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COLLIMATOR TYPE MONOCHROMATOR AS A POSSIBLE IMPURITIES MONITOR FOR FUSION PLASMAS. PRELIMINARY TESTS ON THE TOKAMAK TM–1–MH*

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A collimator type monochromator has been tested for the first time as the impurity monitor on Tokomak. The possibility to use this type of monochromator in fusion devices is analysed and a monoslit device is proposed as a convenient monitor for impurities.

INTRODUCTION

In a number of experiments for the space research, due to the simplicity of the construction, a collimator type monochromator has been used [1]–[3], a concept first proposed by Bedo and Hinteregger. According to this concept, the incident and emergent lights are collimated by a number of grids, the only moving component being the planar grating, which can be rotated. The disadvantages of this system are: the small value of the solid angle viewing the light source and a medium resolution value of 5 Å reported by authors [1]. The main advantage of the system is the simplicity of the construction and of the mechanical movement

The resolution value of 5 Å is unfortunately not good enough for the monitoring of impurities in the Tokamak plasmas.

If we consider the resolution power for such a system, we can see the resolution is in fact equal with the resolution corresponding to only one slit. Indeed, because the adjacent slits are at large distances (in comparison with the wavelength), no interferences between adjoining lights will occur. Consequently, the illuminated surfaces of the grating, from the point of view of the resolution power, will be equal with one slit width, multiplied by grating lines density and the diffraction spectrum order, but not with all illuminated surface of the grating.

At the same time for a better resolution, a more precise angle definition of the incident and emergent lights is necessary, i.e., the slit width must be as small as possible, a requirement which will give an opposite effect, respectively the worsening of the resolution power due to the decrease of the illuminated surface of grating.

The grating equation is:

$$\pm m\lambda = d(\sin\alpha + \sin\beta) \tag{1}$$

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where m is the spectrum order, d is the grating constant, α and β are respectively the incidence and the reflection angles of light.

The instrumental error $\Delta\lambda$ (the minimum wavelength separation) due to the error in the definition of the light direction by the end slits of the collimator (see fig. 1) will be according to eq.(1):

$$m\Delta\lambda = d(\Delta\alpha \cos\alpha + \Delta\beta\cos\beta) \quad (2)$$

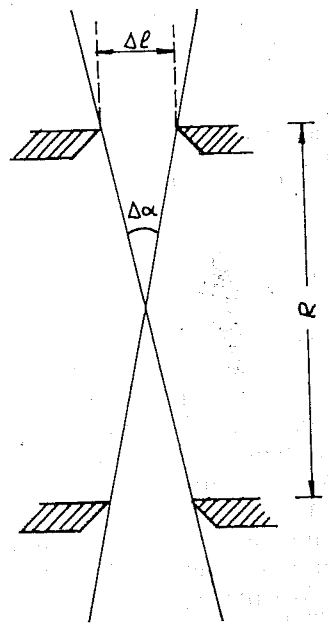

Fig. 1. — The collimator geometrical arrangement. $\Delta\alpha$ — acceptance angle of the monochromator, R — distance between slits, l — the slit

Assuming: $\alpha = \beta$, relation (2) becomes:

$$m\Delta\lambda = 2d\Delta\alpha\cos\alpha \quad (3)$$

where $\Delta\alpha$ is shown in Fig. 1.

Using eqs. (1) and (3) we obtain the relative error in wavelength:

$$\frac{\Delta\lambda}{\lambda} = \text{ctg}\ \alpha \cdot \Delta\alpha \quad (4)$$

If the slit width is Δl and the collimator length R, the value of $\Delta\alpha$ is:

$$\Delta\alpha = \frac{2\Delta l}{R} \quad (5)$$

and the relative error in wavelength due to the slits width will be:

$$\frac{\Delta\lambda}{\lambda} = 2\text{ctg}\alpha\frac{\Delta l}{R} \quad (6)$$

The minimum wavelength separation $\Delta\lambda$ due to the finite value of the resolution power of the grating is given by the relation:

$$\Delta\lambda = \frac{1}{mN}\cdot\lambda \quad (7)$$

where m is the spectrum order and N is the number of lines on the grating which are illuminated by the incident light coming through one slit. If

