MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

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THE APPLICATION OF QWAASS EXPERIMENTS FOR MEASURING THE ION TEMPERATURE, THE PARTICLE DENSITY AND THE PARTICLE FLUXES AT THE PLASMA BOUNDARY

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Abstract

Clean carbon probes have been exposed at different positions to the plasma in the limiter shadow of TFR 600 for a certain number of discharges. After exposure the probes have been analysed with the $D(^{3}He, p)^{4}He$ nuclear reaction in respect to the amount of trapped deuterium. The results have been compared with trapping curves for deuterium in carbon obtained under well defined conditions. This allowed to get information about the ion temperature, the ion density and the ion fluxes for the plasma in the scrape off region.

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Die Anwendung von QWAASS Experimenten zur Messung der Ionentemperatur, der Teilchendichte und der Teilchenflüsse in der Plasma-Grenzschicht

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Zusammenfassung

Zur Bestimmung von Ionentemperatur, Ionendichte sowie den Ionenflüssen wurden reine Kohlenstoffproben für eine gewisse Anzahl von Entladungen dem Deuterium-Plasma im Limiterschatten von TFR 600 ausgesetzt. Die im Kohlenstoff aufgesammelte Menge Deuterium wurde mit Hilfe der Kernreaktion $D(^3He,p)^4He$ bestimmt. Die Ergebnisse wurden sowohl mit Aufsammelkurven, die mit einem Deuterium Ionenstrahl unter wohl definierten Bedingungen gemessen wurden, als auch mit berechneten Aufsammelkurven verglichen. Dieses Verfahren erlaubt eine Bestimmung des Ionenflusses zur Probe und damit eine Abschätzung der Ionentemperatur und der Ionendichte des Randschichtplasmas.

Introduction

In present-day high temperature plasma experiments the central plasma is generally well diagnosed /1/ while the plasma in the scrape off region, defined by a limiter or the separatrix of a divertor is only little investigated, experimentally and theoretically /2-5/. This plasma is in direct contact with the limiters, the diverter plates and the first wall and represents the boundary condition for the central plasma. Thus it plays a major role for the particle and energy balance of the central plasma ,i.e. recycling, fueling and exhaust and the introduction of impurities from the first wall as well as the temperature gradients.

One successful scheme to study this plasma is the use of collection probes in QWAASS experiments /3-14/. Here well defined solid probes are inserted into this region and exposed to discharges. After exposure they are retracted and the particles collected in the surface layers during the discharge are detected by Auger Electron Spectroscopy (AES), Secondary Ion Mass Spectrometry (SIMS), Flash Desorption (FD) or by Rutherford Backscattering (RBS) and Nuclear Reactions (NR). QWAASS experiments are similar to Langmuir probe experiments where the electrons (and ions) are collected and detected by current measurements /3/.

In this work we report about QWAASS experiments using clean carbon probes which have been exposed to the plasma in the limiter shadow of TFR 600. The deuterium trapped was determined as a function of the radial position of the probe and the number of discharges. A comparison of the trapped amount with the results of trapping experiments performed with well defined ion beams and with calculated trapping curves allows to give an estimate of the plasma temperature as well as the density and deuterium fluxes in the scrape off plasma /15/. Hydrogen trapping in the first wall of high temperature plasma experiments has first been described by Martin and Lewin at the A2 Stellarator /16/ and has been investigated meanwhile at several plasma experiments /12-24/. Measurements of hydrogen trapping in clean well defined probes as Carbon or Silicon exposed to the scrape off plasma have first been described by McCracken et al. /14, 18/ and have recently been performed at most tokamaks /12, 15, 25-28/. However, for an evaluation of these measurements to get the plasma parameters the trapping behaviour of the materials has to be known in detail.

Experiments

TFR 600 is a tokamak without a copper shell and has a major radius of 98 cm /29/. The vacuum vessel with an inner radius of 26 cm as well as the limiter, which was at a radius of a_L = 20 cm, are made of Inconel 625. After Taylor type discharge cleaning a Z_{eff} of 1 to 2 has been reached. The tokamak discharges used in these experiments were run in deuterium and can be roughly characterized by a plasma current $I_p \simeq 200$ kA at a toroidal field of $B_T \simeq 4T$; they lasted for about 100 to 120 ms with a mean electron density of $\bar{n}_e \simeq 4 \cdot 10^{13}$ cm^{-3}, a central electron temperature of $T_e(o) \simeq 1200$ eV, and a central ion temperature of $T_i(o) \simeq 400$ eV. The reproducibility of the plasma parameters from shot to shot was rather poor probably due to the plasma position being not well enough controlled.

