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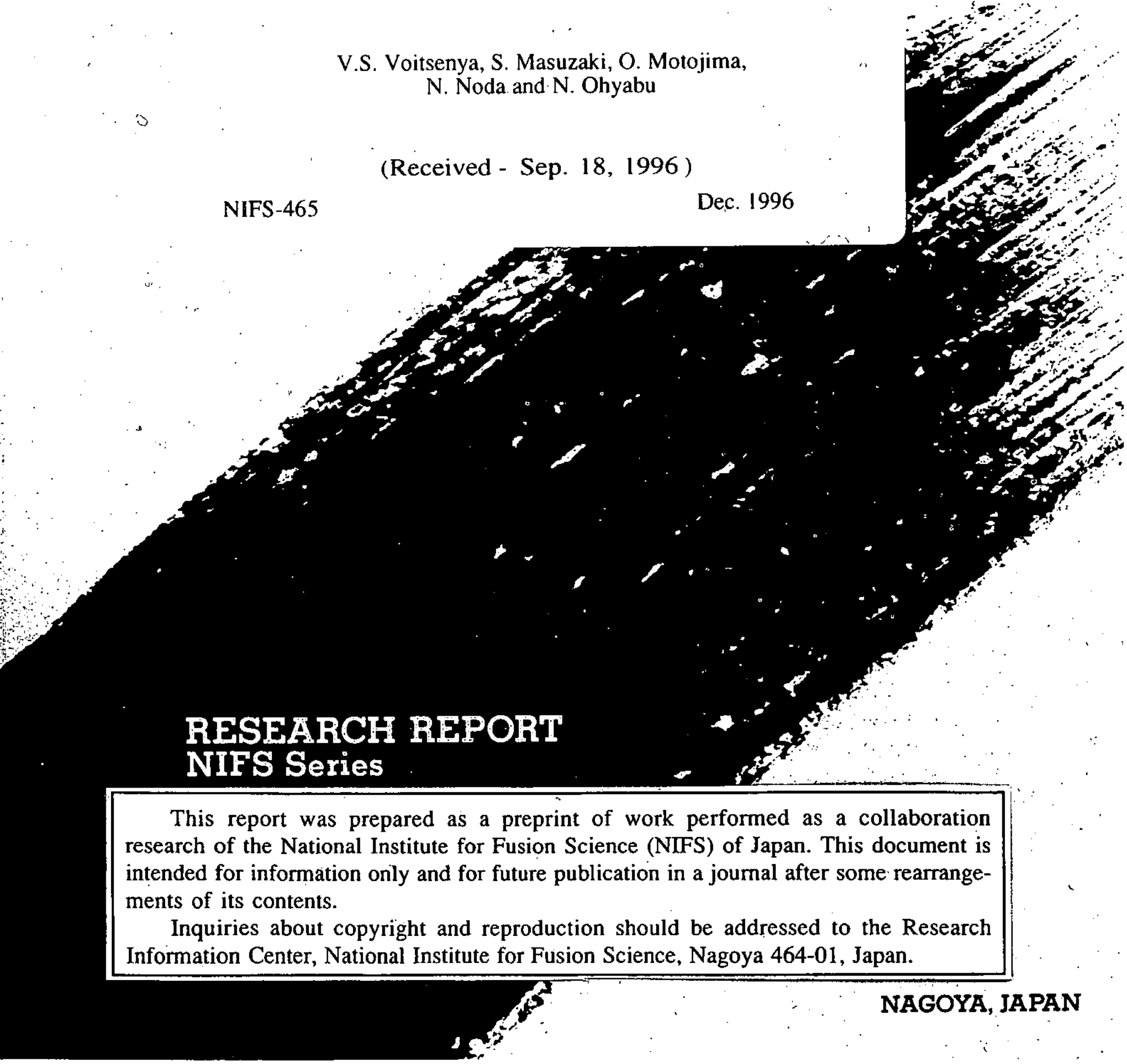

RESEARCH REPORT
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On the Use of CX Atom Analyzer for Study Characteristics of Ion Component in a LHD Divertor Plasma

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Abstract

In this paper the analysis was provided for the possibility to use the charge exchange atom analyzer using the ion reflection phenomena on solid surfaces for measuring the characteristics of the ion component of a divertor plasma in LHD. As an ion-atom converter the target plate made of refractory metal (Ta or W) is proposed to be used. This target plate can withstand the energy flux transported by the divertor plasma during LHD pulse: ~10MW/m^2 for ~2s with water cooling. The particle brightness of such target is much higher than the one of a gas target with a reasonable value of molecular hydrogen density (10^{14}cm^{-3}). The efficiency of W-made ion reflected atom converter is rather high, 40-65% in the incident ion energy range 50-1000eV, however the energy reflection coefficient is lower for these energies: ~20-40eV. Beside, the appearing the carbon or boron film on the target surface can lead to the decrease of ion-atom conversion efficiency. In such conditions the use of a time-of-flight (t-o-f) atom analyzer has some advantages as compare to the device with the gas stripping cell for charge exchange atom-ion conversion and electrostatic analysis of the ion energy distribution.