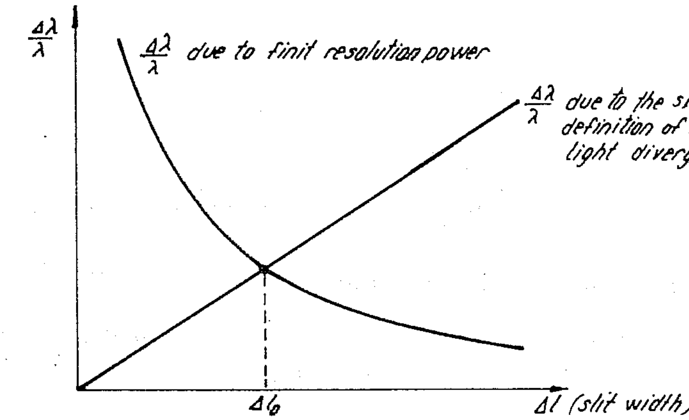

Fig. 2. — The resolution power versus slit width.

α is the incidence angle of the light, $\frac{1}{d}$ is the number of trating's lines per mm and Δl is the slit width, N will be (neglecting the distance between the end slit of the collimator and the grating):

$$N = \frac{1}{d}\cdot\frac{l}{\cos\alpha} \quad (8)$$

From relations (7) and (8), we finally obtain:

$$\frac{\lambda\Delta}{\lambda} = \frac{\cos\alpha}{m\left(\frac{1}{d}\Delta l\right)} \quad (9)$$

If we represent graphically $\frac{\Delta\lambda}{\lambda}$ versus Δl using equation (6) and separately equation (9), we will obtain a crossing point of the curves at Δl_0 (see Fig. 2). The value from equations (6) and (9) is:

$$\Delta l_0 = \left(\frac{(\sin\alpha\cdot R}{m\frac{1}{d}}\right)^{1/2} \quad (10)$$

For $\Delta l > \Delta l_0$, the value of $\frac{\Delta\lambda}{\lambda}$ is controlled only by the error in incidence angle definition and for $\Delta l < \Delta l_0$ by the level of illumination of the grating surface.

From the analysis of the above obtained results, the following conclusions can be inferred:

1. For the collimator type of monochromator $\frac{\lambda\Delta}{\lambda}$ decreases for larger incidence angle and reflection angle of the light.

2. For $\Delta l > \Delta l_0$, the value of $\frac{\Delta\lambda}{\lambda}$ can be maintained at the same value (i.e. constant) if $\frac{\Delta l}{R}$ is kept constant. That means that for large R it is possible to use large slit width Δl, fulfiling by far the condition $\Delta l > \Delta l_0$.

If $\frac{1}{d}$ is high enough, Δl_0 is small and practically we will always have $\Delta l > \Delta l_0$. In table 1, a few numerical values are given using eq. (10), for Δl_0, for various values of R and $\frac{1}{d}$. For simplicity $\sin\alpha$ in eq. (10) has been replaced by unity and we considered $m = 1$.

Table 1

Magnitudes of Δl_0 (mm) for various values of $R(m)$ and $\frac{1}{d}$ (mm^{-1})

R \ $\frac{1}{d}$	1 000	2 000	4 000
1	1	0.71	0.5
5	2.24	1.58	1.12
10	3.16	2.24	1.58

In table 2 are given the values of the error $\Delta\lambda$(Å) of the wavelength values, for $\lambda = 300$ Å, 500 Å and 1000 Å, for various values of Δl. For $\mathrm{ctg}\,\alpha$ a value of 0.4 has been considered (corresponding to $\alpha = 68°$).

Table 2

Computed values of $\Delta\lambda$(Å) for $\mathrm{ctg}\,\alpha = 0.4$, $R = 5$ m, Δl(mm) and λ(Å).

λ \ Δl	1	2	5	10
300	0.05	0.1	0.25	0.5
500	0.08	0.16	0.4	0.8
1000	0.16	0.32	0.8	1.6
$\Delta\alpha$	0.7′	1.4′	3.5′	7.0′

Of course these values are theoretical. The experimental errors will be surely much higher especially due to the mechanical errors in the grating movement.

A complete analysis of the errors will be given for a collimator type monochromator in a separate paper [4].