The probes exposed with the QWAASS device at floating potential were highly polished Si-samples with an evaporated layer of 120 nm Carbon. The position at which the probes were exposed to the plasma in the limiter shadow is shown schematically in fig. 1/11/.
The side Q8 facing the ion Q8 facing the ion drift direction (ion side) is 225 degrees and the side Q2 facing the electron drift direction (electron side) is 135 degrees from the main limiter. The probes were located 14 cm below the mid plane of the torus; they were large enough (0.8 cm x 5 cm) so that a radial profile could be obtained in each measurement. The probes were composed of two pieces so that both (the electron side and the ion side) could be analysed independently. Three sets of samples were exposed, the first set for 3 discharges, the second for 8 discharges and the third for 24 discharges. After exposure to the deuterium plasma the samples were retracted, let up to air and transported to Garching. Here they were analysed using the $D(^3He, p)^4He$ nuclear reaction and Rutherford backscattering /23, 30, 31/. The latter gives the amount of heavy impurities deposited and the results are published already in previous papers /4,11/.

The results for the amount of trapped deuterium are shown in Fig.2 and 3. The absolute amount of trapped deuterium in the probes on the electron side as a function of the minor radius for each set of discharges is plotted in Fig.2. It shows a decrease of the trapped deuterium with increasing distance from the plasma. For the case of 24 discharges the results for the electron side are also introduced. More close to the plasma less deuterium is trapped while close to the first wall more deuterium is trapped than on the ion side. However, the differences are below 30 %. In Fig. 3 the same results are plotted as a function of the number of discharges for 5 different positions relative to the plasma. The amount of deuterium trapped does not increase linearly with the number of discharges, the curves show a bending indicating less trapping for an increasing number of discharges. This behaviour is more pronounced for large radii, i.e. more close to the first wall than at the plasma edge defined by the limiter.

In order to interpret these data, they have to be compared with the results of trapping measurements using well defined ion beams /32, 33/ and with the calculations simulating the bombardment of the probes in the plasma /28, 33, 34/.

Trapping Experiments and Calculations

If energetic particles (ions or neutrals) impinge on a solid, part of them are backscattered /35-37/, while the other part is slowed down in the solid and generally trapped depending on the solubility and diffusivity of the gas atoms in the solid.

Trapping of low energy deuterium in amorphous carbon has been recently investigated experimentally /33/. The implantations were performed both with a single energy and with a simulation of a Maxwellian energy distribution corresponding to a temperature T, at normal incidence. This is given by:

$$d\Gamma(E) = \Gamma_o \frac{1}{kT} e^{-E/kT} dE \qquad (1)$$

where $d\Gamma(E)$ is the differential and Γ_o the total particle flux, E the energy of the particles incident on the sample and k Boltzmann's constant. If the bombardment takes place in a plasma at density n the total ion flux to the solid probe is given by

$$\Gamma_o = n \left(\frac{kT_i}{2\pi m} \right)^{1/2} \qquad (2)$$

Here m is the mass of the ions and T_i the ion temperature of the plasma. For single energy bombardment the trapped amount rises first linearly with the implantation fluence until a transition to saturation occurs, which means that for each incident particle one is reemitted. For implantation with the energy distribution again a linear increase of the trapped gas is found for low doses. For higher doses a bending occurs and the trapped gas increases with a smaller slope, saturation is not reached up to doses of 10^{19} D/cm^2.

The measured trapping curves could be reproduced by calculations using the following model. The range distribution of the implanted deuterium in amorphous carbon was calculated with the computer simulation program TRIM /38, 39/. It was further assumed that all particles coming to rest in the solid are trapped until a saturation concentration is reached. At further bombardment the particles coming to rest at the saturated depth are reemitted. For deuterium implanted in carbon at room temperature good agreement with the measurements was obtained if saturation was assumed to occur for a ratio of deuterium to carbon of $n_D/n_C = 0.3$.

In this model the details of the transition to saturation depend on the range distribution of the ions in the solid. For single energy implantation in the energy range below a few keV, which is of interest here, the range profiles are well defined and relatively flat /30, 39, 40/. The critical concentration is reached at all depths for nearly the same fluence giving the fast transition to saturation. As the range of the ions in the solid increase with the energy, the total amount of gas trapped at saturation depends on the bombardment energy /30, 32/. If the range distribution of the incident particles has tails like for the implantation with a broad energy distribution, the transition to saturation occurs only slowly.

For particles having a Maxwellian energy distribution and an isotropic distribution for the angles of incidence no simulation experiments for the trapping have been performed up to now. In this case the differential flux $d\Gamma(\Theta, E)$ of particles incident on a plane is given by

$$d\Gamma(\Theta, E) = \Gamma_0 \frac{2E}{(kT)^2} e^{-E/kT} \sin\Theta \cos\Theta \, d\Theta \, dE \qquad (3)$$

where Θ is the angle of incidence in respect to the surface normal. For this case again the TRIM-program was used to get the range distribution of the ions in the solid. Trapping curves have been calculated using the same model and the same saturation concentration as in the case of normal incidence.

The results for all three cases of deuterium trapping in carbon for an ion energy and for an ion temperature of 150 eV are plotted in Fig. 4. The abscissa is the total ion fluence ϕ after the discharge time given by $\phi = \Gamma_o \cdot t$. The trapping is always lower than 100 % due to the backscattered particles.

