INVESTIGATION OF THE HOLLOW BEAM STRUCTURE ON OPTICAL TRANSITION RADIATON

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In this paper we represent the experimental data on measurement of the transverse current density distribution of the annular beam with the sub-millimeter wall thickness. A digital photo camera was used to increase sensibility and possibility of image processing.

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1. INTRODUCTION

One of directions in development of powerful RF sources is the development of cluster klystrons with the annular structure of a beam [1]. Experimental studying both stability and formation of such beams requires a spatial resolution of measurement of their structure less than 0.01 mm. This requirement, at a beam power density of about 10^{10} W/m^2, makes usage of a conventional probe or scintillator techniques rather complicated. Optical transient radiation (OTR) from thick cooled targets is an alternative technique in this case. However, till now, OTR diagnostics was utilized, basically, for relativistic beams at small thermal loads of the target. Application of this technique for diagnostics of low energy electron beams that began recently [2] still requires extensive researches.

The present work describes features of studying the structure of a dense annular beam with OTR from metal targets at the electron energy ≤50 keV. Possibility of OTR registration in this case is limited by the two main factors. Firstly, a solenoid, which is needed to transport the beam, limits an aperture of the optical system. Secondly, because of low energy of particles all the beam power is dissipated in a thin surface leer of a target that causes its thermal erosion. Necessity of carrying out researches of an transversal structure of an annular beam arises in the context of development of a X-band cluster klystron with an anode voltage of 50 kV [3].

2. THEORY

It is convenient to analyse the transversal structure of a beam in the plane, which is perpendicular to the direction of beam propagation. Therefore orientation of a target was chosen perpendicularly to the beam. Further, beams with a longitudinal energy, which essentially exceeds transverse one, will be considered. In this case it is possible to take into account only normal incident angle of electrons on the target.

The spectral density of the radiation energy of a charge e crossing on a normal a metal boundary is given by an expression [4]:

$$\frac{d^2W}{d\Omega\, d\omega} = \frac{e^2}{\pi^2 c}\left[\frac{\beta\sin\theta}{1-(\beta\cos\theta)^2}\cdot\frac{\varepsilon^{1/2}\cos\theta}{\varepsilon^{1/2}\cos\theta+1}\right]^2 , \qquad (1)$$

where $\beta = v/c$ - relative velocity of an electron, θ - observation angle, $\delta\Omega$ - solid angle in the direction of observation, ω - circular frequency of radiated waves, ε - relative dielectric permeability of the metal.

Brightness of the beam radiation with the pulse current density j is defined as:

$$B(\theta) = \frac{ej}{\pi^2 c}\left[\frac{\beta\sin\theta}{1-(\beta\cos\theta)^2}\cdot\frac{\varepsilon^{1/2}\cos\theta}{\varepsilon^{1/2}\cos\theta+1}\right]^2 \Delta\omega , \qquad (2)$$

where $\Delta\omega = 2.018\cdot10^{15}\,Hz$ is the visible part of the spectrum.

Proceeding from the above-mentioned goal of a practical application of the OTR technique, we shall consider the radiation of an annular beam with an energy of 50 keV, external radius of 4 mm, thickness of a wall of 1 mm and a current of 10 A (j = 45 A/cm^2). For this case dependence (2) is shown in Fig. 1.

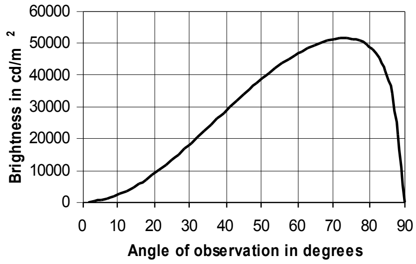

Fig.1. Radiation brightness versus the angle of observation

This dependence can be used for calculation of an exposition at photographing. However, at visual research of pulse beams, it requires the correction. It is connected with inertia of the visual sensation which disappears gradually, during a relaxation time $\tau_f = 0.05 - 0.2$ s, depending on the brightness. At the period of pulse repetition $T << \tau_f$, the brightness being observed not essentially differs from its average value [5]. It can be shown that for our experimental conditions (pulse duration of $4\cdot10^{-6}$ s and pulse repetition period of 0.1 s) the brightness being observed is $1.38\cdot10^{-4}$ time of that from Eq. (2).

