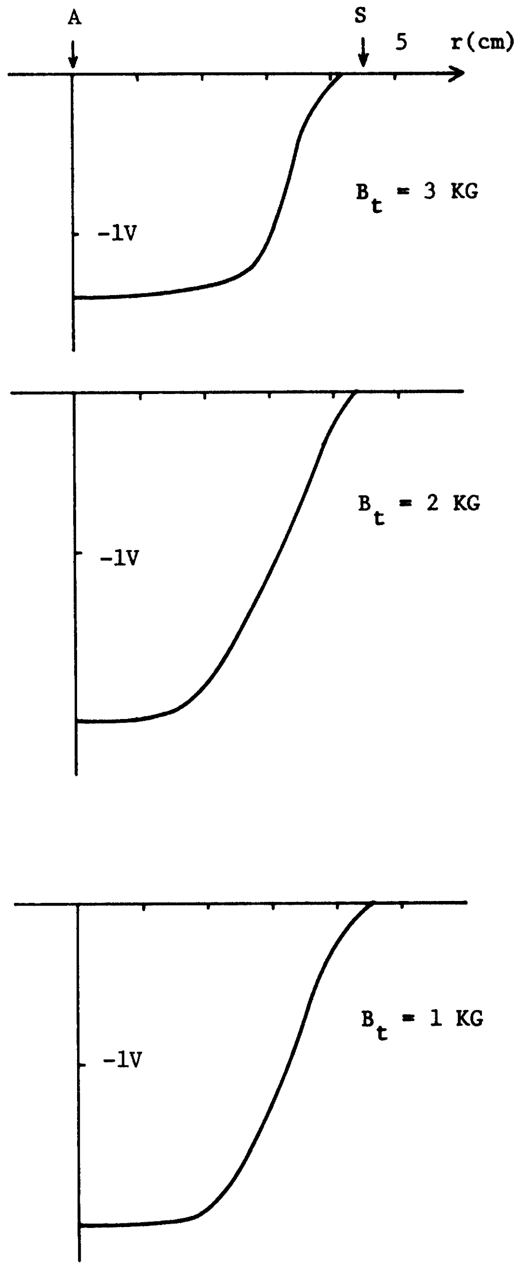


Fig. 12 The radial distribution of the floating potential at 1.2ms after switching off the gun for the different magnitude of the toroidal field when $I_H/I_T = 2$. A and S indicate the positions of the magnetic axis and the separatrix.

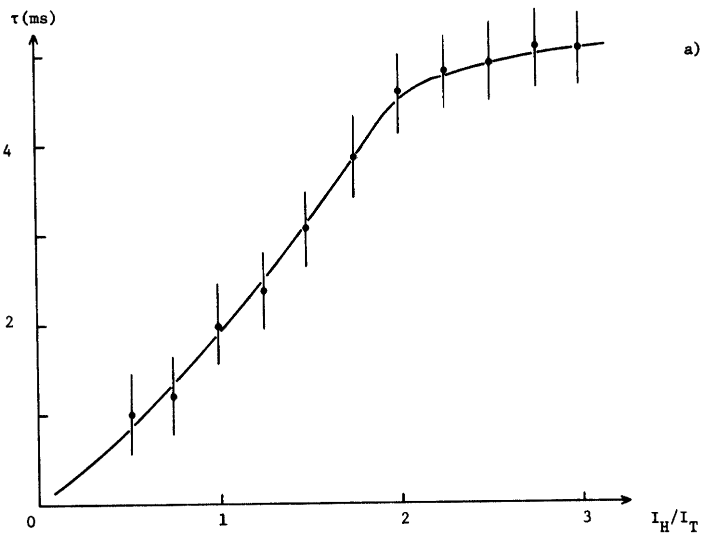


Fig. 13 a) The dependence of the confinement time τ of the Ar plasma of J × B gun on the ratio of I_H/I_T when the toroidal field B_t = 2kgauss.