For single energy implantation the trapping rises first linear with the ion fluence until at $\approx 3 \times 10^{16}$ D/cm^2 a bent to saturation occurs. The experimental points /33/ show reasonable agreement with the calculated curve.

For implantation with a Maxwellian velocity distribution at "normal" incidence bending starts already at a lower dose, however, saturation is not reached up to doses of 10^{19} D/cm^2.

For an isotropic Maxwellian distribution the reflected fraction is higher due to the oblique angles of incidence. This gives lower trapping at low implantation fluences. However, the bending to smaller trapping occurs at higher implantation fluences and more deuterium can be trapped at the higher fluences than for the case of "normal" incidence. This can be understood from the range distributions calculated with TRIM. For a given energy the range of the ions in the solid does not decrease with $\cos\theta$ for oblique angles of incidence but remains nearly constant up to very gracing incidence. Only the reflection coefficients increases with the angle of incidence. Thus the isotropic incidence distribution (equation 3) gives larger ranges than the "normal" incidence distribution (equation 1).

Plasma Parameters in the Limiter Shadow

In order to determine the plasma parameters and particle fluxes in the limiter shadow for the discharges investigated in TFR 600 the amount of trapped deuterium at different radial positions have been compared with the calculated trapping curves obtained for different ion temperatures taking a Maxwellian energy distribution with an isotropic distribution for the angles of incidence. The results are shown in Fig.5. The best fit between the measured amount of trapped deuterium at the three radial positions r and the calculated trapping curves is obtained for the values summarised in Table 1. While the plasma temperature $T_i(r)$ and the particle fluences ϕ are obtained directly from fig.5 the plasma density is calculated using equation (2).

Discussion

The values obtained for the ion temperature are in good agreement with the results for the neutral particle temperature in this region, obtained from the D_α-Doppler broadening /41/, while the particle densities and fluxes are somewhat lower than expected.

However, the uncertainties in the experimental values and in the evaluation of the data have to be regarded in detail:

- In the QWAASS experiments all deuterium atoms hitting the probes during the discharge contribute to the amount of trapped deuterium. The fluxes during the start and the end of the discharge may be comparable with the fluxes during the flat top but probably have lower energies. This means that in these measurements some mean ion temperature is obtained.

- We have assumed that the plasma in the limiter shadow can be described by a Maxwellian distribution. This may be only a first approximation as the real energy distribution is not yet known.

- The plasma in the limiter shadow is in direct contact with the first wall and the limiters where ions get neutralised /36/. A certain concentration of neutral particles will thus be present in this region. These may also not have a Maxwellian distribution and may not be in thermal equilibrium with the plasma /42/. However, detailed measurements with the QWAASS set up using diaphragms in front of the collector have shown that the contribution of neutral particles to the amount of trapped deuterium is small /43/.

- A further complication for interpreting the measurements is the presence of a sheath potential in front of the sample. This gives the particles an additional energy component normal to the surface resulting in higher trapping. It would mean that the temperatures obtained present an upper limit.

- The transport of the samples through air before analysis does not seem to influence the results.It is known that D is trapped stable in carbon at room temperature /32/ and the built-up of an impurity (CO, H_2O) layer on the surface would not influence the results.

- In the simulation experiments carbon in the form of PAPYEX is used while for the trapping probes at TFR 600 evaporated carbon films were applied. The two different kinds of carbon may show a different saturation concentration, but the differences expected are below the other experimental uncertainties. More detailed measurements are necessary.

- During the discharge also a layer of Fe, Ni, and Cr is deposited on the QWAASS probe /4, 11/. This increases the reflection coefficient especially for the very low energy deuterons, resulting in lower trapping of D. This effect has also to be looked at in detail.

- The range profiles for deuterium have been calculated with the TRIM program using Moliére potentials and Lindhard's stopping powers. Several cases had also been calculated with the more refined program MARLOWE (amorphous) /39/ using the same input parameters as for TRIM. For the values of interest here good agreement was found between the results of both programs.

- It is not yet established whether the deuterium is trapped within the range profile or the damage profile of the incident ions. This is important for the concentration of deuterium at saturation, however, it does not enter directly into the results of the experiments reported here.

- Recently trapping curves for D in amorphous carbon have been calculated also by Cohen and McCracken /12, 34/ using a different approach than in this work. The ranges of the D implanted with an isotropic Maxwellian distribution were calculated from the mean range and the range straggling obtained by Brice for the case of normal incidence. For obtaining the range distribution at oblique angles of incidence the mean projected range was assumed to be shortened by cos θ, while the straggling was assumed spherically isotropic centered around the range of the ions. These assumptions give shorter ranges at oblique angles of incidence then the TRIM calculations. The model to calculate the trapping curves from these range distributions and the saturation concentration was the same as used here. Due to the lower ranges lower trapping is obtained for the isotropic than for the normal incidence Maxwellian distribution. The opposite effect was found in this work for high enough fluences. The application of these trapping curves for the evaluation of trapping measurements in carbon at PLT, gave thus higher ion temperatures and higher deuterium fluences /12/.