In this paper we give the short description of energy component of the scheme with t-o-f atom analyzer in use, and the estimation of atom fluxes into the direction of atom analyzer with metal and gas targets.

Keywards: divertor plasma, ion-atom converter, particle reflection, chopper,
time-of-flight atom analyzer, charge exchange atoms

1. Introduction

One possible method for obtaining data on parameters of the ion component in a divertor plasma of LHD is to utilize the charge exchange (CX) atom flux analyzer for measuring the flux and energy distribution of hydrogen (deuterium) atoms reflected from the target crossing the divertor layer. Similar method (analyses of reflected particles) has already been applied for investigating the ion component in a divertor region of the tokamak ASDEX [1], in the limiter shade plasma of the FT-1 tokamak [2] and in the observation of the point of a plasma "footprint" on the wall of the L-2 stellarator [3].

There are several arguments to use this method in LHD experiments. One of the most important is that because of high energy flux density transported by a divertor plasma, any contact methods (multigrid or Katsumata type ion energy analyzers) probably cannot be utilized routinely. In the case of reflected particles detection, the ion-to-atom converter (target) could be made of the same material which is planned to be used for the divertor plates, or of any other material which has a high resistance to sputtering with ions of a divertor plasma and also has rather high thermal conductivity (i.e., W, Ta, Mo). With the same (or identical) converter there is a possibility to use optical methods for investigating the energy distribution of reflected particles, by measuring the shape of H alpha (D alpha) line, similar to what have been done for helium and hydrogen atoms in papers [4] and [5]. The inverted problem of obtaining the ion energy distribution can be solved by means of a program similar to programs ACAT and ACOCT [6] and TRIM [7], which take into account the results of experiments and Monte-Carlo computer simulations on the reflection of particles from targets of different materials. Some results on such modeling for measured neon atoms distribution reflected from the limiter have recently been published in [8].

For measurements of reflected particle flux characteristics, in the case of LHD, mostly suited is the time-of-flight analyzer [9-12] which, principally, gives the possibility to analyze atoms beginning from much lower energy (~15-20 eV) as compare to what is possible by means of analyzer with electrostatic analyzing the energy of atoms after conversion them into ions in a gas stripping cell. Here the practical threshold energy for detection is ~0.3 keV.

Thus, the scheme of measurement must include the following parts: ion-atom converter, the vacuum duct, chopping device, time-of-flight duct and the system of detection. All parts of an analyzer have to be additionally pumped to decrease the particle scattering on the way from target to detector, and all fast rotating components (turbomolecular pumps, chopper motor) as well as the particle detector are needed to be shielded from a stray magnetic field of LHD magnetic system.

2. Target

The ion-to-atom conversion process is very important one for the method based on the registration of reflected particles. For the fixed characteristics of an ion flux the reflection coefficient as well the energy spectrum of atoms depend on the target material and its structure (poly- or monocrystal), surface roughness and cleanness, and angle of incidence of ions [13-26]. In the magnetic field, in turn, the angle of particle incidence is a function of the magnetic field inclination to the target surface and plasma parameters [8, 27, 28].

Let us analyze the influence of indicated factors on the process of hydrogen (deuterium) atom reflection.

Both reflection coefficients, for particles (R_N) and for energy (R_E), increase with increasing elemental mass of a target material for any value of an initial particle energy [15-20, 22, 24, 25]. Fig.1 shows such dependencies (reflectance of deuterium atoms versus atomic mass of target) found from data presented in the review paper [7]. The reflection coefficient values for carbon-based material in Fig.1 are in a very good agreement with data published recently in [26].

For high mass metals, like tungsten, the portion of reflected hydrogen (deuterium) atoms exceeds 50% [7, 20, 23, 24], and this portion approaches 100% with increasing angle of incidence in the particle energy interval of interest (20-500 eV). So, the distribution of ions on the angle of incidence is rather important, but up to now such data (with taking into account the ion gyration and plasma-wall sheath potential difference) were calculated only for one concrete case [28], and usually some averaged values of the angle of incidence are calculated as a function of magnetic field lines inclination to the target surface and plasma-target sheath potential [8, 27, 28].