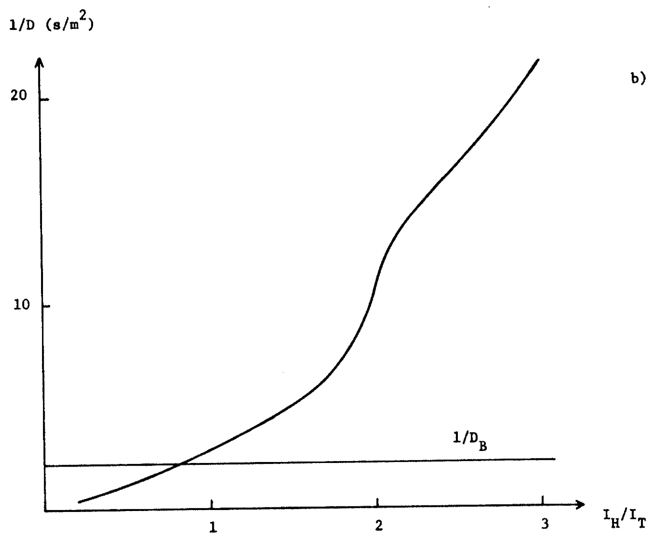


Fig. 13 b) The dependence of the inverse of the diffusion coefficient calculated by $1/D = \tau(2.4/a_s)^2$ on the ratio I_H/I_T, a_s being the average radius of the separatrix. $1/D_B$ corresponds to the Bohm diffusion of B = 2kgauss, and T_e = 1.5eV.

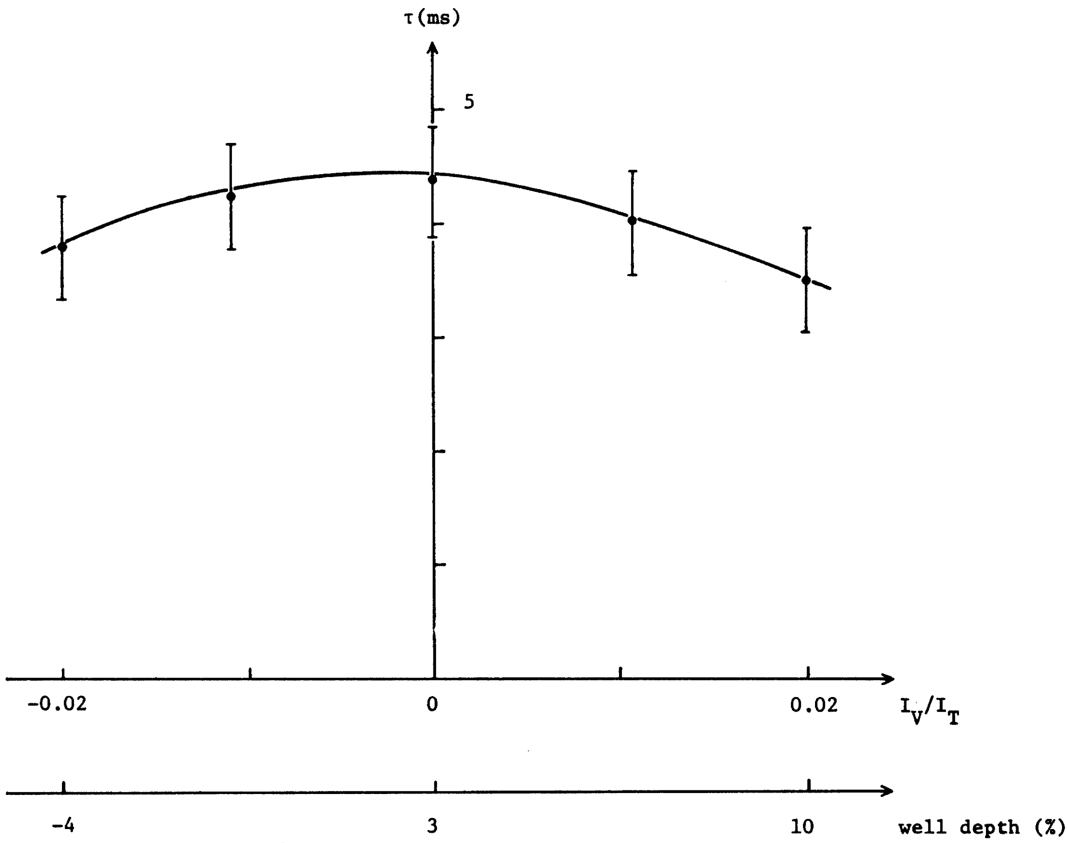


Fig. 14 The dependence of the confinement time τ of the Ar plasma of J × B gun on the well depth when $I_H/I_T = 2$, B_t = 2kgauss. I_V is the current of the coil for the vertical field.

