INVESTIGATION OF THE HOLLOW BEAM STRUCTURE ON OPTICAL TRANSITION RADIATON

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The features of studying the structure of a dense annular beam with OTR from metal targets at electron energy ≤ 50 keV are described. The image of the cross section of the annular beam with sub-millimeter wall thickness is obtained.

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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 study of the stability and formation of such beams requires 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 alternative technique in this case. However, till now OTR diagnostics was utilized, basically, for relativistic beams under small thermal loads of targets. 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 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 the total power of the beam is dissipated in a thin surface layer of a target that causes its thermal erosion. Necessity of carrying out researches of transversal structure of an annular beam arose 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 analyze a 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.

Using the spectral density of the radiation energy of a charge e crossing a boundary of a metal on a normal [4], the OTR brightness emitted by the electron beam with the pulse current density j is defined as:

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

where $\beta = v/c$ is the relative velocity of an electron, θ is the observation angle, $\delta\Omega$ is the solid angle in the direction of observation, ω is the circular frequency of radiated waves, ε is the relative dielectric permeability of the metal, $\Delta\omega = 2.018\times10^{15}$ *Hz* is the visible part of a spectrum.

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

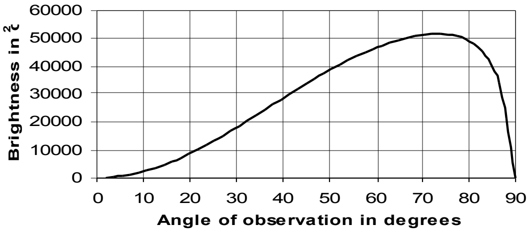

Fig.1. *The dependence of radiation brightness on the angle of observation*

This dependence can be used for calculation of an exposition at photographing. However, for the visual research of pulse beams, the correction is required. It is connected with the inertia of visual sensation which disappears gradually during a relaxation time τ_f = 0.05...0.2 s depending on the brightness. At the period of pulse repetition $T << \tau_f$, the brightness of observation $B(T, \tau)$ slightly differs from its average value [5]. It can be shown that for our experimental conditions (pulse duration of $4\cdot10^{-6}$ s and repetition period of 0.1 s) the brightness of observation is $1.38\cdot10^{-4}$ times of that value from (1).

3. ANALYSIS OF OPTICAL SYSTEM

As follows from Fig. 1, the maximum of radiation is at θ_m = 73°. Capture of such an angle by the optical system, without significant aberrations is impossible [5]. Therefore, the optical system directed at an angle $\theta \approx \theta_m$ usually sees only a limited area around of the maximum of radiation. Such a scheme is shown in Fig.2. In this case the position of the target is inclined relatively to the optical axis that causes known difficulties during transfer of the three-dimensional image because of a limited depth of focus and perspective distortions. Therefore, the small angle θ is preferable.

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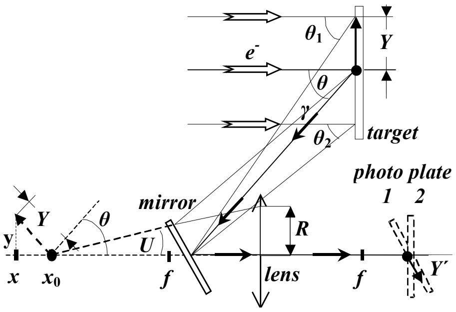


Fig. 2. *The scheme of registering OTR*

The condition of sharpness of the image is given:

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

where Y is the beam radius on the target, ΔY is the needed linear resolution, U is the aperture angle.

A high resolution can be obtained at a large θ only for small U as it follows from Eq. (2). For $\Delta Y/Y = 0.01$ and $\theta_0 = 30°$, U = 0.009°. This limitation of the system optical power can be removed by arrangement of a registering photoplate in the plane of the image 1, as it is shown in Fig. 2. To estimate a gain in sensitivity of measurements, we will define luminosity of the images in planes 1 and 2 taking into account (2) and definition:

$$E = \frac{1}{M}\int_0^U\int_0^{2\pi} B(u,\theta,\varphi)\sin(u)d\varphi\, du, \tag{3}$$

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

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

The relation of E_1/E_2 at $K = 3$ and $A = 1/5.6$ is given in Fig.3.