According to these calculations, the particle angle of incidence increases with increasing inclination angle of magnetic field lines to the target surface for any given set of plasma parameters. But the inclination of the target (to the orientation of magnetic field lines) can result in some decrease of a number of ions that will be reflected and measured with CX atom analyzer. To optimize the geometry of measurements, as a first step, it is necessary to make additional calculations with utilization of respective codes, and also to foresee the possibility of changing the target position relatively the divertor flux (and the line of observation) after LHD starts to operate.

In connection with binary collisions play the main role in a process of particle reflection, impurities on the surface of an ion-atom converter can result in significant change of the reflectance coefficient depending on the elemental impurity/target mass ratio. According to measurements and calculations, some amount of hydrogen trapped in the near surface layer of a carbon target leads to measurable decrease of portion of reflected particles [19] of the same energy range. Qualitatively similar result was obtained by the ACAT program for tungsten coated with nitrogen [6].

It follows from these data that even thin layer of low-Z materials being appeared on the converter surface (due to wall conditioning or as a result of redeposition process during working discharges) can lower the ion-to-atom conversion efficiency and signal/noise ratio. For LHD the most probable is the carbon deposition on the target surface, and maintaining the high level of the surface cleanness during long experimental time could be very difficult problem.

However, results of papers [4] and [5], surprisingly, do not indicate the existence of a strong effect of carbon film deposition when atoms reflected from the limiter surface in the tokamak TEXTOR have been analyzed. As it was already mentioned, these papers are devoted, correspondingly, to the investigation of characteristics of reflected helium and hydrogen atoms. In both papers the spectroscopic measurements of Doppler broadening of lines radiated by reflected atoms were carried out. In [4] the portion of fast helium atoms (>50%) reflected from the stainless steel limiter was in agreement with calculation for a nickel target with taking into account the electron temperature near the limiter and data on the reflection mechanism published by M.Eckstein in his review papers. And in

[5] the Hα line profiles were clearly distinguished for the limiters made of stainless steel and graphite (Fig.4 in that paper): the energy and a number of fast reflected atoms were observed significantly higher in the case of stainless steel limiter as compare to the limiter made of graphite.

One possible way to decrease the rate of carbon deposition on the metal converter is to heat it during experiment up to ~700°C, to increase the chemical sputtering of depositing carbon layer. In the case of high ion flux to the converter, another way to avoid this problem is to utilize from the very beginning the target made of the same type graphite which will be used for manufacturing the divertor plates with much lower, according to data of Fig.1, reflection coefficient in comparison to what is typical for heavy metals.

Concerning effects of surface roughness on the reflectance coefficients - not many data are published up to date. In the respective part of the review paper [7] there is marked that the surface roughness influences stronger on reflectance of particles with lower energy and especially for glancing angle of incidence: the difference in reflectance values becomes to exceed the 50% level at the angle ~1 radian [21]. Qualitatively agrees with this assertion a result obtained in [24].

The first direct measurements of hydrogen atom reflection coefficient from a graphite surface with known microrelief, as a function of incidence angle, were carried out by authors of [26]. They showed that with a rough surface the angular dependence of reflection coefficient becomes weaker, and the difference in reflection coefficient values for particles with different energy decreases significantly.

If the target-converter is grounded, ions will be additionally accelerated due to the sheath potential difference between the target surface and a plasma. The gain of an energy has to be close to ~$3T_e$ and will not influence seriously on the energy distribution of reflected atoms when $T_e << T_i$. But in the case of target is isolated from the vacuum chamber there exists also a principal possibility to change the plasma-target potential difference for the optimization of the ion-atom conversion process.

3. Vacuum duct

This part of the device serves as a guide for reflected atoms from LHD vacuum vessel to the chamber where chopper is located. The low background pressure in duct (~ 10-5 Pa) will guarantee the low decay of atom flux (due to scattering and ionization processes when colliding with H2 molecules) on the way from the entrance slit to the chopper. With such pressure value the major scattering effects will appear inside LHD vacuum vessel itself, where the working pressure is estimated to be at a level ~0.1 mTorr. Taking into account the distance from target to the duct slit, DR = 170 cm, the "gas target" thickness will consist of ~$6\times10^{14} H_2/cm^2$. The size of the slit between vacuum vessel and the duct depends on the pumping speed of the duct pump and on the duct size.