- All calculations have been performed for ideally flat surfaces. Rough surfaces decrease the reflection yield. This means that the trapping curves calculated may show too low trapping compared to reality. The effect gets especially large for oblique angles of incidence.

- In these experiments only the information of the total amount of trapped deuterium is used. So far we have not used the depth distribution of the trapped deuterium, since the depth resolution of the nuclear reaction technique applied here of about 100 to 200 Å is not sufficient. However, it was demonstrated recently that depth profiles with better depth resolution can be obtained by SIMS depth profiling /12/. These profiles can be directly used to get the ion temperature even after only one exposure. The total ion flux and the ion density can also be obtained if the total amount of trapped deuterium is measured. The simultaneous use of both methods probably would give the best results.

Summary

Detailed measurements of the amount of trapped deuterium in clean carbon probes which had been exposed for a certain number of discharges to the plasma in the limiter shadow of TFR 600 have been compared with deuterium trapping curves obtained under well defined ion bombardment conditions. From this comparison mean values for the ion te-perature, the ion fluxes and densities are obtained which are in reasonable agreement with other estimates. The results deviate, however, from the results of similar experiments performed recently /12/ but evaluated with slightly different assumptions /34/. These differences have to be clarified.

The technique applied here could be extended to more refined measurements as the time dependence of the plasma parameters or the magnitude of sheath potentials in front of the probes. Further, depth profiles should be measured for ion beam simulations and in the QWAASS probe measurements to get more and additional information. A disadvantage of the method used here is till that the analysis to get the plasma parameters took a relatively long time.

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TABLE 1: Parameters for the plasma in limiter shadow obtained in these measurements

r (cm)	20.1	22.1	23.6
Trapped after 24 shots (D/cm^2)	2.7×10^{16}	1.75×10^{16}	0.95×10^{16}
Fluence after 24 shots ϕ (D/cm^2)	2×10^{17} to 1×10^{18}	1.3×10^{17} to 5×10^{17}	$\approx 3 \times 10^{17}$
$\Gamma_o \left(\frac{D}{cm^2 s}\right)$	8×10^{16} to 4×10^{17}	6×10^{16} 2×10^{17}	$\approx 1 \times 10^{17}$
kT_i (eV)	50 ± 10	30 ± 10	≈ 10
$n_i (cm^{-3})$	4×10^{10} to 2×10^{11}	3×10^{10} to 1.3×10^{11}	$\approx 1 \times 10^{11}$

Figure Captions

Fig. 1 Schematic view of horizontal cross section of TFR 600 showing the location of the probe with respect to the limiters and other structures.

Fig. 2 Radial profile of deuterium trapped in a carbon sample exposed in the limiter shadow region.

Fig. 3 Deuterium trapped in carbon as a function of the number of discharges. The data are taken from Fig.2 for 5 different minor radii indicating the distance from the plasma edge at a_L = 20 cm.

Fig. 4 Calculated trapping curves for 150 eV deuterium in carbon for the cases: (....) Single energy at normal incidence, (— — —) Maxwellian energy distribution at normal incidence, Eq. 1, (——) Maxwellian energy distribution and isotropic icidence, Eq. 3. For the first case experimental values /33/ are also introduced.

Fig. 5 Calculated trapping curves for deuterium in carbon for an isotropic Maxwellian distribution at 6 different temperatures. The experimental values from fig.3 are introduced with a best fit to the shape of the curves.