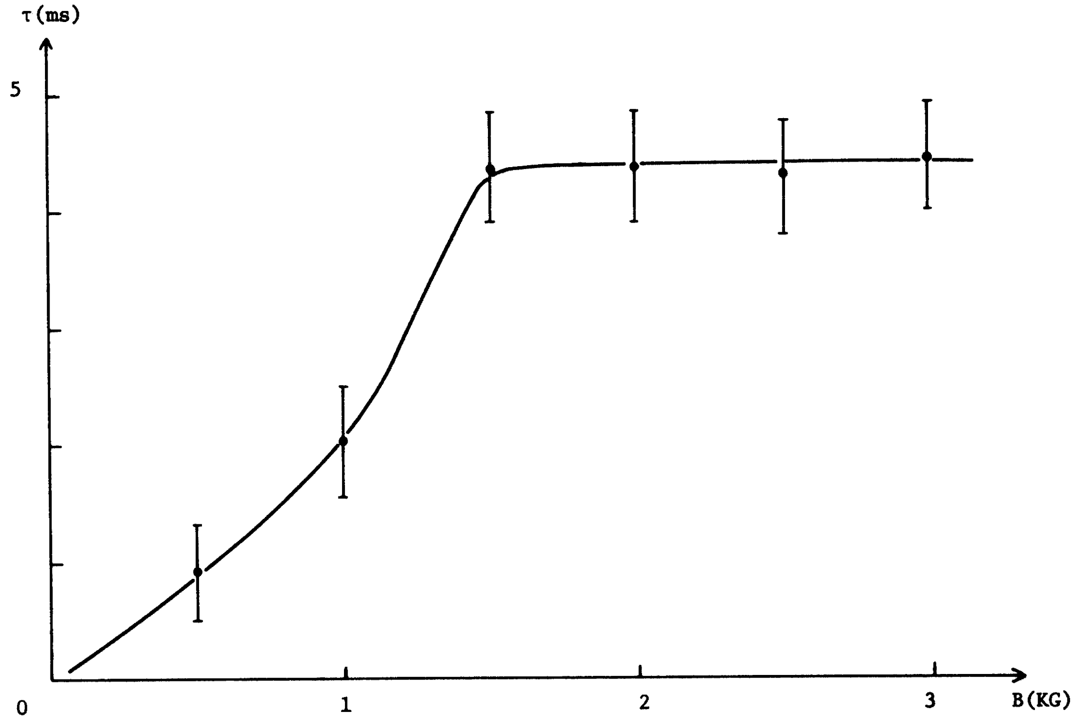


Fig. 15 The dependence of the confinement time τ of the Ar plasma of J × B gun on the magnitude of the toroidal field, (I_H/I_T = 2, I_v = 0).