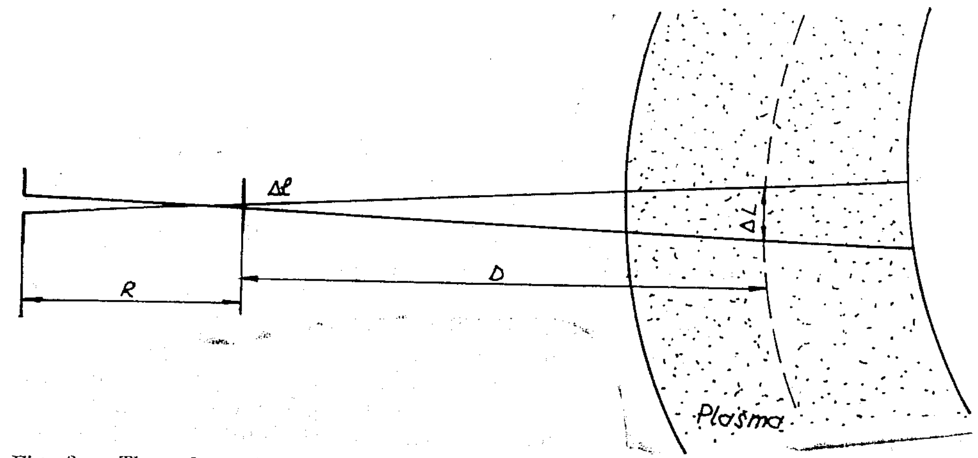

Fig. 3. — The schematic arrangement of the measuring system for the Tokamak device. D — the distance between the first slit of the monochromator and the plasma center ($D \sim 1$ m).

One of the most important problems is the intensity of the signal received by the photon detector. Instead of computing this value, we will compare the signal obtained in case of collimator type monochromator with that obtained with a usual VUV concave grating monochromator. In the case of this former monochromator in order to increase the signal level, a high volume of plasma is viewed due to the conveniently high solid angle of the monochromator-plasma system. Usually the photons are received from a plasma volume exceeding 10 cm^3.

In these conditions one of the questions is:

"Can a collimator type monochromator ensure enough signal at the detector to be able to detect a comparable level of impurities in a Tokamak plasma as a classical spectrometer?"

Before answering this question we must point out one of the conditions of use of VUV diagnostics in the future fusion reactors. Because of the size of the torus, of the blanket and of the shieldings, the distance between plasma and the VUV spectrometer must exceed 5 meters.

In these conditions even for the usual VUV spectrometer with concave grating, the solid angle will be smaller than in the case of the experiments on laboratory tokamaks.

Let us consider now the signal received by the collimator type monochromator. Instead of computing the solid angle we will compare directly the plasma volume viewed in both cases — collimator type monochromator and classical spectrometer.

In Fig. 3 is shown schematically the arrangement of the measuring system.

If D is the distance between the entrance slit of the collimator type monochromator and the center of the plasma, the value of ΔL — the average length of the toroidal plasma viewed by the collimator — is :

$$\Delta L = \frac{\frac{R}{2} + D}{\frac{R}{2}} \cdot \Delta l \qquad (11)$$

For example for $\Delta l = 5$ mm, $D = 5$ m, $R = 5$ m, we receive $\Delta L = 30$ mm according to eq. (11). This value has nearly the order of magnitude as the size viewed by classical VUV-monochromator. Consequently, the ratio between the plasma volumes viewed by collimator type and classical type monochromators is expected to be 10^{-1} —10^{-2}.

However, we may expect some increase of this ratio, taking into account the solid angle of viewing the slit by an elementary plasma volume ΔV of the Tokamak plasma. This solid angle due to the large width (of the order of mm) of the slit, will be much higher in the case of collimator type monochromator than in the case of usual VUV monochromator. In the evaluation of this solid angle, the surface of the end slit of the incident collimator must be considered.

In these conditions, we may conclude that for large tokamaks, especially for fusion reactors, in order to survey fusion plasma via v.u.v. diagnostics, the collimator type monochromator might be more suitable than any other type of VUV spectrometer.

The following advantages of the collimator type monochromator must be pointed out :

— for constant $\frac{1}{R}$ ratio, the monochromator can be mounted as far as imposed by the sizes of the blanket and shieldings of the fusion reactor. The light intensity decreases with the increase of the plasma-grating distance (which permits higher values for R — collimator length) being slower than for the other type spectrometers due to the possibility to increase the collimator slit width with R, keeping $\Delta\alpha$ constant.