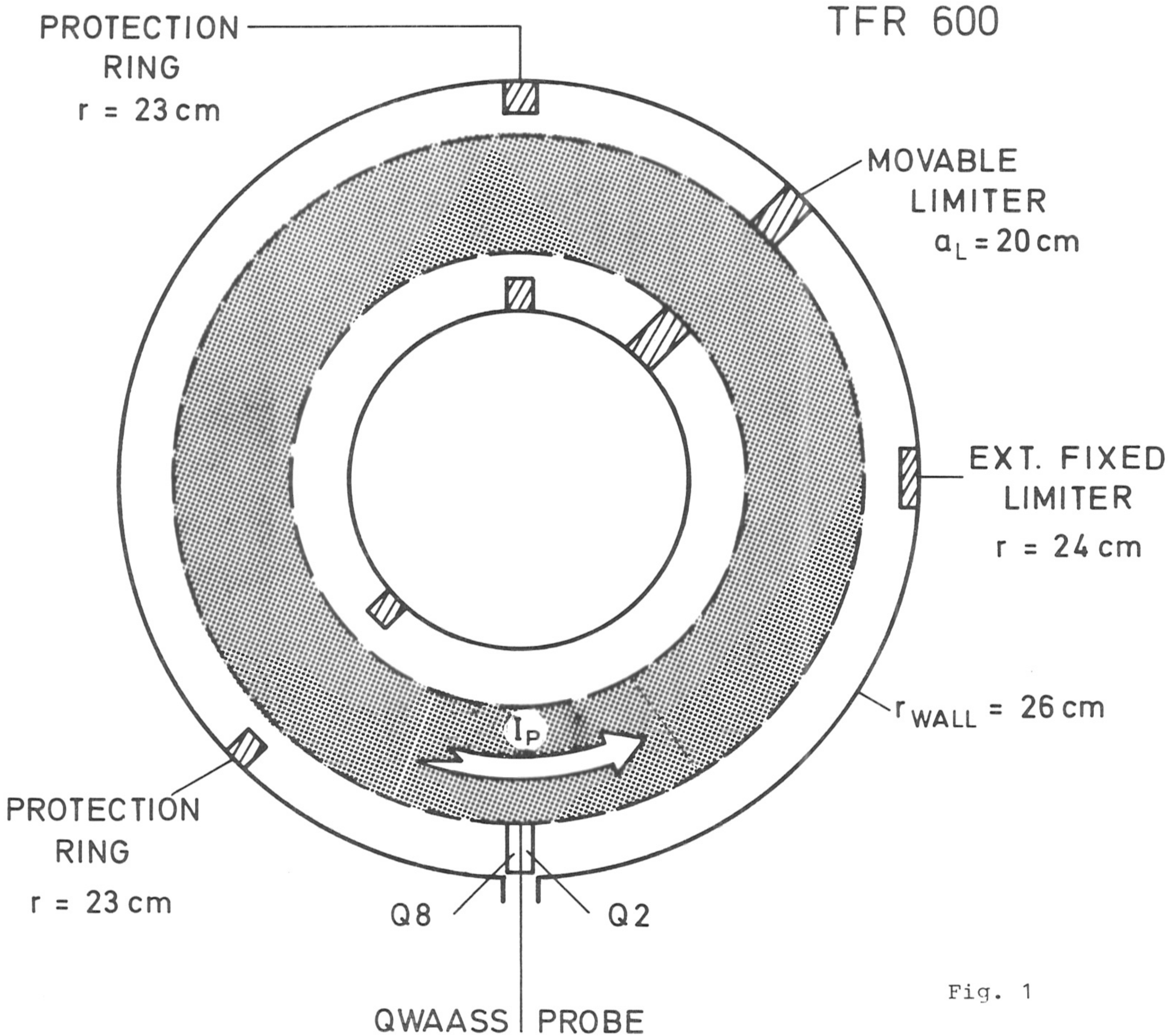
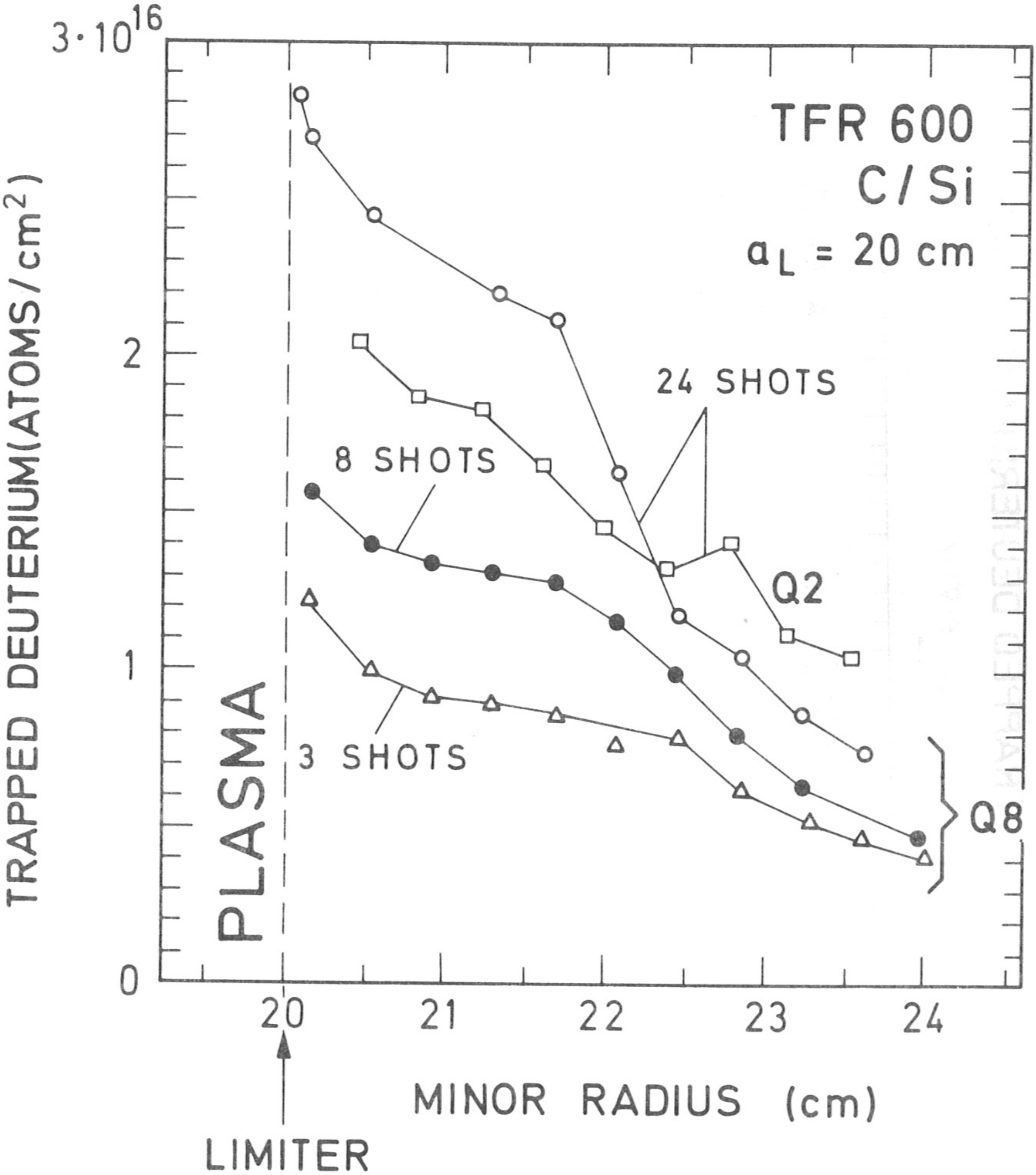