3. ANALYSIS OF OPTICAL SYSTEM

As follows from Fig.1, the maximum of radiation is at $\theta_m = 73°$. Capture of such an angle by an optical system, without significant aberrations is impossible [3]. Therefore, an optical system directed under the angle $\theta \approx \theta_m$ usually sees only a limited area around of the maximum of radiation. Such a scheme is given in Fig.2. In this case the position of the target is inclined relatively to the axis of the optical system that causes known

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difficulties of transfer of the three-dimensional image that is connected with the depth of focus and perspective distortions. Therefore a small angle θ is preferable to limit such difficulties.

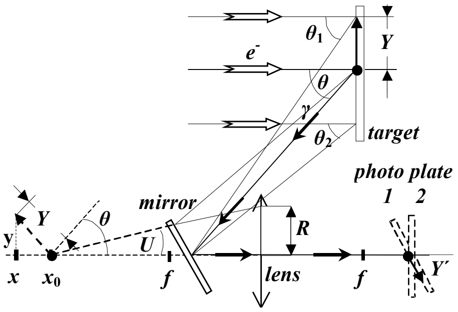

Fig. 2. The scheme of OTR registration

Using Fig.2 it is possible to derive a condition of sharpness of the image:

$$\mathrm{tg(U)}\ \text{J}\ \frac{1}{2\mathrm{tg}(\theta\ )}\text{ч}\frac{\Delta\,Y}{Y}, \tag{5}$$

where Y is the beam radius on the target, $\Delta\,Y$ is the needed linear resolution.

It is possible to obtain a high resolution at high θ only at a small aperture angle U as it follows from (5). For example, at $\Delta Y/Y = 0.01$ and $\theta_0 = 30°$ the aperture angle U is equal to 0.009°. The specified limitation of the optical power of the system can be removed by the arrangement of a registering photoplate in a plane of the image 1, as it is shown in Fig.2. To estimate a gain in sensitivity of measurements in this case, we shall define the luminosity of the images in planes 1 and 2, taking into account (5).

By definition:

$$E\{M,U,\theta\ \} = \frac{1}{M}\int_0^U\int_0^{2\pi} B(u,\theta\ ,\varphi\ )\sin(u)d\varphi\ du\ ,$$

where u - aperture angle of the ray, φ - azimuth of the ray, M - magnification of the subject area. If the optical axis coincides with the direction of observation then from (2) $B(u,\theta,\varphi) = B(\zeta)$ where

$\cos(\zeta) = \cos(u)\cos(\theta) + \cos(\varphi)\sin(u)\sin(\theta)$.

It yields in plane 1:

$$E_1 = E\{K^2(1+K^2\tan^2(\theta))^{1/2}\cos(\theta), AK/(1+K), \theta\}, \tag{6}$$

where $A = R/f$ is the relative aperture of an objective; and in plane 2:

$$E_2 = E\{K^2\cos(\theta), (\Delta Y/Y)/2\tan(\theta), \theta\}. \tag{7}$$

The relation of E_1/E_2 at $K = 3$ and $A = 1/5.6$ is given in Fig.3. Let us analyse the relationship connecting A, K and U. The aperture angle U in expression (6) has the limitation caused by non-uniform brightness of the target which is connected with different angles of observation θ_1, θ, θ_2 of various points on the target (see Fig.2). Let d denote a distance from an objective to the target then:

$$\mathrm{t}g(\theta\,{}^1_2) = \mathrm{t}g(\theta\ ) \pm \frac{Y}{d\cos(\theta\ )}. \tag{8}$$