The special pumping of a vacuum duct is not entirely necessary in the case of CX atom flux measurements (like in experiments [9]), but the sure registration of reflected particles will be, probably, impossible without lowering a background pressure in this part of equipment to above mentioned value. The possibility to control the background gas pressure inside a vacuum duct can be realized by using the deep separately pumped "vacuum well" with an entrance slit located close to the target-converter, as it is shown schematically in Fig.3.

4. Chopper

The chopper system forms the pulses of atom fluxes (bunches) of rather short time duration. With a proper time-of-light length (L~ 200 cm) the bunch duration, to, has to be ~2µs. In this case it will be possible to analyze hydrogen or deuterium atoms with an energy from ~20 up to ~ 2000 eV.

The formation of the periodical pulses of neutral atoms is possible only by use the mechanical system. In all four analyzers described in [9-12] for this purposes the disk rotating with high speed (167, 760, 300 and 333 Hz, correspondingly) was the main component of a chopper. The width of slits in the rotating disk must be ~0.2 mm for the initial (just behind the chopper disk) bunch duration does not exceed 2µs.

The time of flight of atoms with lowest detected energy determines the minimum time interval between two pulses and respective number of slits for the chosen size and rotation speed of the chopper. With L = 200 cm the appropriate repetition time could be > 200ms. So, about 20 slits have to be equally distributed on the radius 5-10 cm, depending on the number of disk revolutions/sec.

Very different construction of a chopper for beams of neutral particles was developed and tested recently [30]. It has now rotating disk with many slits, and the only slit is made directly in the rotor of 5.6 mm in diameter. This chopper is rather compact device but it needs the very high rotation frequency: ~10 kHz in the need to get the particle beam pulse length of ~1ms.

5. Detector

The detection of low energy hydrogen atoms in [9-11] was realized by means of a converter with registration of secondary electrons (and partly, probably, H- ions) released from the converter surface under bombardment with atoms. In all cases the converter electrodes were made of Cu-Be plates, and in [9,10] open electron multipliers served as detectors of negatively charged particles released from the Cu-Be surface due to hydrogen (deuterium) atoms bombardment. In [11] the energy of secondary electrons was ~20 keV and for their detection the scintillator was used. Author of [10] did not take any special measures to clean the surface of the converter, but there was not found any significant influence of the Cu-Be surface oxidation on the effectiveness of such scheme of particle flux measurement. The detail analysis of this method of particle detecting with different constructions of the converter part is done in [29], and the efficiency of such a converter, i.e., the ratio of negative particle flux to the H atom flux, from [10] is shown in Fig.2.

To suppress the noise signal connected with photons emitted by a plasma, authors of [9,10] used additional generator to pulse positively the converter plate during those time intervals when plasma light illuminates the plate through the chopper slit. In experiments [11] the thin aluminum film coating on a scintillator surface served as a protection for the light coming out from the core plasma.

In the [12] the process of converting was realized directly inside the open electron multiplier used (20-CuBeO-dynode box-and-grid type). The recovery time of the multiplier (Hamamatsu R595) was only ~5ms after maximum of the light signal, and thus even H atoms of ≤3 keV energy could be registered.

6. Estimation of reflected atom flux

The lowest CX atom flux values to the vacuum vessel wall that was measured with this type of analyzer for lower part of CX atom energy distribution are a little less than 10^{14} at/cm^{2}s [31-33]. This level of flux is probably near the threshold of t-o-f analyzer sensitivity.

Taking account this value, let us evaluate the flux of reflected atoms from the metal target crossing the divertor flux of LHD.

Now-a-days estimated divertor plasma density and ion temperature in LHD, depending on regime of machine operation, are as follows: ~ 10^{13} /cm^3 and ~ 400 eV [34] or ~ 10^{11}/ cm^3 and ~ 3 keV [35]. The most probable divertor plasma parameters at the initial stage of machine operation will be somewhere between indicated values. For estimation, let us take ~ 200 eV and ~ 10^{12}/cm^3 as starting meanings for averaged ion energy and density in a diverted flux near the position of the ion-atom converter location (i.e., rather far away from the divertor plates). Then the ion flux density in a divertor flux is to be ~ 2×10^{19}/cm^{2}s, and the total ion flux along the diverted magnetic field lines will be about two times of this value, ~ 4×10^{19}/cms.

If the whole "footprint" of a diverted plasma flux is seen by the detector system of an analyzer, the "brightness" of the target, e.g. reflected particle flux, will depend only on the effective incidence angle of ions, and does not depend on the "footprint" width. As was mentioned above, the optimization of "brightness" demands the possibility to adjust the target orientation during initial stage of analyzer operation. For our rough estimation the reflectance coefficients for the normal incidence, R_0, can be quite satisfactory ones.