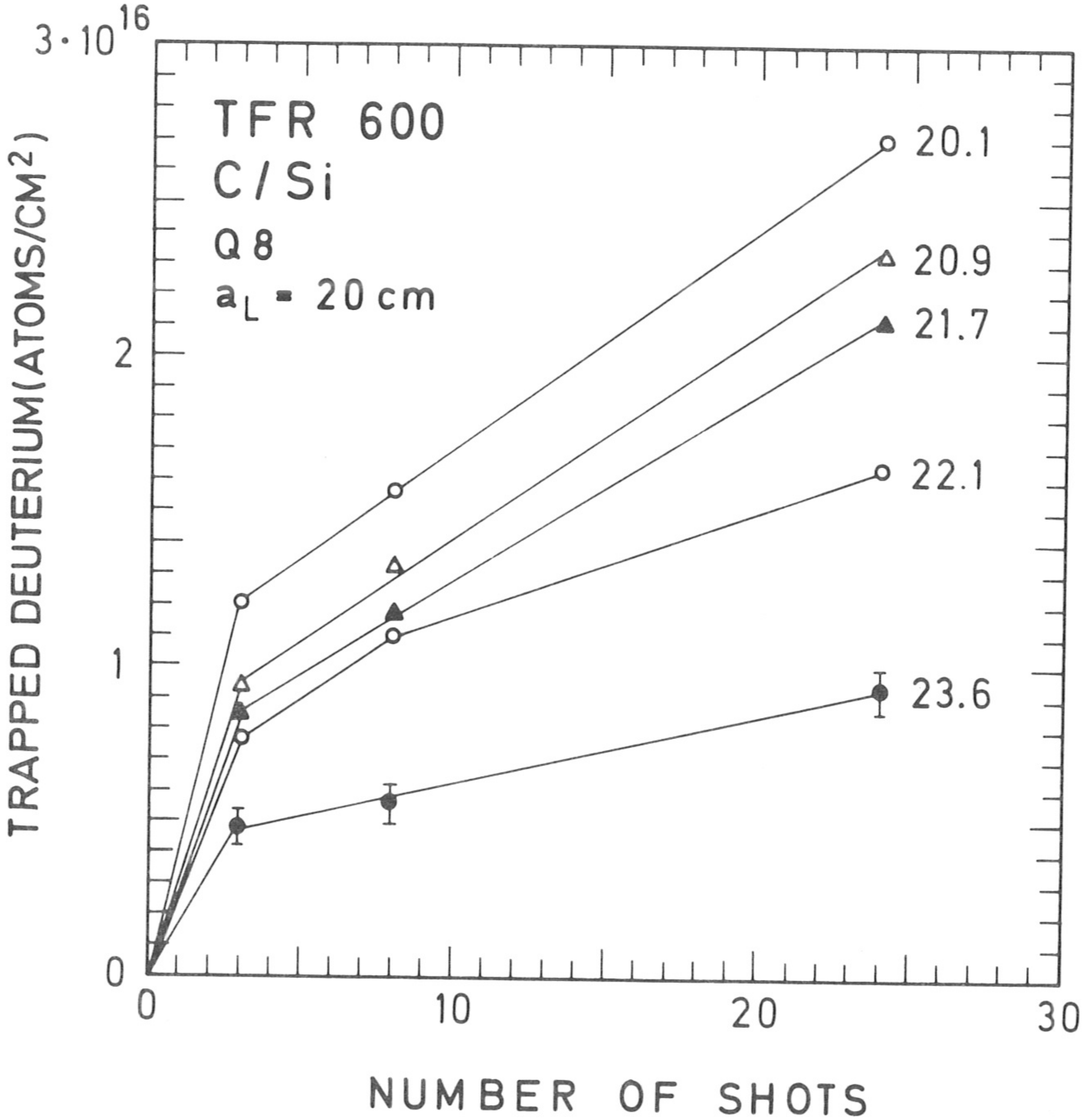

