Radiation emitting screen performances for low emittance, low energy, beam measurements

M. Castellano[#], L. Catani[$]

[#]INFN-LNF, C.P. 13, 00044 Frascati, Italy
[$]INFN-Roma II, via della Ricerca Scientifica 1, Roma, Italy

Abstract

The optical emitting efficiency and transverse resolution of different type of screens are compared as candidates for detecting the electrons from a pepper pot emittance measurement device to be used on the two RF photoinjectors planned for the TTF superconducting linac.

1 - Introduction

For the TESLA Test Facility (TTF) two RF photoninjector are in preparation: the first one will deliver a high charge (8 nC) per microbunch at a repetition rate of 1 MHz to test the superconducting cavities behaviour with the beam structure foreseen for the TESLA linac, the second one will deliver only 1 nC per microbunch, at 9 MHz, but with a normalised transverse emittance as low as 2 10^{-6} m rad. The latter will be used to test the possibility to generate and preserve the quality of a very low emittance beam, needed for high luminosity linear collider, and will be used as injector for a single pass UV FEL based on the SASE amplification process.

In both cases the measurement of the transverse beam emittance at the gun exit is of fundamental importance. Due to the large space charge effects, the traditional method of measuring the beam profile as a function of the strength of a focusing element is not applicable, then only the pepper-pot technique may be used, and, in particular for the low emittance case, with very small holes. A very accurate study of the pepper pot technique applied to the low emittance gun is presented in [1], where it is shown that, in order to avoid space charge effects, only a fraction of the order of 10^5 electrons, over the total 10^{10} of a single microbunch, must be selected from each 10 μm hole.

In these conditions, we are not only in the presence of technical difficulties for the pepper pot realisation, mainly due to the manufacturing of a screen that can sustain the beam power, with very precise holes, but also of the problem of the efficiency and resolution of the screen that must allow the determination of the dimension and charge distribution of all the beam spots.

As shown in [1], the requirements are of measuring a beam spot size of the order of 100 μm, produced by 10^5 electrons, with a resolution of 10 μm.

In this note we will summarise the performances, mostly well known, of different kind of screens that can be used for this measurement, as a problem guide towards the design of a real device. Our analysis will cover ceramic screens, Optical Transition Radiation (OTR) mirrors and Cerenkov radiators.

2 - Ceramic screens

The ceramic screens, in their most used form of Cr doped Al_2O_3, are widely used in beam diagnostics. Different type of production technique have been used, from deep anodization of bulk aluminium to allumina powder sinterization.

We have not found in the literature a systematic study of these type of screens, their knowledge being deeply hidden in the experience of each laboratory, so the data we will present here are mainly based on a single paper and on our personal experience [2].

The measured sensitivity of 10^9 e/cm^2 sec for a vidicon camera is more than adequate to our case, taking into account the superior sensitivity of modern CCD camera.

Transverse resolution is mainly limited by the surface granularity, which is of the order of 50-100 μm. In [2] it is reported the observation of "bright spots" on a screen obtained by deep anodization of a bulk aluminium screen. In our work on the LISA accelerator in Frascati we have observed "bright spots" on anodised aluminium (not Cr doped) but not on sinterized allumina screens, although it should be noted that we have never tried to observe the screens with a very high magnification.

Other resolution limits are the non linear response to high charge beams, that should not be of concern in our case, and the range of secondary (Auger) electrons in the screen, which should be of the same order, or less, than the surface granularity. Another effect that can reduce the resolution, but that we have never found exactly quantified, is the screen "transparency", that is the possibility to observe photons emitted inside a rather thick target.

The spectral emission of Cr doped ceramics is mainly in the red part of the spectrum, well matched with the sensitivity of Si CCD camera, and this feature may reduce the possible chromatic effects of the optics.

As a conclusion we can state that standard ceramic screens are well suited for the detection of a small number of electrons giving a transverse resolution of the order of 50 μm, and that almost nothing is known for better resolutions.

3 - OTR mirrors

OTR is becoming an ever more used source for beam diagnostics, its main advantage being the absolute linearity with the beam intensity and the prompt time response (in the sub picosecond range), together with a peaked angular distribution that allows also measurements of different beam parameters as angular spread and energy.