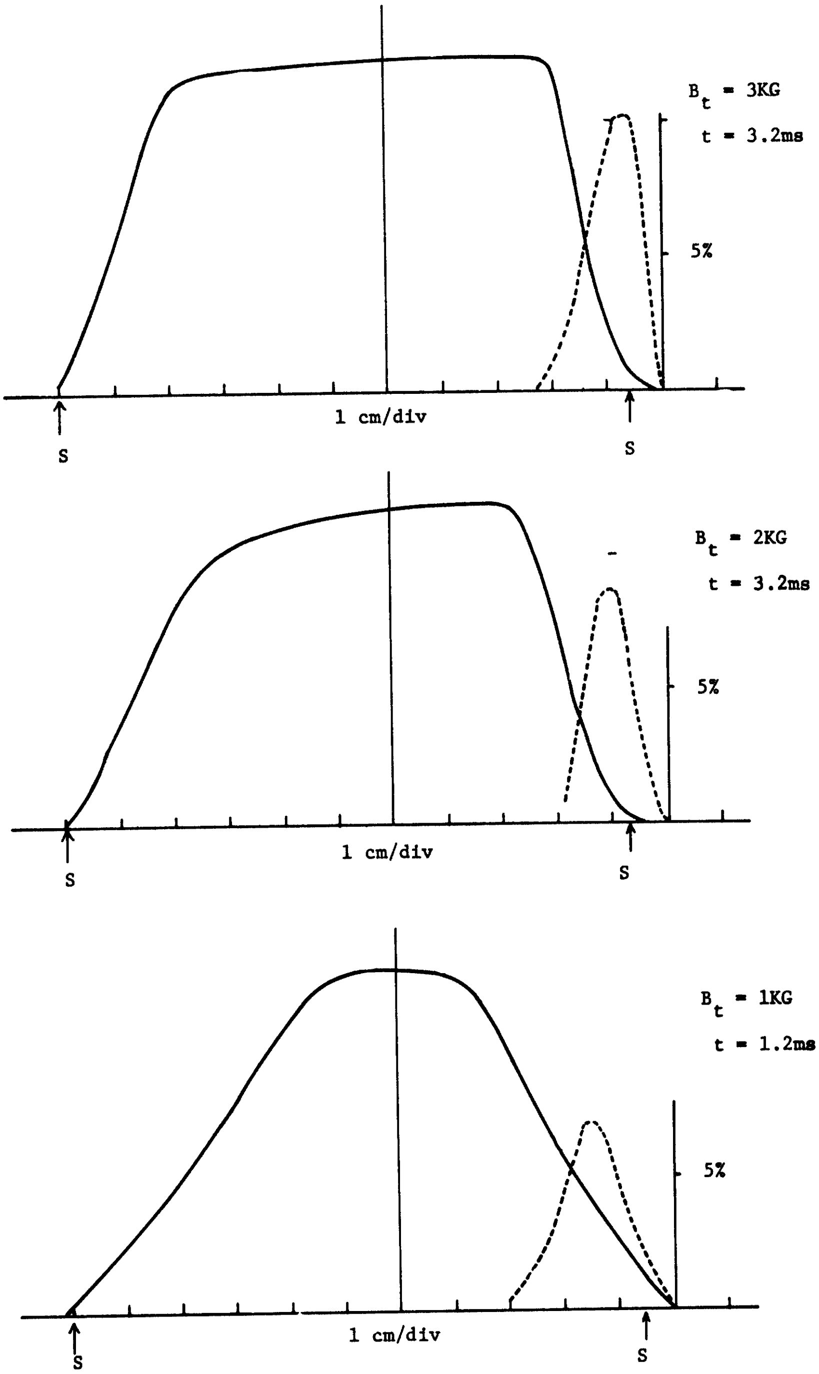


Fig. 16 The radial distribution of the density of the Ar plasma of J × B gun for the different magnitude of the toroidal field keeping $I_H/I_T = 2$. The ratios of density fluctuation to the density $\Delta n/n$ are plotted. S indicates the position of separatrix. t is the time from the switching off the gun.