From (8) it is easy to see, that a difference $\theta_1 - \theta_2 \sim 1/\theta$ reaches the minimum value of $2Y/d$ at $\theta = 0$. From Eq. (8) and Eq. (2) it is possible to show that $\Delta B/B < 0.1$ at $d > 300$ mm for $Y = 5$mm and $\theta = 30°$. Using relations $AK/(K+1) = R/d$ and $R \leq D/4$, where D is a diameter of a vacuum chamber, which limits transversal dimension of the optical system, we shall obtain:

$$A \leq D(K+1)/(4Kd). \tag{9}$$

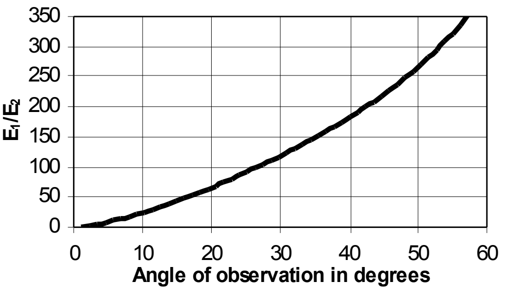

Fig. 3. The simulated relation of the image luminosities in planes 1 and 2 (see Fig.2)

The depth of focus at visual researches does not limit A, due to focusing. At equivalent pupil magnification [5] the luminosity of the image on a retina of the eye, is determined in this case from the formula:

$$E_e = {}_{\lim K\to 0}\,E\{K^2\cos(\theta), \delta K/2f_e(1+K), \theta\}, \tag{10}$$

where δ is a diameter of the pupil, $f_e = 17$ mm is the eye focal length [3].

The reason of perspective distortion is the dependence $K(x) = f/x$. Its value is estimated as:

$$\frac{\Delta\,K}{K_0} = \frac{Y\sin\theta}{x_0} \tag{11}$$

Here $K_0 = K(x_0)$, $\Delta K = K(x) - K(x_0)$. For technical reasons: $f \geq 4R$ [3], and $R \leq 0.25D$. Therefore,

$$K_0\ \text{J}\ \frac{\Delta\,K}{K_0}\text{ч}\frac{D}{Y\sin\theta}, \tag{12}$$

It is necessary to note that the value D is less than the diameter of the solenoid.

As follows from (8) and (11), the reduction of an error in the transfer of luminosity and the form of cross section of the beam requires reduction of the observation angle that results in reduction of brightness and, hence, a current measurement threshold of the beam. From (6), (12) one can see, that small optical magnifications are necessary for reduction of distortions of the image and increase of its luminosity.

4. EXPERIMENTAL SETUP AND RESULTS

The special device (see Fig.4) was created for the visual observation of transversal distribution of electron beam generated by the magnetron gun [3] with the error $\Delta Y = 0.1$ mm. Diameter of the vacuum chamber D was 140 mm. The optical aperture of the device was limited with the radius of the output optical window $R_w = 22$ mm. The distance between the target and the objective d in experiments was 548 mm. As a basic element of the optical system, the objective with the resolution in the focal plane of 1/30 mm, $A = 1/9$ and $f = 105$ mm, an ocular - $f_{oc} = 17.8$ mm and $\theta = 30$ were chosen. Simulated values were the following: $K = 0.28$, $\Delta Y = \Delta Y'/K = 0.12$ mm, $\Delta Y/Y = 0.024$, subjective magnification $G = f/f_{oc} = 5.9$, diameter of the output iris $\delta = 2R/G = 4$ mm, $\mathrm{tg}(U) = 23.3/548 = 0.024$.

At a given D, from Eq. (8) it is supposed that $A = ½$. It is much more than the chosen $A = 1/9$. This circumstance is caused by additional requirements to the experiment.

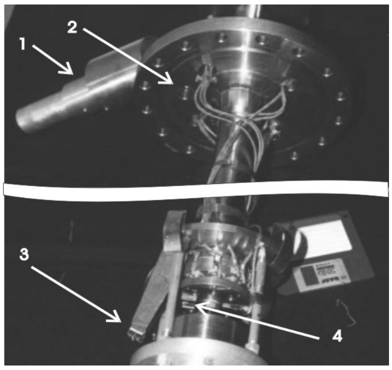

Fig.4. Experimental setup: 1 - block of objective, ocular and mirror, 2 - output window, 3 - mirror, 4 - target

Reduction of A does not result, however in he loss of luminosity of the retina, and only limits the allowable subjective magnification [5]. Such system, is inefficient at photographing, due to the loss of light exposure $E \sim A^2$. The condition (5) was satisfied therefore the focusing was not required. As follows from (10), $\Delta K/K_0 = 0.15$, i.e. exceeds the given accuracy 0.1 because of perspective distortions. As $d > 300$ mm, the error in luminosity of a target is less than 10%. To linear resolution $\Delta Y = 0.12$ mm at $G = 5.9$ the angle of view 2.7′ corresponds, that is higher then the eye resolution, but it is below than the recommended [5] value 4′. Such choice of G, below recommended value, explains aspiration to preservation of subjective brightness of the image.