The ultimate transverse resolution obtainable by OTR is still an open question in the scientific community. Someone think that such a limit is constituted by the transverse formation zone of the radiation (that coincide with the extension of the particle electromagnetic field, is proportional to the observed wavelength and increases linearly with the relativistic factor gamma). In a recent experiment [3], not yet published, performed at the 2 GeV Orsay linac, we have measured beam dimensions more than two times smaller than the OTR formation zone. The spot size was limited by the focusing capability of the machine. At the TTF gun energy of 5 MeV the only limit is the radiation diffraction effect, giving a resolution of the order of 1 μm.

A disadvantage of OTR at low energy is that the radiation is mostly emitted at large angles, with almost no radiation along the axis. In this case a well compensate optical system is needed to avoid too strong aberrations, both chromatic and spherical, that would otherwise largely increase the resolution limit.

The practical limitation in the use of OTR for the pepper pot measurement is its very low efficiency. In fact at 5 MeV the total number of photons in the whole visible spectrum (400÷800 nm) collected by a 50 mm diameter lens at 25 cm distance from the source (almost the maximum solid angle that can reasonably be implemented) is only $4\ 10^{-4}$ for each electron, so that, for 10^5 electrons, we are left with 40 photons, a number absolutely inadequate to reconstruct an image even with an intensified camera.

4 - Cerenkov radiator

Cerenkov radiation has been extensively used for particle identification due to its threshold behaviour with particle velocity. In beam diagnostics it has been often used for its timing properties to measure short bunch lengths by means of streak camera. Its possible use as radiation source for high accuracy imaging of beam spot size has never been fully exploited. In the literature we have found only a paper dealing with the problem of transverse resolution [4]. Even in this case the main concern was the time behaviour.

Having no previous experience with this type of screen, we have tried to analyse at least its main properties, as intensity distribution of emitted radiation and transverse resolution.

For practical solid radiators, thus not considering special material with very low refraction index as Aerogel, the Cerenkov radiation emission angle is very large, resulting quite impossible to collect all the emission cone on an imaging device. In [4] this problem was solved by rotating the radiator so that part of the photons were emitted at 90° from the beam direction, see Fig. 1. The beam direction is along the x axis, the screen is rotated around the y axis, while the radiation is observed in a solid angle around the z axis.

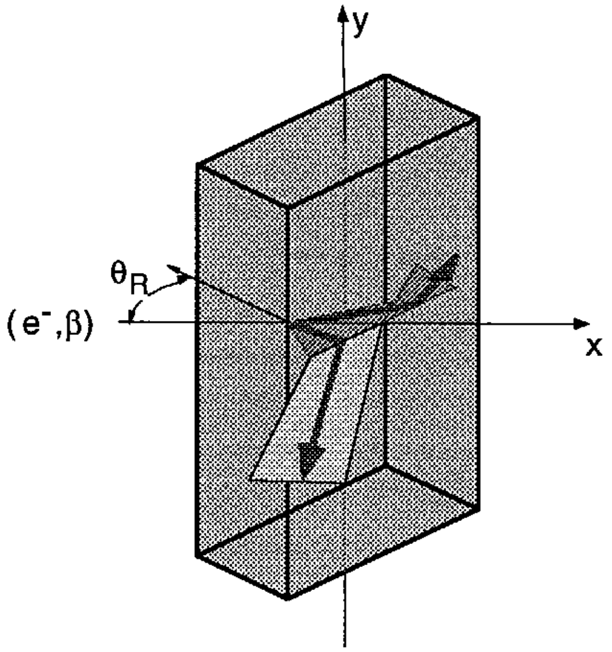

Fig.1 - Pictorial view of tilted Cerenkov radiator showing emitted radiation in x-z plane.

In calculating efficiency and resolution of this screen, we have followed the same approach. If we want Cherekov radiation emitted at 90°, no real solution exists for refraction index less than 1.4. To evaluate the efficiency of the light collection, we have chosen the same material as in ref. [4], that is sapphire which has a refraction index of n=1.77. In this case the screen must be rotated by .427 rad respect to the normal incidence direction.

The angular distribution of Cherekov radiation from a finite length radiator shows a "diffraction" behaviour with a rather large main peak followed by less intense secondary maxima that depends on the particle energy, wavelength and refraction index of the medium.

To calculate the radiation angular distribution we have followed an elegant and simple formalism [5], completely equivalent to the original Tamm derivation [6].