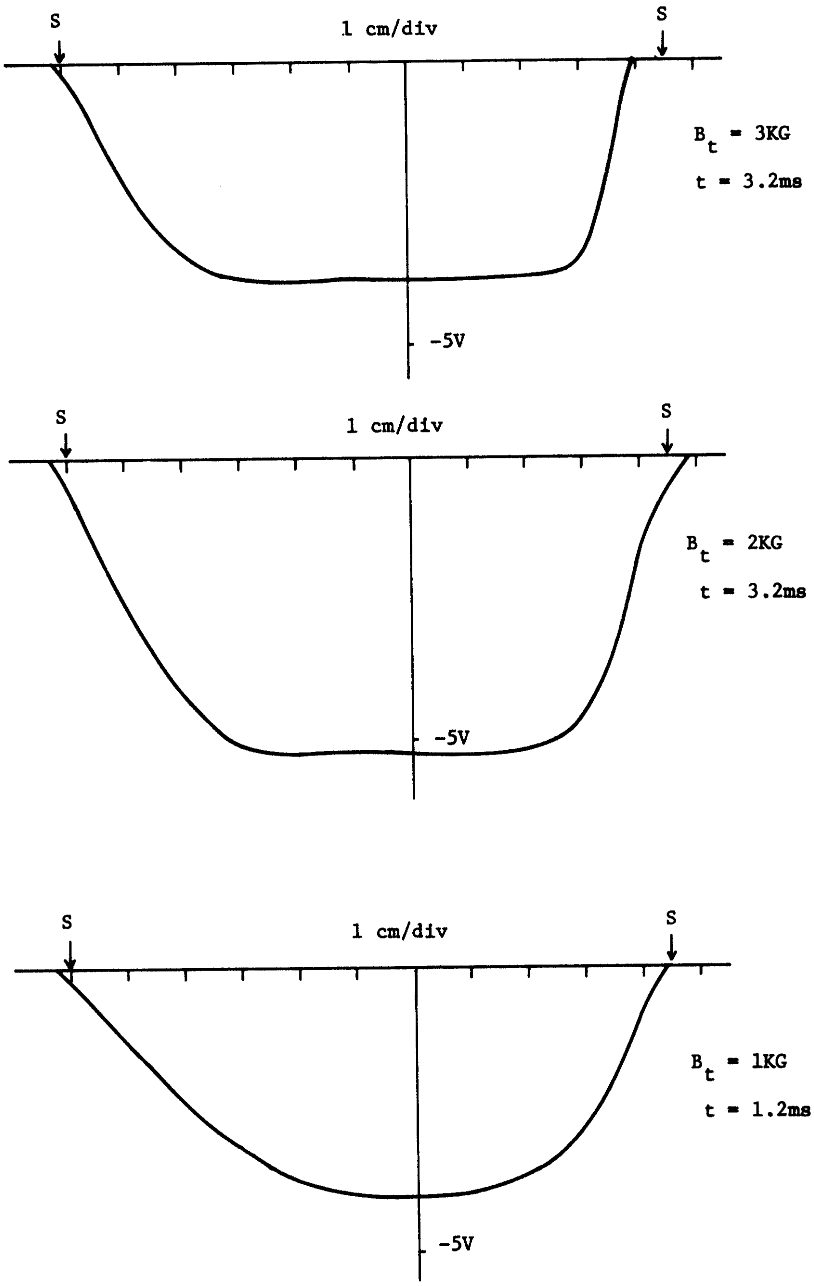


Fig. 17 The radial distribution of the floating potential for the different magnitude of the toroidal field, when $I_H/I_T = 2$. S indicates the position of separatrix t is the time from the switching off the gun.

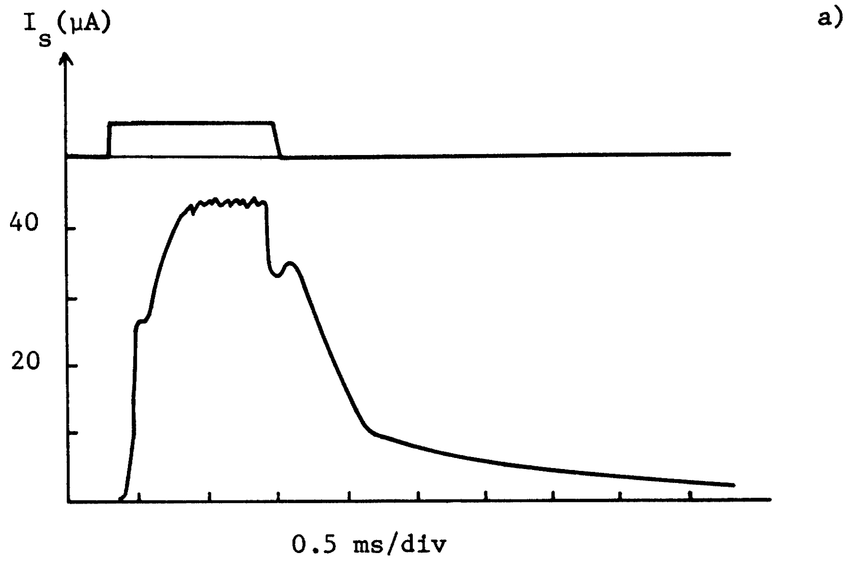


Fig. 18 a) The typical signal of the plate current of magnetron (upper trace) and the ion saturation current of the ECRH plasma of helium.