According to data of Fig.1, the reflectance of ions with ~ 200 eV energy, $R_0(200)$ is near 50% for the target made of a refractive metal.

With the converter length 5 cm the total reflected flux will be ~10^{20} H atoms. To compare with lowest values measured on PLT and ASDEX [31, 32] of CX atom flux to the wall we need to estimate the flux of reflected particles on the large horizontal flange of LHD, i.e. at the distance ~ 1.7 m from the target-converter. It is known (e.g., [13]), that the angular distribution of reflected particles for the normal incidence agrees rather well with the cosine distribution, and the flux density decays with increasing distance from the target by factor ~3 lower than $(\Delta R)^{-2}$. Qualitatively this tendency conserves also for non normal angle of incidence if it is not close to the sliding one. Thus, density of reflected atoms on flange will be not less than ~8×10^{14}/cm^{2}s, e.g., several times of minimum values measured in real experiments.

For target made of carbon-based material the portion of reflected particles will be several times lower ($\leq$ 4 times for ion energy < 0.4 keV), but still their flux will be enough to be detected. However, in this case the energy reflection efficiency is very small, only 4-6% for energies 400-50 eV (Fig.1b), and this can lead to large errors when solving the inverted problem.

It is interesting to compare this atom flux density with CX atom flux from a divertor region if the gas target (molecular hydrogen) is used to convert plasma ions into the CX atoms. In this case the rate of CX atom production in a divertor plasma will be connected mainly with the process

$$H^+ + H_2 \rightarrow H^0 + H_2^+, \qquad (1)$$

because the density of hydrogen atoms will be too low that resonant process ($H^+ + H^0 \rightarrow H^0 + H^+$)

plays any significant role. The cross section of process (1) depends strongly on the energy of hydrogen ions (for example, [36]) in the energy range of interest (i.e., 0.2 -1 keV), and for E_H=0.2keV $\sigma_{10} \approx 1\times10^{-16}$cm^2, giving $(\sigma v)_{10} \approx 2\times10^{-9}$cm^{3}s^{-1}. Thus, the CX atom flux density from every cm^3 of a divertor plasma volume will be: $\Gamma_0 = n_H + \times\, n_{H2} \times (\sigma v)_{10}$, which corresponds to $\Gamma_0 \approx 7\times10^{15}$cm^{-3}s^{-1} for the divertor plasma density ~10^{12}cm^{-3} and the background hydrogen pressure ~1mTorr. If the surface of a divertor plasma visible by the CX atom analyzer is 5cm^2 and the divertor flux thickness is 2cm, the total flux of CX atoms from the whole "background gas target" seen through the analyzer solid angle will be ~7×10^{16}s^{-1}, and only approximately half of them will have a velocity along the analyzer direction. It follows from this estimation that "background" CX atom flux from a divertor plasma will be several orders of magnitude lower than the flux of reflected particles, and probably will be not enough for analyzing. Correspondingly, it means that there will be necessary to realize the additional local gas puffing into the divertor plasma stream, in the direct view of the analyzer, to increase a CX atom flux to the value which is sufficient to be measured.

With such an "artificial gas target" the line of observation will not be tangential to the divertor flux. As is seen from the geometry of measurements, Fig.3, the angle between line of observation and the diverted field lines is near 45°. Thus, the mean velocity of CX atoms in this direction has to be ~0.7 of the mean velocity of CX atoms moving tangentially to the diverted magnetic field lines, if one supposes the cosq distribution for atoms, where $q=\mathrm{arctg}(v_\perp/v_{||})$. In turns, the average CX atom energy in the direction of analyzer will be about half of the mean ion energy in the divertor stream. Therefore, to measure the CX atom flux the t-o-f analyzer is also sufficient to be used.

7.Location

The mostly suitable port for measuring with t-o-f analyzer is large horizontal port 1-0 or any identical one. It is not necessary to occupy the symmetrical cross section which can be used for other purposes.

There is the strict demand as for the location of ferromagnetic materials near LHD, and because some parts of analyzer equipment has to be shielded from a stray magnetic field, this demand defines the minimum distance of the analyzer from the plasma center. The nearest part of the equipment that has to be shielded is the chopper, and it has to be situated not close than 8.5 m from the torus major axis to gratify the demand and not to surpass the allowed level of an error magnetic field contributed by its ferromagnetic shield. With taking account the target-flange length (~1.7m) the minimum duct length is ~1.5 m. The chopper part occupies ~ 0.3m and then ~2m - the flight pass. The scheme of displacement of an analyzer equipment is shown in Fig. 3.