A charged particle crossing at constant velocity the boundary between different media is considered as stopping just before the boundary, followed by an instantaneous start, at the same velocity, at the other side of the boundary.

The radiation amplitude is derived as the sum of all the "prompt" bremsstrahlung amplitudes, multiplied by the Fresnel reflection and/or refraction coefficient as required by the observation direction. This formalism incorporates both the transition radiation and the Cerenkov radiation as a single process.

In our calculations we neglected the contribution of the stop and the start respectively before and after the radiator, these amplitudes giving only a very small "transition radiation like" intensity.

To evaluate the intensity collected on the imaging device, we have considered the same solid angle as for the OTR, that is the one subtended by a 50 mm diameter lens at 25 cm from the source. We have also assumed a 100 μm thick radiator, that we consider to be a limiting practical value.

Due to the angular incidence of the beam, the radiation shows two distinct polarisation state: the radiation plane, that is the plane defined by the radiation direction and the normal to the radiator surface (parallel polarisation), and the plane normal to it (normal polarisation). For a small angular acceptance at 90° to the beam direction, the parallel polarisation intensity is more than one order of magnitude larger than the normal one, thus in the following we will consider only the former one.

The angular distributions of the parallel component, around the 90° direction to the beam, for the two extreme visible wavelengths of 800 and 400 nm, are shown in Fig. 2 and 3. To make more evident the diffraction behaviour, in the figures the horizontal and vertical scales are different.