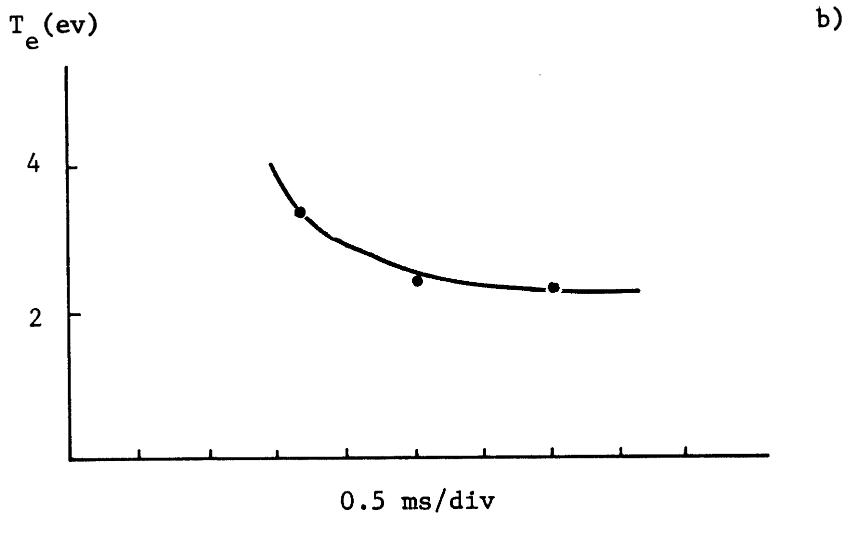


Fig. 18 b) The time dependence of electron temperature.

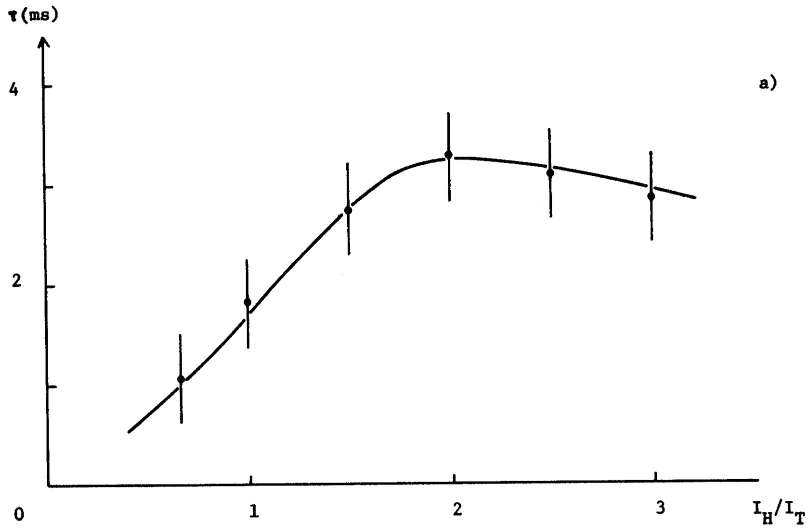


Fig. 19 a) The dependence of the confinement time τ of the He plasma of ECRH on the ratio of I_H/I_T when the toroidal field B_t = 875gauss.

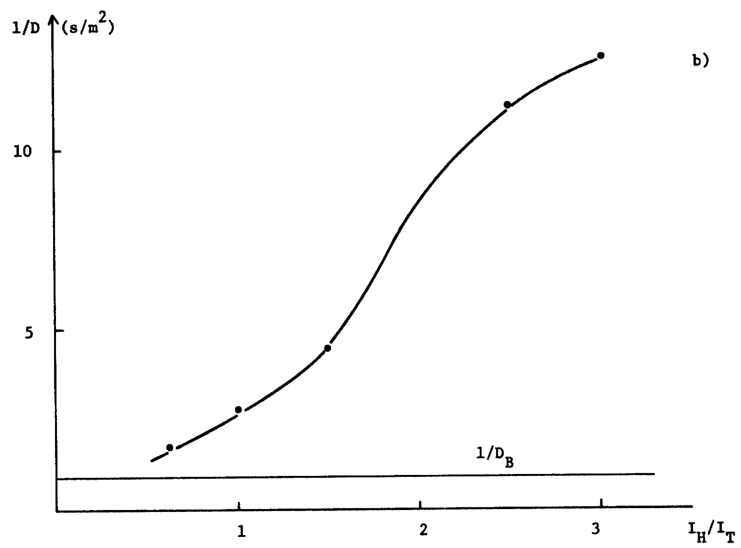


Fig. 19 b) The dependence of the inverse of the diffusion coefficient calculated by $1/D = \tau(2.4/a_s)^2$ on the ratio I_H/I_T, a_s being the average radius of the separatrix. $1/D_B$ corresponds to the Bohm diffusion of B = 875gauss and T_e = 2eV.