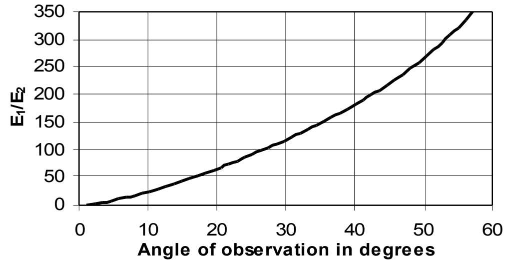


Fig.3. *The simulated relation of the image luminosities in planes 1 and 2 (see Fig.2)*

Let us analyze the relationship connecting *A, K* and *U*. The aperture angle *U* in Eq. (3) has the limitation caused by the non-uniform brightness of the target which is connected with the different angles of observation θ_1, θ, θ_2 of the various points on the target (see Fig.2). Let *d* denotes a distance from the objective to the target, then

$$\mathrm{tg}(\theta_2^1) = \mathrm{tg}(\theta) \pm \frac{Y}{d\cos(\theta)}. \tag{4}$$

From Eq. (4) and Eq. (1) it is possible to show that $\Delta B/B < 0.1$ at $d > 300$ mm for $Y = 5$mm and $\theta = 30$˚. Using the relations $AK/(K+1) = R/d$ and $R \leq D/4$, where D is the vacuum chamber diameter, which limits transversal dimension of the optical system, we obtain:

$$A \leq D(K+1)/(4Kd). \tag{5}$$

The depth of focus at visual researches does not limit *A*, due to focusing.

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

$$\frac{\Delta K}{K_0} = \frac{Y\sin\theta}{x_0}. \tag{6}$$

Here $K_0 = K(x_0)$, $\Delta K = K(x) - K(x_0)$. For technical reasons: $f \geq 4R$ [5], and $R \leq 0.25D$. Therefore,

$$K_0\ \mathrm{J}\ \frac{\Delta K}{K_0}\text{ч}\frac{D}{Y\sin\theta}. \tag{7}$$

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

As follows from Eq. (4) and Eq. (7), the reduction of the luminosity error and of the beam cross-section error requires the reduction of θ that results in reduction of the brightness and, hence, of the current measurement threshold of the beam. From Eqs. (5), (7) one can see, that small optical magnifications are necessary for reducing the distortions of the image and increasing its luminosity.

4. EXPERIMENTAL SETUP AND RESULTS

The special device (see Fig.4) was created for the visual examination of the electron beam generated by the magnetron gun [3] with the error $\Delta Y = 0.1$ mm.

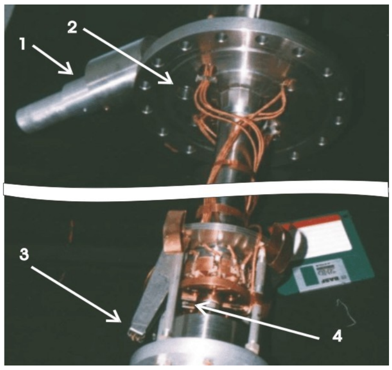
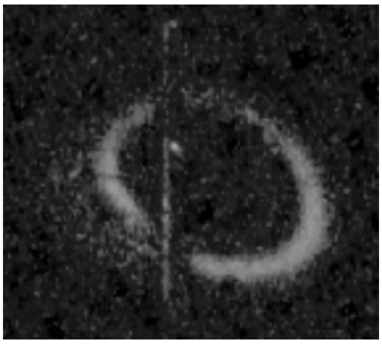


Fig.4. *Experimental setup: 1 - block of objective, ocular and mirror, 2 - output window, 3 - mirror, 4 - target*