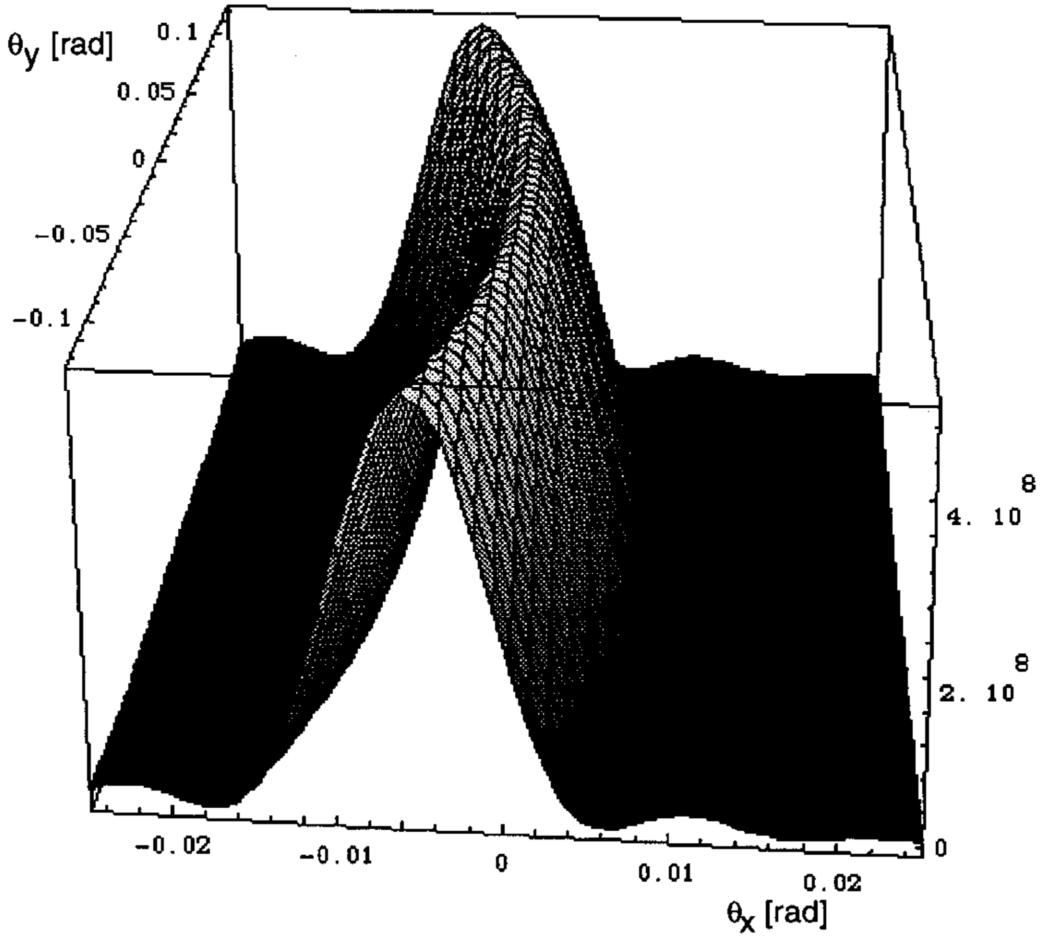

Fig. 2 - Angular distribution of Cerenkov radiation at 800 nm

The total number of photon integrated on the full visible range (400÷800 nm), in a cone of 100 mrad semiaperture defined by the assumed optic set up, is 20 phs/electron. This number is four order of magnitude larger than the OTR one, and, due to its particular angular distribution, scales almost linearly with the angular acceptance.

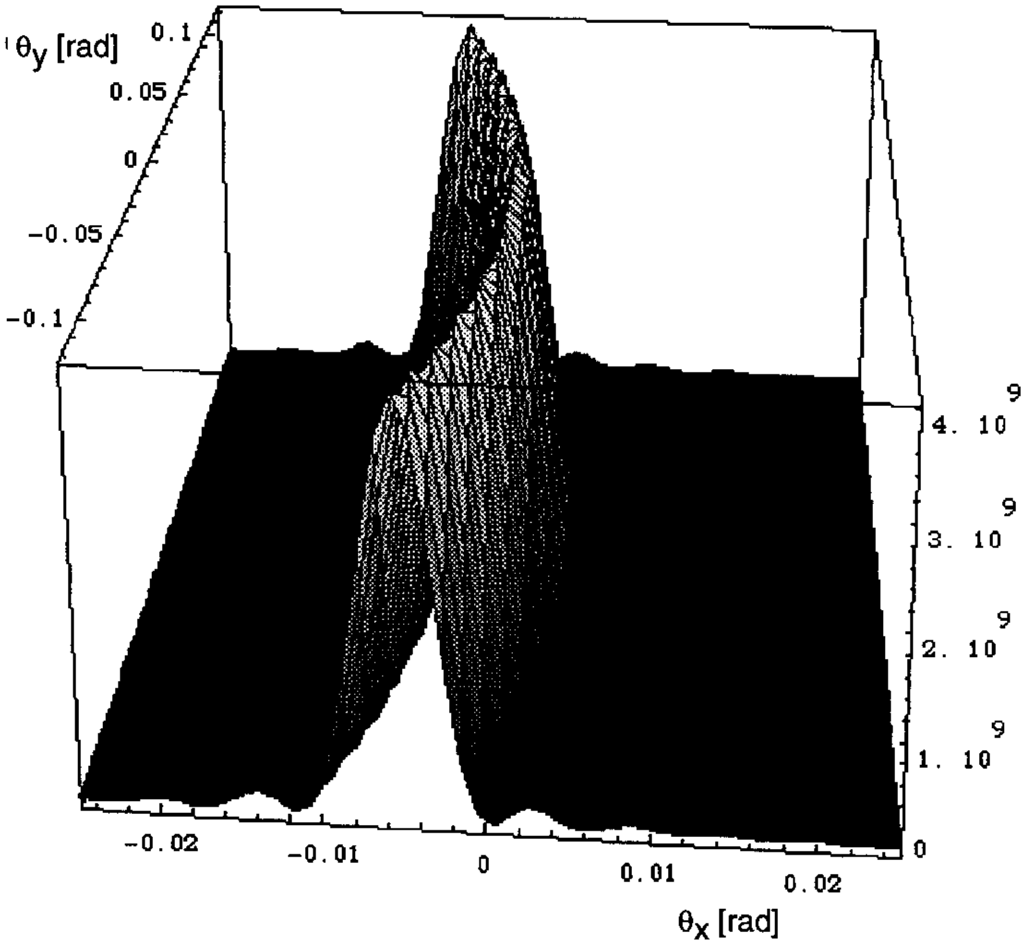

Fig. 3 - Angular distribution of Cerenkov radiation at 400 nm

The number of photons, as function of wavelength, collected through a 40 nm bandwidth, a standard value for interferential filters, is shown in Fig. 4. In this evaluation we have not taken into account the filter transmittivity. It results that the radiation is more intense at shorter wavelengths.