Calculation under formula (8) at specified $\delta = 4$ mm gives the luminosity on the retina $E_e = 894.77$ lx. With taking into account (4) the subjective luminosity B (T, τ) = 0.12 lx, that makes 30 % of a normal light exposure of the retina, corresponding to the angular resolution of the eye in 1′ [5].

The experiment has shown, that observation of the beam with a current 10 A does not cause difficulties. Appreciable lacks of luminosity of the image and the resolution is sensitive at currents of about 2 A and energy of 25 keV. It corresponds to $j = 9$ A/cm^2 and power density $2.2 \cdot 10^5$ W/cm^2. The simulated light exposure of the retina makes thus of 5% from normal. The specified parameters correspond to the sensitivity of the device developed.

As have shown researches of a titanic and silver target, the beam thus forms the autograph with the sizes of a surface roughness 0.02…0.05 mm. The view of such a beam in the ocular is shown in Fig.5.

This image was obtained by the digital camera and numerically corrected on the angle $\theta = 30^\circ$. The elliptic form of the cross section is caused by conditions of the beam formation [3].

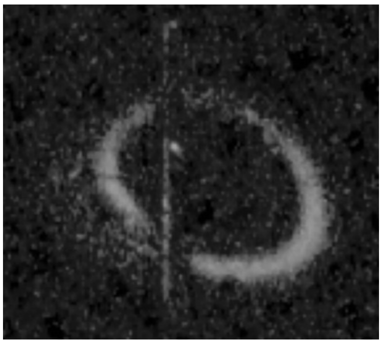

Fig.5. OTR from the target at a threshold of sensitivity

5. DISCUSSION

Sensitivity of the installation developed is limited by the aperture of the eye, therefore is limiting for visual researches. The detailed description of the image structure requires brightness on the order greater than a detection threshold of the luminescence. Therefore for OTR - diagnostics at electron energy up to 50 keV it is necessary to count the current density of about 45 A/cm^2.

The spatial resolution thus is limited by the diameter of the solenoid (see (11)), and in real conditions of the free space for accommodation of optical system which can be much less. The obtained resolution of 0.12 mm, can be improved, as follow from technical possibilities of solenoids, up to 0.03 mm. The threshold power density $2.2 \cdot 10^5$ W/cm^2, exceeds a limit $\sim 1 \cdot 10^5$ W/cm^2 on evaporation. Therefore, finally, the resolution is limited by the sizes of surface protrusions 0.02…0.05 mm. As a probable decision, of interest is a graphite target [2] though carry of carbon to vacuum, in this case, requires studying.

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ИССЛЕДОВАНИЕ СТРУКТУРЫ КОЛЬЦЕВОГО ПУЧКА ПО ПЕРЕХОДНОМУ ОПТИЧЕСКОМУ ИЗЛУЧЕНИЮ

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Представлены основные характеристики разработанной системы визуализации и экспериментальные данные по измерению поперечного распределения плотности трубчатого пучка с субмиллиметровой толщиной стенки. Для повышения чувствительности и возможности коррекции изображения пучка используется цифровая фотокамера.

ДОСЛІДЖЕННЯ СТРУКТУРИ КІЛЬЦЕВОГО ПУЧКА ПО ПЕРЕХІДНОМУ ОПТИЧНОМУ ВИПРОМІНЮВАННЮ

М.І. Айзацький, В.Ф. Жигло, В.А. Кушнир, В.В. Митроченко, А.Н. Опанасенко

Представлено основні характеристики розробленої системи візуалізації і експериментальні дані по вимірі поперечного розподілу густини трубчастого пучка із субміліметровою товщиною стінки. Для підвищення чутливості і можливості корекції зображення пучка використовується цифрова фотокамера.