TFR 600
PROTECTION RING
r = 23 cm
MOVABLE LIMITER
$a_L = 20$ cm
EXT. FIXED LIMITER
r = 24 cm
r_{WALL} = 26 cm
I_P
PROTECTION RING
r = 23 cm
Q8
Q2
QWAASS PROBE

Fig. 1



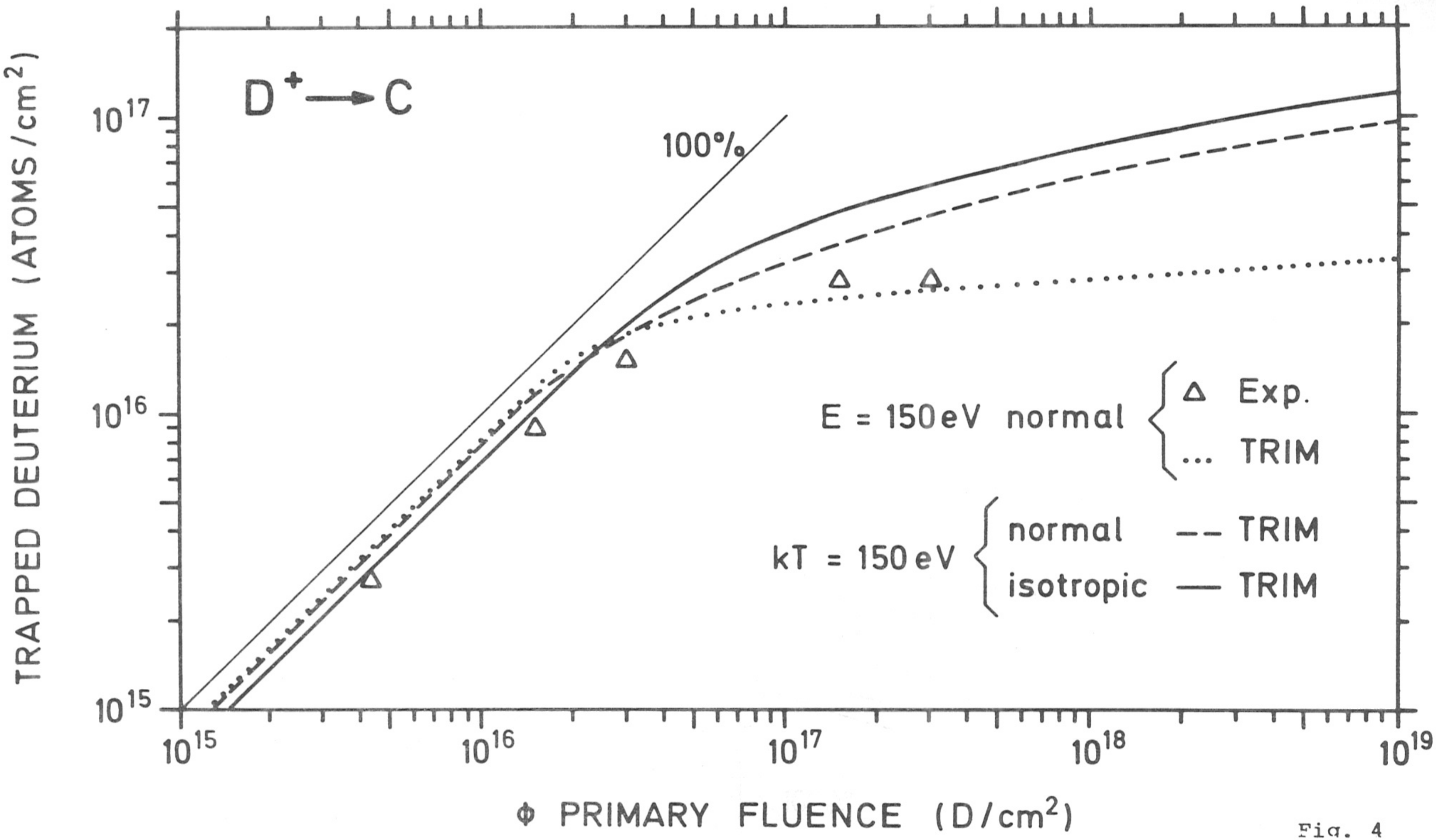
3·10^16
2
1
0
TRAPPED DEUTERIUM(ATOMS/cm²)
TFR 600
C/Si
a_L = 20 cm
24 SHOTS
8 SHOTS
3 SHOTS
Q2
Q8
PLASMA
20
21
22
23
24
MINOR RADIUS (cm)
LIMITER