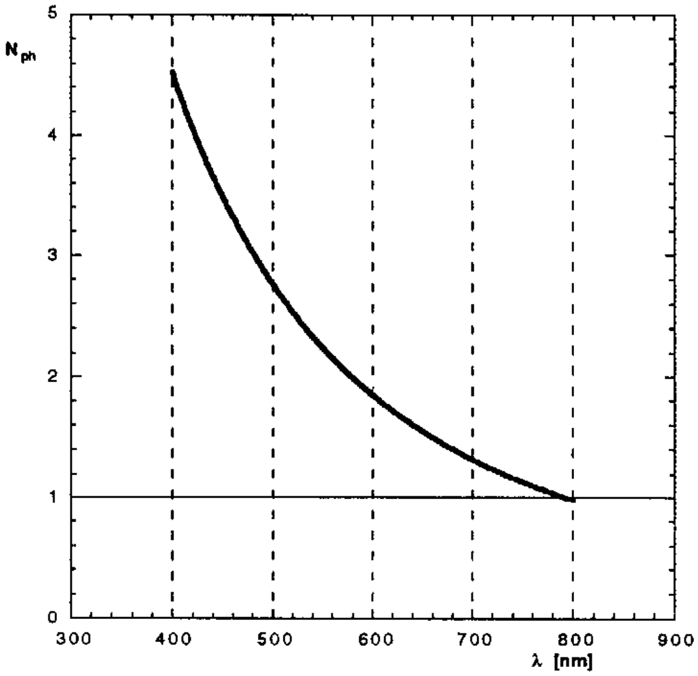

Fig. 4 - Number of photons for each electron collected through a 40 nm fixed bandwidth as function of wavelength

The image of a beam spot in the yz plane will be formed in a plane parallel to the xy one, so we are interested in the resolution achievable along these two axes. To evaluate the resolution along the x axis we refer to Fig. 5, which shows the radiation emission in the xz plane.

A single particle will emit radiation all along its path in the radiator (P_1-P_2), but, due to the refraction effect, the image of this trajectory segment will appear distorted (P_0-P_2). A limit to the resolution, proportional to the screen thickness, is the projection of this apparent source on the x axis (Δ_x). For 100 μm of shaffire we obtain a value of 44. This is not the only limit to the transverse resolution along the x axis, but the largest. This effect is increased by the small rotation angle of the screen, in fact the radiation emitted by a beam spread along the z axis is compressed in the plane of view (see Fig. 6). In our case the minimum distance δ_z between two electrons that allows a separation of the relative radiation (at twice the rms value) comes out to be of 66 μm, and this can be considered the real beam transverse resolution along the z axis.

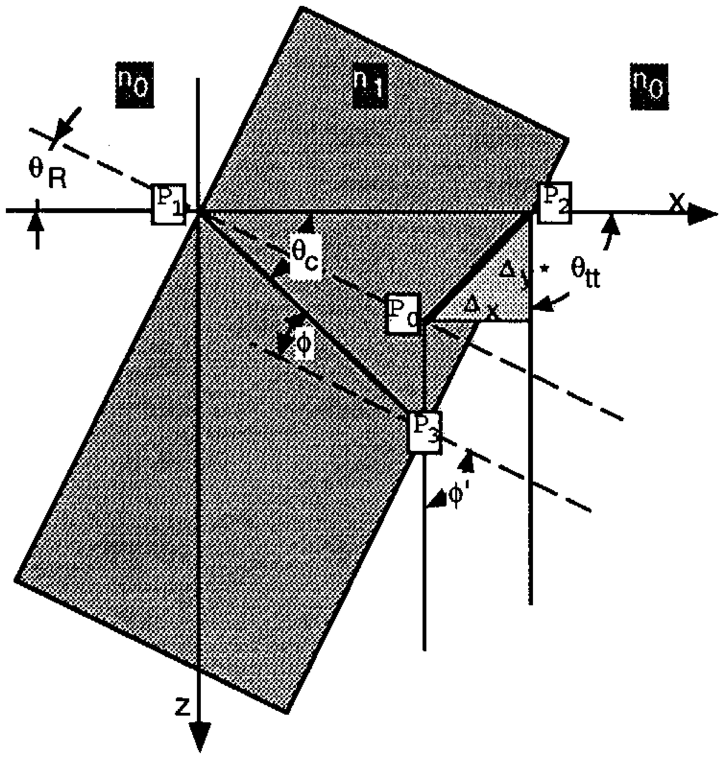

Fig. 5 - Image of a single electron trajectory inside the radiator in the xz plane