— the window in the Tokamak first wall and size of the vacuum tubing, provided for the light coming out from the fusion plasma towards the collimator type monochromator, can be smaller than that for other type of VUV spectrometers. This fact is important from the point of view of the fusion reactor construction. This possibility is due to the fact that the light intensity depends simultaneously on the solid viewing angle of the plasma from the collimator and the solid viewing angle of the slit from an elementary volume ΔV of fusion plasma. In the collimator type monochromator this last solid angle, due to the large value of Δl, has a quite important contribution, which partly compensates the smallness of the above mentioned first solid angle — which permits a smaller size of the vacuum tubing between Tokamak and monochromator.

— at large plasma-grating distances a *mono-slit* collimator can be used due to the fact that Δl is quite large in this case, and the corresponding illuminated surface of the planar grating at $\alpha \geqslant 70°$ is high enough being of the order of 10^2—10^3 cm^2.

In this case the construction of the collimator type monochromator is more simple.

That means that with the increase of the size and complexity of Tokamak, the construction of the VUV collimator type monochromators becomes easier.

Due to the construction simplicity, such type of monochromators can be used as a usual monitoring equipment for fusion reactors, various possible solutions increasing the facilities provided by such system like simultaneous temporal and space control of a given plasma impurity using electron multiplier plates as VUV photon detectors at the exit slit of emergent light collimator.

COLLIMATOR TYPE TEST MONOCHROMATOR FOR VUV

A VUV collimator type monochromator has been projected and built [5]—[6] in order to check the compatibility of such devices with Tokamak and the possibilities to obtain data on plasma impurities using a collimator type monochromator.

Taking into account the above mentioned objectives of the programme, the size of this first collimator type monochromator for fusion plasma has been chosen to be not very large. Consequently, the length of the collimators has been taken in the project to be 0.5 m. Because of the reduced length R of the collimator, the slit width cannot be very large. The selected value for the slit width was 1 mm.

In order to increase the light flux, a number of multislit grids have been used on both incident and emergent light collimators. The grids number were 8 for each collimator, every grid being mounted on stainless steel holder arms.

The collimator of the emergent light can be moved around the grating axis. Due to this rotation possibility, the angle between incident and emergent lights direction can be changed between 110° and 140°.

The grating is a planar one, with 1800 lines/mm, produced by Baush and Lomb, with an effective surface of 30 mm × 30 mm. The resolution power is $R = \frac{\lambda}{\Delta\lambda} = m\bar{N}$, where m is the order of the spectra and $\bar{N}$ the number of grating lines illuminated by the incident light.

For an illuminated surface of grating of 0.1 mm width, the resolution power will be $\frac{\lambda}{\Delta\lambda} = 180$.

For $\lambda = 1000$ Å, $\Delta\lambda$ will be > 5 Å.

The dependence of the selected wavelength on the monochromator and grating angle is practically linear for a constant value of $\alpha + \beta$, where α is the incident light angle and β is the emergent light angle, the value $\alpha + \beta$ corresponding to the angle between the axes of collimators

The equation for grating permits to compute (for a given value of $\alpha + \beta = 110°$) the angular dispersion,

$m = 1$	110	Å/degree
$m = 2$	54.7	Å/degree
$m = 3$	36	Å/degree

where the angle values correspond to the grating rotation angle.

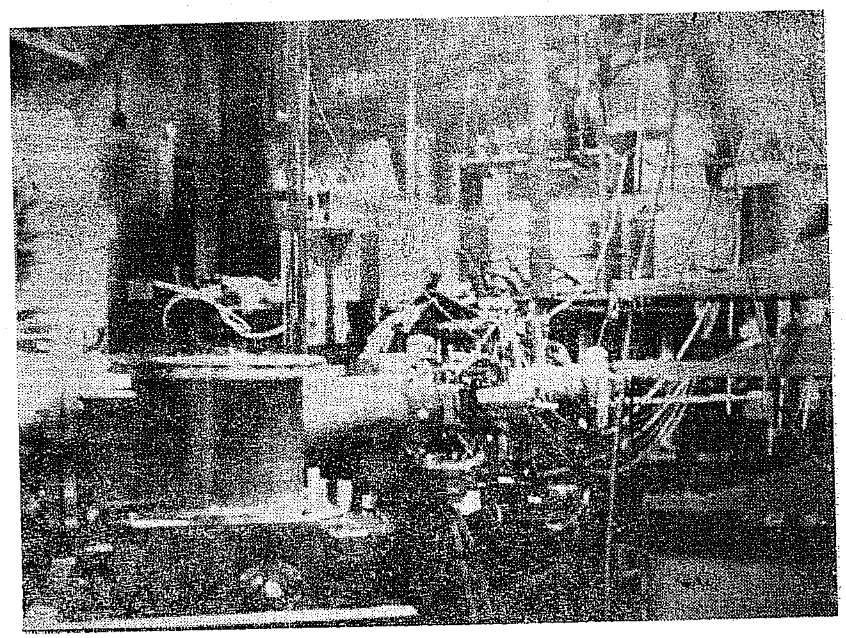

Fig. 4. — General view of the installation.
The grating is contained in the center of the vacuum vessel appearing in the front.
The collimator of the incident light is contained in the cylinder outgoing backward from the above mentioned vessel.