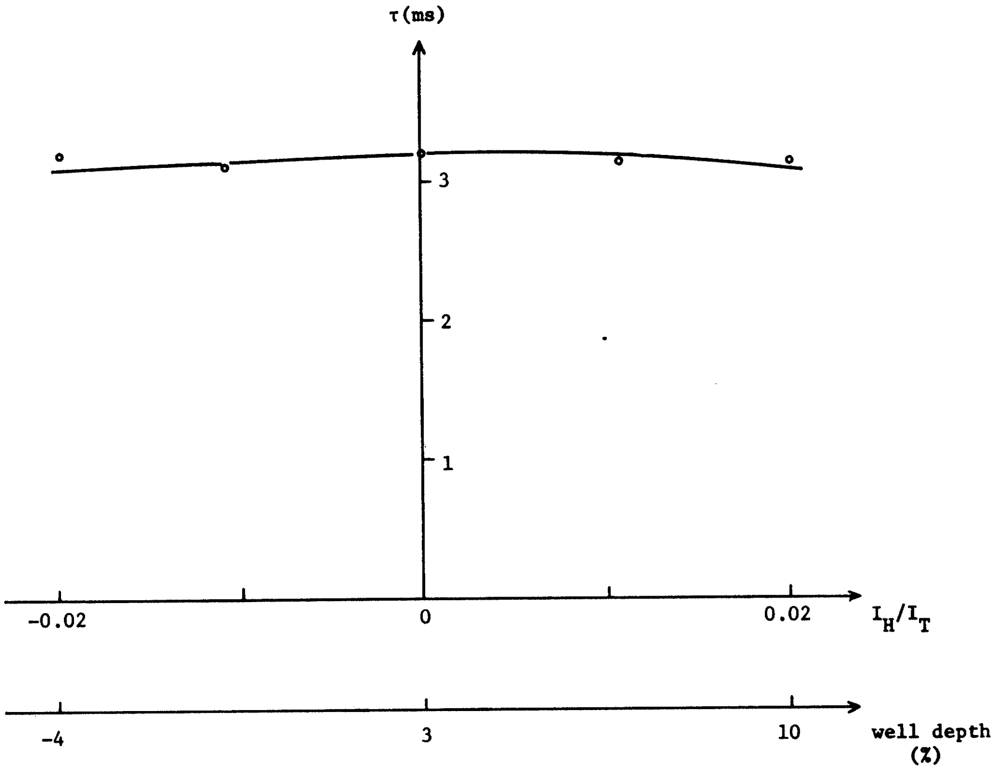


Fig. 20 The dependence of the confinement time τ of the He plasma of ECRH on the well depth for I_H/I_T = 2, B_t = 875gauss.