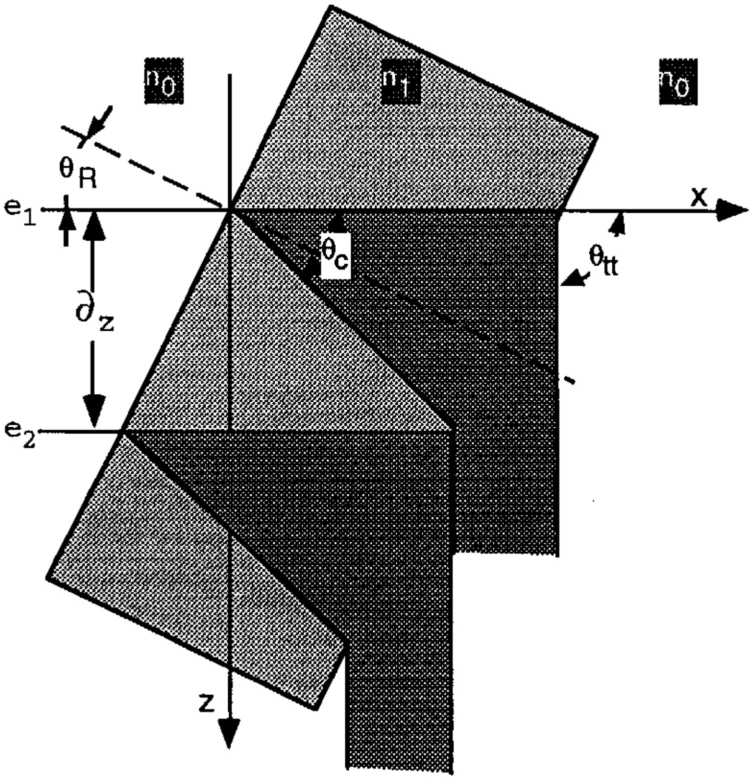

Fig. 6 - Minimum distance along axis z between two electrons that allows a separation of images

The profile along the y axis do not suffer of this limitation, the projection of the whole trajectory being a single point. The limit derives from other two effects, negligible in the previous case: the multiple scattering of the electron inside the radiator and the finite field depth of the optic system.

The first effect can be easily calculated and gives, for a 5 MeV electron and a 100 μm radiator tilted by a .427 rad angle, an rms value of 1.8 μm. The second effect derives from the fact that the apparent source (P_0-P_2 in Fig. 5) is not parallel to the x axis, and cannot be entirely focused on the image plane. Also in this case the resolution is linearly dependent on the radiator thickness, but it is also proportional to the tangent of the maximum acceptance angle of the optics. For the conditions we have used so far, its rms value is of the order of 1 μm.

5 - General considerations

Although at least a screen seems to allow the possibility to reach the desired resolution of 10 μm, even if only in one plane, it should be noted that in reality this goal is not anyway an easy task and that other difficulties must be overcome.

In particular much care must be put in the optics design, that should provide an adequate magnification to avoid that the resolution results limited by the imaging device (i.e. the pixel dimension of a CCD camera), and must be fully compensated for chromaticity. On the other hand, if the angular acceptance is too much reduced in order to avoid spherical aberration and a narrow band filter is needed to counteract chromaticity, it is easy to fall in a situation in which the resolution is dominated by the photon statistics and/or the diffraction limit that, for small acceptance angles, may be larger than 10 μm.

It should be noted that the vacuum window, that must be of good optical quality, cannot be compensated for chromaticity, and its effect should be taken into account.

The design of a real device must find a good compromise between these opposed requirements.

References

[1] - K. Flöttmann, TESLA-FEL 96-09, Desy 1996

[2] - S.Yencho and D.R. Walz, SLAC-PUB-3671, SLAC 1985

[3] - X. Artru et al., to be published

[4] - S. Battisti, CERN/PS 93-40 (BD), CERN 1993

[5] - V.P. Zrelov and J. Ruzicka, Czech. J. Phys. **B39**, (1989), 368

[6] - I.E. Tamm, J. Phys. USSR **1**, (1939), 439