The mechanical demultiplication system insures a displacement of a measurable division on the mechanical scale rotation of the grating of 1/200 from one degree.

The crossing point of the axis of the collimators is geometrically on the axis of rotation of the planar grating.

The wavelength can be scanned by simple rotation of the plane grating, parallel to the rullings, around the axis which is geometrically in the surface of the grating.

All construction is of stainless steel and mounted in a stainless steel vacuum vessel.

The VUV photons are detected using an EMI type open ended electron multiplier, mounted inside of vacuum vessel, at the exit of the collimator of the emergent light.

The function of the VUV collimator type monochromator was tested on the TM—1—MH Tokamak (Institute of Plasma Physics, Prague) [8].

The monochromator has registered the VUV radiation from the central chord of the plasma column. The vacuum vessel of the monochromator was pumped differentially by a small pumping unit (~100 l/s). The vacuum valve allowed to detach the monochromator from the Tokamak discharge chamber; a general view of the installation is seen in Fig. 4.

The cylinder in front of the photo is a part of the vacuum vessel and contains the grating in the center.

The metallic cylinder outgoing from the above mentioned vessel toward the backside contains the collimator for the incident light.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Because the Tokamak TM—1—MH is working at a low current regime ($I_p = 14$ kA, $B_T = 1.3$ T) as main impurities in the plasma, low ionized states of oxygen and carbon are present. Consequently, we may expect to detect the radiation or the two, three or four time ionized atoms of oxygen or carbon. The typical time evolution of the macroscopic plasma parameters is shown in Fig. 5.

The main aim of the present experiment was to test the collimator type monochromator as a plasma impurity detector in order to obtain a

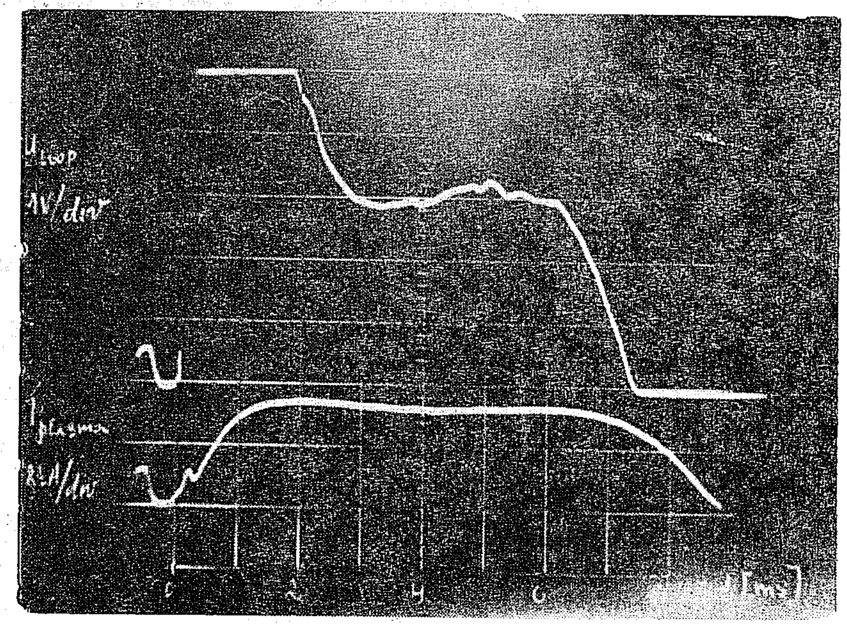

Fig. 5. — The loop voltage (upper trace) and the plasma current (lower trace) characteristic time evolution in the Tokamak TM—1—MH discharge
Sensitivity: upper trace: 1 V/div.
lower trace: 8 kA/div.
time scale: 1 ms/div.