Fig. 2



3·10^16
TFR 600
C/Si
Q8
a_L = 20 cm
20.1
20.9
21.7
22.1
23.6
2
1
0
0
10
20
30
TRAPPED DEUTERIUM (ATOMS/CM²)
NUMBER OF SHOTS

Fig. 3



D+ → C
100%
TRAPPED DEUTERIUM (ATOMS/cm2)
10^17
10^16
10^15
E = 150 eV normal
Δ Exp.
... TRIM
kT = 150 eV
normal -- TRIM
isotropic — TRIM
10^15
10^16
10^17
10^18
10^19
Φ PRIMARY FLUENCE (D/cm2)

Fig. 4

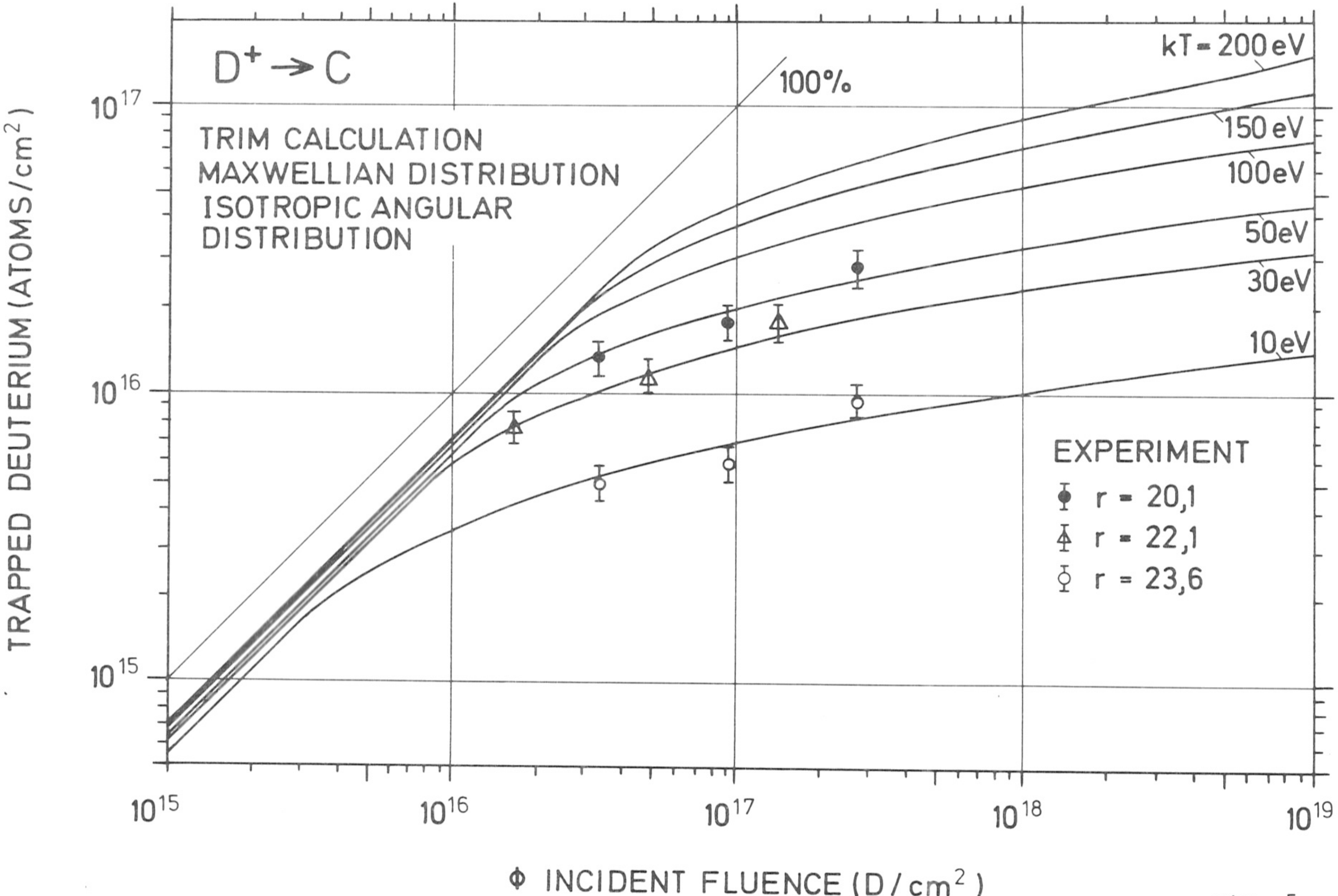

D+ → C
TRIM CALCULATION
MAXWELLIAN DISTRIBUTION
ISOTROPIC ANGULAR
DISTRIBUTION
100%
kT = 200 eV
150 eV
100eV
50eV
30eV
10eV
EXPERIMENT
r = 20,1
r = 22,1
r = 23,6
TRAPPED DEUTERIUM (ATOMS/cm2)
10^17
10^16
10^15
10^15
10^16
10^17
10^18
10^19
Φ INCIDENT FLUENCE (D/cm2)

Fig. 5