The stray magnetic field amplitude at the chopper motor position will be a little less than 0.01 T, and there will be not a difficult problem to shield it.

With such location of analyzer there will be possible also to measure flux of CX atoms escaping from the edge part of the core plasma volume, just by taking target out from the divertor plasma and opening the pass for CX atoms. The chord of observation of the main plasma depends on the location and orientation of the analyzer, and can be changed by changing its orientation relatively to the core plasma.

Depending on the orientation of the line of observation, some number of CX atoms from the core plasma will also be reflected from the target. But as it is seen from the geometry of measurements (Fig.3), these particles will hit the target surface at a sliding angle. As a result, after being reflected from a smooth surface they also will move close to the target surface, not giving significant contribution to the flux of particles reflected from the target due to ion-atom conversion in a divertor plasma.

8. Conclusion

This consideration shows that time-of-flight analyzer would be successfully used for investigation of the ion component in a diverted plasma for a wide range of its parameters. It can also be used for measuring CX atom flux from an edge region of the main plasma confinement volume. But much work has to be done at the stage of preparation of this method of divertor plasma diagnosing in LHD as it is indicated in Appendix 1.

In the case that ion mean energy in a divertor flux significantly exceeds 300 eV, the device with electrostatic analyzing of reflected atoms will also be sufficient with a gas stripping cell utilization for ionization of neutral particles. Similar analyzers have been used in all three experiments on fusion devices [1-3] with measuring reflected particles.

The use of t-o-f analyzer will have advantage only in the case that mean ion energy in a diverted flux is less than ~ 300 eV and also in the case that ion energy distribution is not the Maxwellian one.

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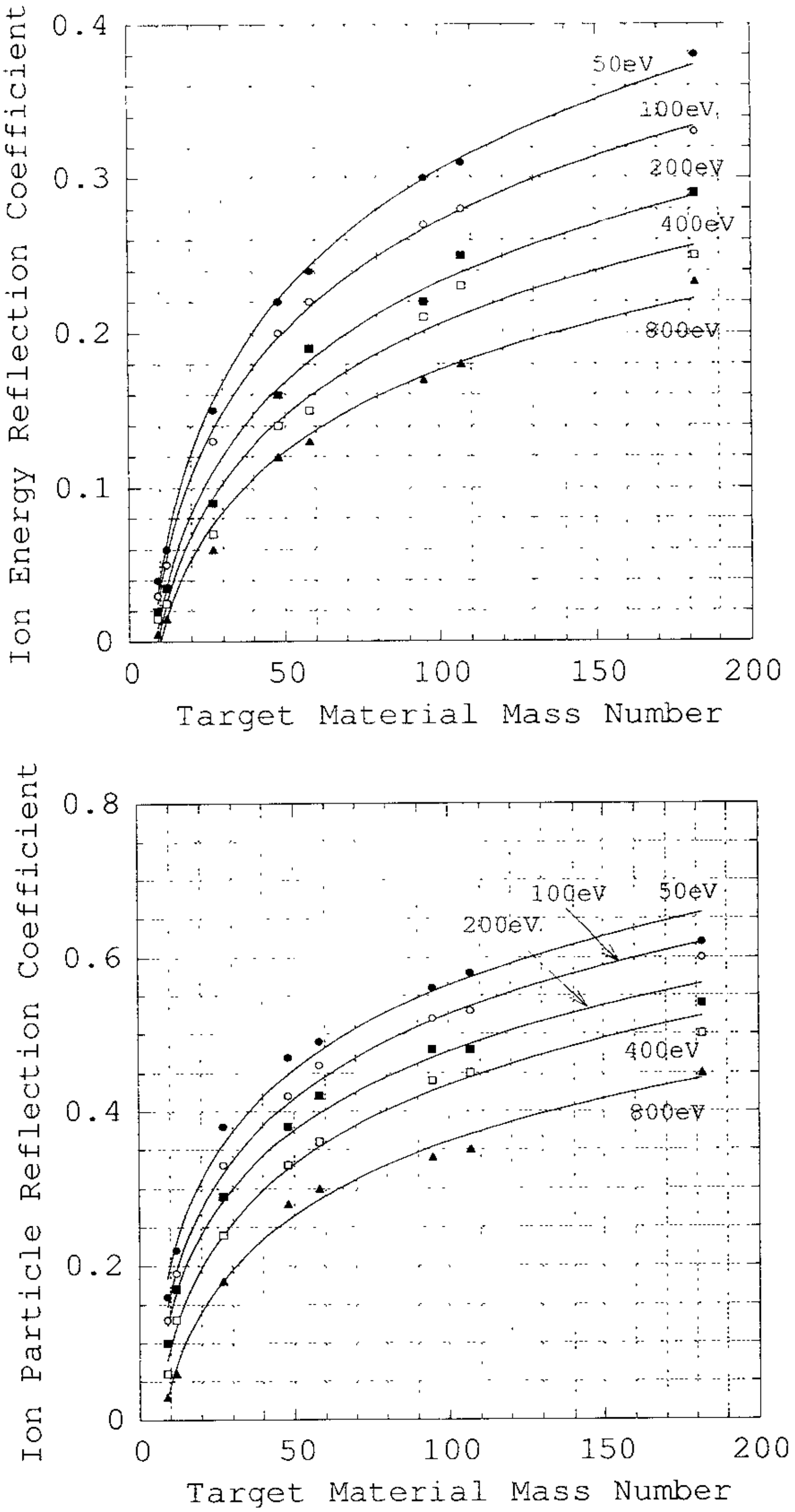