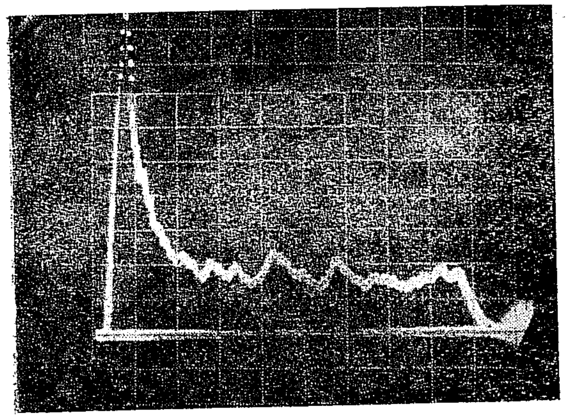

Fig. 6. — The time evolution of the Lyman α line intensity. Time scale : 1 ms/div.

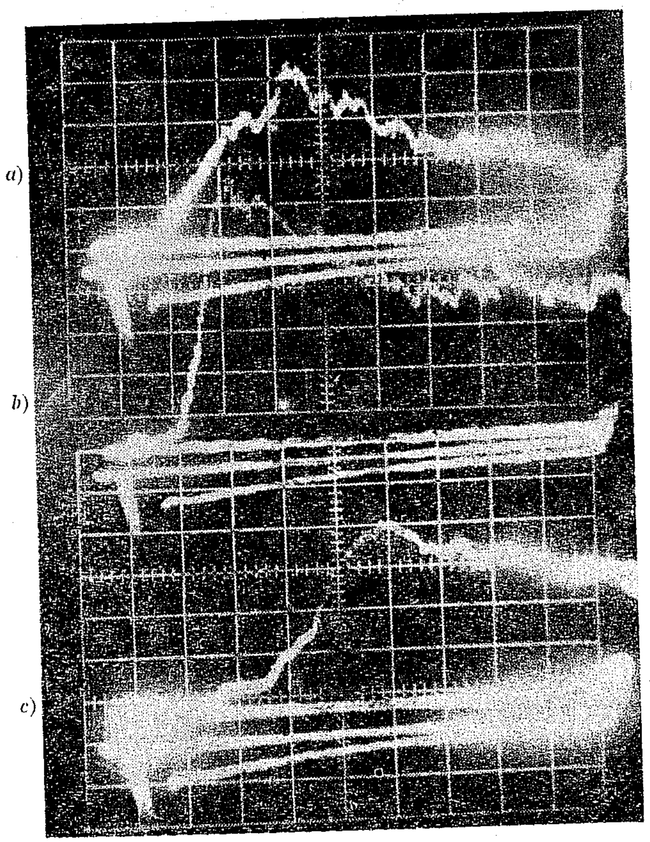

Fig. 7. — The typical time-evolution of some impurity line intensities. Time scale 0.25 ms/div. The time shifts of the maxima for the lines of different impurities are clearly seen.

sufficiently high signal at the photon detector ; the resolution of the monochromator was not chosen very high.

In Fig. 6, the time evolution of the most intensive line is presented. The curve has maxima soon after the beginning of the discharge ($\sim$0.5ms). By comparison with the results of visible range spectroscopy and with data given by other authors [9], we identified this line as Lyα ($\lambda =$ $= 1218$ Å).

As expected, Lyα radiation appears from the very beginning of the Tokamak discharge, due to the excitation of the neutral hydrogen atoms. A fast decrease of the Lyα radiation follows because of the decrease of the neutral hydrogen atoms density.