The diameter *D* was of 140 mm. The radius of the output optical window of 22 mm limited the optical aperture. The distance between the target and the objective *d* was of 548 mm. As basic elements of the optical system the objective with the resolution in the focal plane of 1/30 mm, $A = 1/9$, $f = 105$ mm and the ocular with $f_{oc} = 17.8$ mm and $\theta = 30°$ were chosen. The calculated values were the following: $K = 0.28$, $\Delta Y = \Delta Y'/K = 0.12$ mm, $\Delta Y/Y = 0.024$, the subjective magnification $G = f/f_{oc} = 5.9$, the diameter of the output iris $\delta = 2R/G = 4$ mm, tg$(U) = 23.3/548 = 0.024$. At the given *D*, from Eq. (5) it follows A = ½. It is much more than the chosen $A = 1/9$. Reducing of *A* does not cause, however, the loss of luminosity of the retina, but only limits the allowable subjective magnification [5]. Such system is inefficient at photographing because of the loss of light exposure $E \sim A^2$. The condition (2) was satisfied, therefore, focusing was not required. As follows from Eq. (6), $\Delta K/K_0$ is 0.15 that exceeds the required value 0.1. As $d > 300$ mm, the error in the luminosity of the target is less than 10%. To the obtained linear resolution $\Delta Y = 0.12$ mm corresponding is the angle of view 2.7′ (at $G = 5.9$), that is higher then the eye resolution, but lower than the recommended value 4′ [5]. Such a choice of G is made to preserve the subjective brightness of an image.

For specified $\delta = 4$ mm the calculated subjective luminosity is 0.12 lx, that is 30% of the normal light exposure of a retina [5].

The experiments have shown that a beam with the current 10 A is easily observed. However, at decreasing the beam current and energy down to 2 A and 25 keV, respectively, the luminosity of the image and the resolution is deficient for correct measurements. It corresponds to $j = 9$ A/cm^2 and the beam power density of $2.2 \cdot 10^5$ W/cm^2. In this case, the calculated light exposure of a retina is 5% of normal. We can state that the above-specified beam parameters correspond to the sensitivity of the device. The view of this beam in the ocular is shown in Fig.5. This image was obtained with the digital camera and numerically corrected on the angle $\theta = 30°$. The elliptic form of the beam is caused by the conditions of its formation [3].



The visual examination of the titanic and silver targets showed that the beam forms a mark with the surface roughness sizes of 0.02...0.05 mm.

5. DISCUSSION

The sensitivity of the created installation is limited by the aperture of an eye, therefore it is maximal for visual researches. The detailed description of the image structure requires a brightness which is on the order of magnitude greater, than the sensitivity. Therefore for the visual OTR - diagnostics at the beam energy 50 keV the limit of the beam density is about 45 A/cm^2.

The spatial resolution is limited by dimensions of the solenoid (see (7)), or by sizes of the free space needed to contain the optical system, that can be much less than the solenoid diameter. The obtained resolution of 0.12 mm can be improved, as follows from the technical capabilities of solenoids, up to 0.03 mm. The threshold power density of $2.2 \cdot 10^5$ W/cm^2 exceeds the evaporation limit ~ $1 \cdot 10^5$ W/cm^2. Therefore, finally, the linear resolution is limited by the sizes of surface protrusions 0.02...0.05 mm. As a probable decision, of interest is the graphite target [2], though the carrying of carbon in vacuum requires study in this case.

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ИССЛЕДОВАНИЕ СТРУКТУРЫ КОЛЬЦЕВОГО ПУЧКА ПО ПЕРЕХОДНОМУ ОПТИЧЕСКОМУ ИЗЛУЧЕНИЮ

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Описаны особенности исследования структуры плотного кольцевого пучка электронов с помощью переходного оптического излучения из металлических мишеней при энергии электронов до 50 кэВ. Получено изображение поперечного сечения кольцевого пучка с толщиной стенки меньше миллиметра.

ДОСЛІДЖЕННЯ СТРУКТУРИ КІЛЬЦЕВОГО ПУЧКА ЗА ПЕРЕХІДНИМ ОПТИЧНИМ ВИПРОМІНЮВАННЯМ

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Описані особливості дослідження структури щільного кільцевого пучка за допомогою перехідного оптичного випромінювання з металевих мішеней при енергії електронів до 50 кеВ. Одержано зображення поперечного перерізу кільцевого пучка з товщиною стінки менше міліметра.