Fig. 1. Deuterium ion reflection coefficients from targets made of different materials.

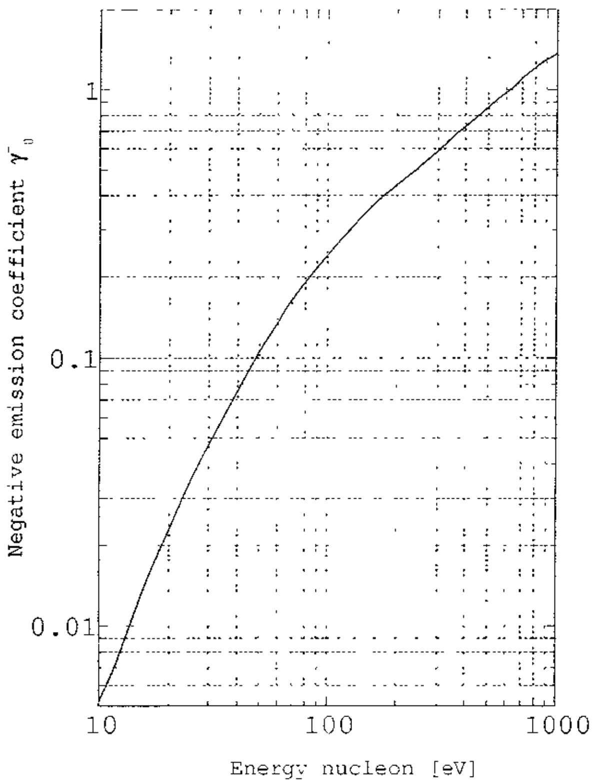

Fig.2. Calibration curve of Cu-Be atom-negative particle converter for hydrogen atoms (from [8]).