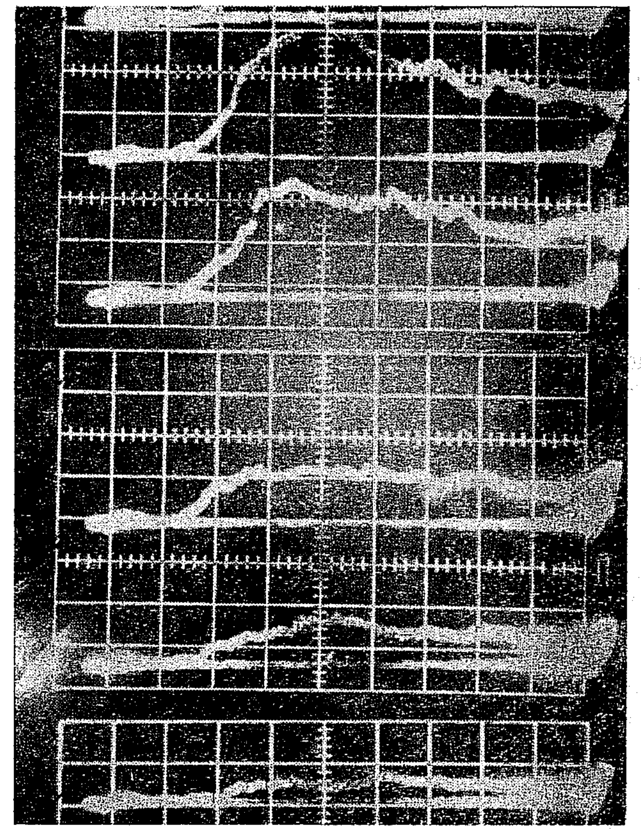

Fig. 8. — The time evolution of an impurity line ($\lambda \sim 900$ Å) for the grating angles varying from shot-to-shot. The corresponding step of the wavelength is approximately 5 Å.

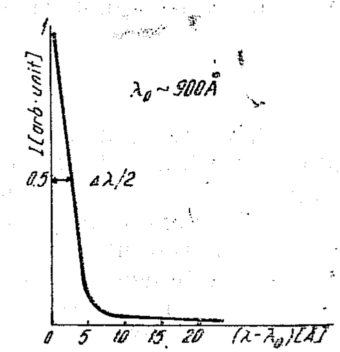

Fig. 9. — The profile of the impurity line ($\lambda \sim 900$ Å).

The maximum values of the radiation of multiple ionized ions of impurities appear later than Lyα maximum. It is due to the temporal electron temperature growth during the initial stage of the Tokamak discharge. Such a behaviour is demonstrated in Fig. 7. The maximum of the signal in Fig. 7 c appears at 1.25 ms in comparison with the maximum of hydrogen line ($\sim$0.5 ms).

Line identification can be performed using the linear dependence of the wavelength on the rotational angle of the grating. The Lyman α line can be used as a reference one. Using dispersion value (see page 10), the wavelength can be assigned to the experimentally observed lines. Using this method in the range of wavelength 500–1218 Å, C^{III} line at 703.8 Å has been tentatively identified.

The value of the resolving power of the collimator type monochromator was experimentally verified by the measurement of a certain line profile (line was not identified exactly) under knowledge that this line is sufficiently narrow. Fig. 8 shows the time evolution of a line intensity for several positions of the grating (central wavelength about 900 Å); Fig. 9 gives the corresponding profile reconstructed at the peak intensity (~1 ms after the beginning of the discharge). It may be seen that the halfwidth observed is $\simeq 6$ Å, which is really much larger than the maximum of Doppler or Stark broadening in the conditions of the TM–1–MH Tokamak plasma (from values $n_e \simeq 2 \cdot 10^{13}$ cm^{-3} and $T_i \simeq 30-50$ eV it follows that Doppler or Stark broadening for carbon and oxygen lines is not larger than 0.1 Å). Therefore, the profile shown in Fig. 9 gives us the apparatus function.

The measured value of the resolution power $\left(\frac{\lambda}{\Delta\lambda}\right)_{exp} \simeq 150$ is so in good agreement with the theoretical estimation $\left(\frac{\lambda}{\Delta\lambda}\right)_{theor} = 180$.

The stray light in the monochromator was negligible in comparison with the actual level of signals. This was checked with grating arranged in such position that no direct light from grating can arrive at the detector. The measured signal was negligible in this case.

CONCLUSIONS

The preliminary results of testing the collimator type monochromator on TM–1–MH Tokamak have proved the potential possibility of the use of this device for fusion plasma survey.

The next important step in the development of this programme is to test the resolution power increase for a monochromator with a *monoslit* collimator longer than 5 m.

Further studies should clarify experimentally the influence of some construction details (such as the errors in the parallelism of grating rules and rotation axis, that in the position of the crossing point of the collimator axis with grating surface, etc.) on the resolution power of the collimator type monochromator.

Absolute calibration and sensitivity evaluation are necessary too.

The above mentioned programme is now in progress, joint research of the authors of the present paper being planned at the end of this year on the monoslit collimator type monochromator in the final stage of construction.

All the tests are planned to be done with an especially bright VUV light source mounted without any envelope in the vacuum tubing for incident light collimator.

Due to the length of the collimator, a number of differential pumping systems will be provided for the vacuum tubing between the light source and the grating.

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