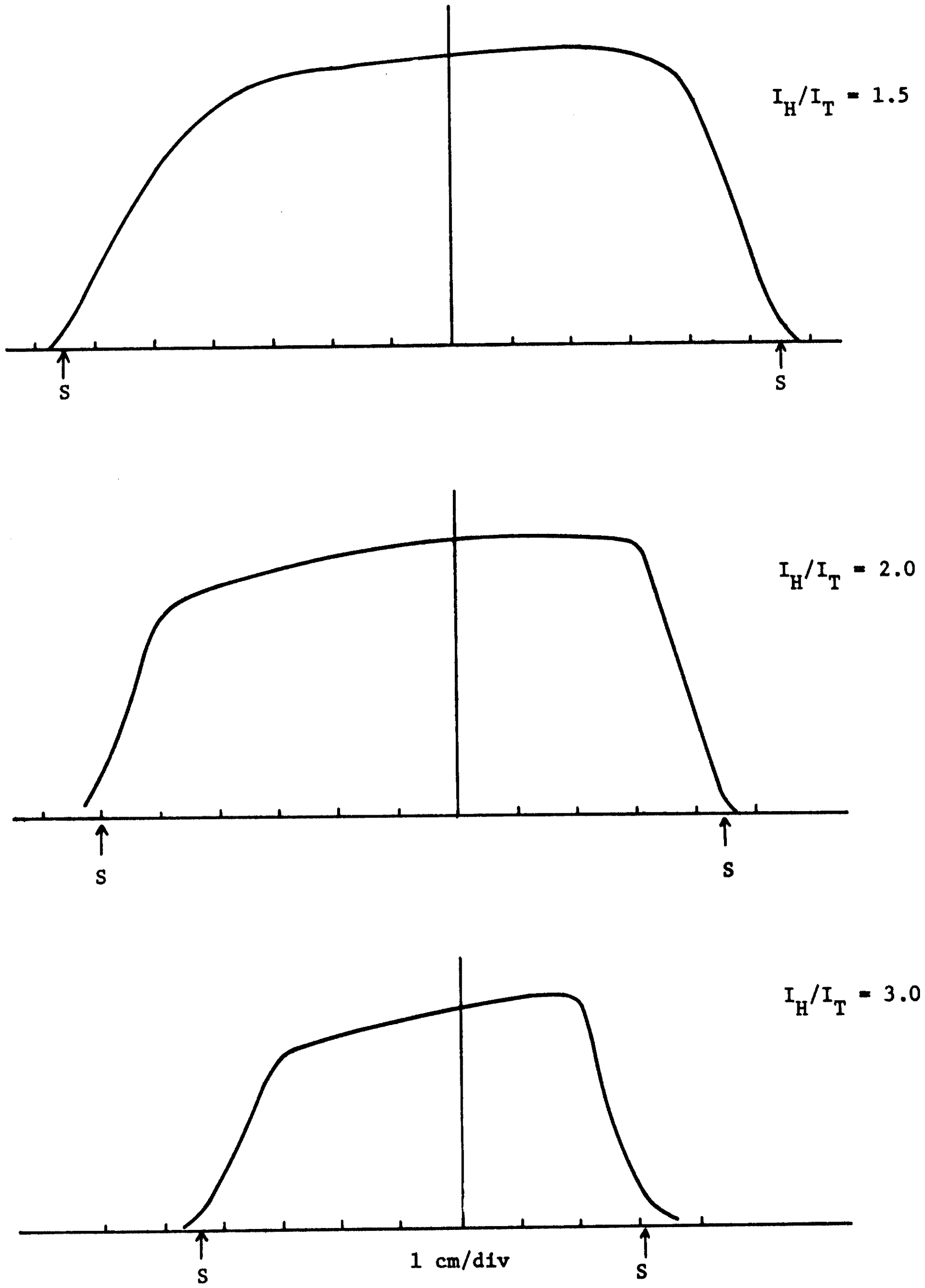


Fig. 21 The radial distribution of the density of the He plasma of ECRH at 0.6ms after the switching off the power of the magnetron for the different ratio of I_H/I_t while B_t = 875 gauss. S indicates the position of the separatrix.

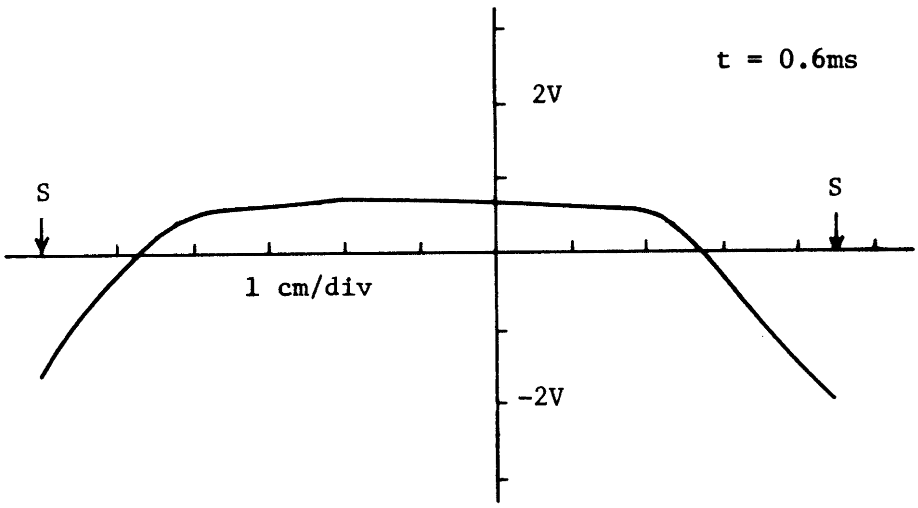


Fig. 22 The radial distribution of the floating potential of the He plasma of ECRH for $I_H/I_t = 2$ and $B_t = 875$gauss at 0.6ms after the switching off the power of the magnetron. S indicates the position of the separatrix.