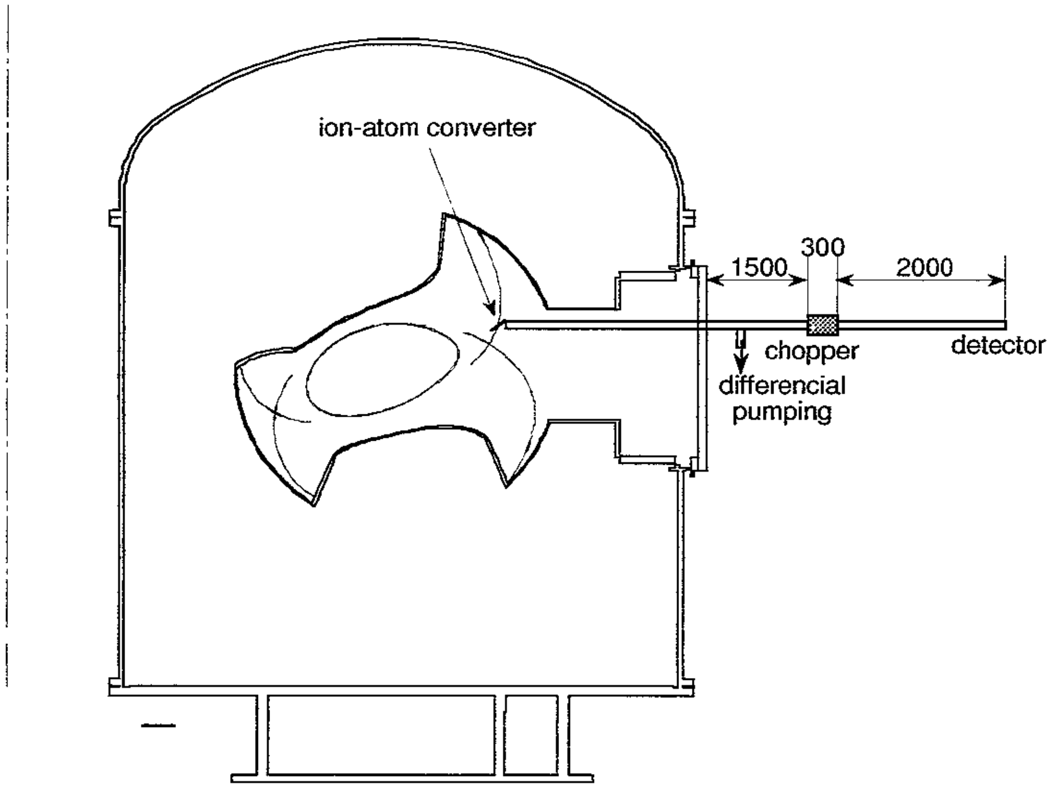

Fig.3. Scheme of disposition of equipment for measuring the flux of reflected atoms.

Appendix 1

PROPOSAL ON THEORETICAL AND EXPERIMENTAL PREPARATION TO PROVIDING MEASUREMENTS OF REFLECTED PARTICLES ON LHD

There are several critical points in the method of divertor plasma investigation based on measuring characteristics of the reflected atoms flux, using both CX atom analyzer and spectrometer for analyzing the H alpha line. Some of these points can be lighted by providing the special theoretical (computational) and experimental works directed to the better understanding of the limitations on these methods utilization in concrete conditions of LHD machine operation.

Let us enumerate the most important questions which have to be answered at the stage of such diagnostics preparation.

Now-a-days there are not enough experimental data concerning the low energy hydrogen ions reflection from surfaces when the angle of incidence is not normal. It is not studied in detail the effect of roughness on the total reflected flux and on its angular distribution when ions are coming not along the surface normal. Only a few data are concerned with impurity effects on efficiency of particle reflection. And there are practically no information as for the influence of magnetic field inclination on the particle reflection. Without these data the inverted problem cannot be solved, i.e. the primary ion energy distribution cannot be calculated in a proper way using experimental data on parameters of reflected atom flux. Also, such data base is necessary for the better understanding of operation of any LHD divertor scheme.

At the same time, in NIFS there exists experimental base for providing the respective measurements concerning this subject. Besides, a great work on computer simulation and analysis of empirical formulas on particle reflection have been done by the group of Theory and Data Analysis Division.

Principally, useful information can be obtained on straight machines TPD-1 or TPD-2 if some modification of plasma-wall-interaction parts are possible. In particular, it is desired to improve the vacuum conditions and to undertake measures for decreasing plasma density. One possible way for decreasing density of plasma near the target is the extension of magnetic flux in front of the target, e.g., by switching off some magnetic field coils near this part of the machine. In addition, it will be useful to foresee the target heating to decrease (or fully exclude) the low Z materials deposition or trapping hydrogen atoms in the near surface layer.

The unique feature of both these devices is a very low ion temperature, and because of this there is a possibility to carry out the investigation effect of magnetic field lines inclination to the target surface on characteristics of reflected particles flux. The matter is that according to calculation [1], the incidence angle of ions in the T_i~0 approximation is a rather definite function of the magnetic field lines inclination angle.

With plasma density $\sim 2\times10^{11}/\mathrm{cm}^3$ and electron temperature ~10 eV the ion flux density to the target surface will be $\sim 0.5 n_e C_s \sim 4\times10^{17}/\mathrm{cm}^2\mathrm{s}$, and the total flux depending on surface area can be ≥

10^{18}/cm^2. The energy of ions hitting the target surface will be determined by the biasing potential, due to small T_i value. Thus, the correlation could be found between the angle of ion incidence and energy and angle distributions of reflected atoms. All data obtained in such a way can be compared with computer simulation results.

In addition, the roughness of the target can be easily controlled and changed without opening vacuum vessel if the gate valve is used, giving the possibility to obtain results concerning the influence of surface microrelief on reflected atoms flux.

The control of the material of surface target is probably more difficult because of deposition of impurities, even if the target temperature will be maintained high enough. But at any fixed regime of machine operation the surface composition will be saturated after rather short period of time and the deposit can be analyzed by known methods of surface analysis. Besides, in these modeling experiments the particle reflection coefficient value itself can serve as a measure of the surface purity and can be used for in situ controlling the conditions on the target surface when target is being heated.

[1] R.Chodura. Numerical analysis of plasma-wall interaction for an oblique magnetic field. - J. Nucl. Mater., 111-112 (1982) 420.

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