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DEVELOPMENT OF AN OPTICAL TRANSITION RADIATION BEAM MONITOR FOR FREE-ELECTRON LASERS

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Japan Atomic Energy Research Institute

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Development of an Optical Transition Radiation Beam Monitor for Free-electron Lasers

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(Received November 4, 1992)

An optical transition radiation (OTR) beam monitor has been developed for the beam diagnostics in free-electron lasers experiments. The OTR lights from an aluminized synthetic quartz screen under passage of the 12MeV electron beam from the RF linac at University of Tokyo were observed with an Intensified-CCD(I-CCD) camera. The spatial profiles of the beam were measured when the camera was focused onto the screen, while the OTR angular distribution patterns were measured at the infinite focal length. The beam energy and divergence were also obtained through the analysis of these patterns.

Keywords: Free Electron Laser, Optical Transition Radiation, Screen Monitor, High-brightness Beam, Emittance, Alignment, Macropulse

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自由電子レーザー用OTRビームモニターの開発

日本原子力研究所東海研究所物理部
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（1992年11月4日受理）

自由電子レーザー実験におけるビーム診断のためのOTRビームモニターを開発している。東大RFライナックからの12MeVの電子ビームがアルミニウムを蒸着した合成石英スクリーンを通過する時にでるOTR光がI-CCDカメラで観測された。カメラの焦点をスクリーン上にあわせた時にはビームの空間分布が測定され、無限遠にあわせた時にはOTR光の角度分布が観測された。これらのパターンの解析により、ビームのエネルギーと発散角に関する情報が同様に得られた。

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1 Introduction*

Beam diagnostics hold an important position in the development of high-brightness electron beams for free-electron lasers (FELs). The measurement of the beam emittance is especially an essential matter of this concern. For example the emittance can be measured by quadrupole magnets and screen monitors which are widely used to measure the position and the profile of the beam in linear accelerators. [1] In the FEL experiments, the screen monitor has another important role: alignment of the electron beam, because the spatial overlap between the electron beam and the laser beam should be ensured for the FEL interaction. Ceramic plates, which emit fluorescence by the collision of high energy particles, have been commonly used as the screen monitors.

An optical transition radiation (OTR) monitor was suggested for the beam diagnostics.[2] OTR is a radiation emitted from charged particles transitting an interface between two media which have different dielectric constants. Figure 1 shows OTR from an electron-beam transitting a thin foil in vacuum.[3]

The OTR angular distribution pattern has a specific profile depending on the energy of the particle as shown in figure 2. The lobe has an opening angle $\theta_M = 1/\gamma$, a peak intensity proportional to γ^2, a lobe-width proportional to beam divergence. This brings the unique properties to the OTR beam monitor, which gives not only the position and the spatial profile of the beam but also the energy and the divergence. Consequently, the beam emittance, a correlation of the spatial profile and the divergence, can be measured. The OTR is emitted only during particles transitting the screen. Therefore, the beam emittance of a single macropulse can be measured with the use of a time-resolvable Image-Intensifying multi channel plate (MCP) and CCD camera (I-CCD camera), while the emittance obtained from the combination of a ceramic screen and a

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*Collaboration between JAERI and University of Tokyo quadrupole magnets is a value averaged over many macropulses.

The OTR beam monitor also has possibility of a low X-ray producing monitor. X-rays generated by particles bombarding a screen causes serious damage to optical instruments, especially for a high average current or high energy beam. The OTR intensity is independent of the thickness of the screen, because OTR is emitted at the interface of the media. Therefore, the OTR screen can be made thinner than the fluorescence screen monitor or Cerenkov radiation monitor to reduce the amount of X-ray radiation.

However, there are some difficulties in the beam measurements with the OTR monitor. For one thing, the radiation yield of the OTR is so small, roughly one photon per hundred electrons,[5] that an image intensifier must be installed on a CCD camera. For another thing, the optical instruments should also be arranged in due consideration of the divergence of the OTR lights.

In this paper, we describe the procedures and the results of experiments performed for the development of the OTR monitor. The preliminary experiment can be found.[9]

2 Experiments

The intensity of the forward emission from a single particle of charge e crossing an interface (from the medium to the vacuum) at normal incidence is given by [5]

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\frac{\beta^2 \sin^2\theta}{(1-\beta\cos\theta)^2}\,, \tag{1}$$

where β is the particle velocity in units of c, θ is the angle of emission with respect to the direction of the particle velocity and the intensity is normalized at frequency range $d\omega$ and solid angle $d\Omega$. In this equation, we assumed that the particle is relativistic, i.e. $\beta \sim 1$. The intensity of the backward emission quadrupole magnets is a value averaged over many macropulses.

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$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\frac{\sin^2\theta}{(1-\beta\cos\theta)^2}\left|\frac{\varepsilon^{1/2}-1}{\varepsilon^{1/2}+1}\right|^2 , \tag{2}$$

where ε is a complex dielectric constant of the medium. These two equations show that the intensity of the backward emission is just the product of the intensity of the forward emission and the Fresnel formula for reflection. Therefore, the intensity of the forward emission is typically several times larger than the backward emission.

Two kind of OTR images can be observed according to the focus of the camera.[6] When the lens of the camera is focused onto the OTR screen, spatial distribution of the emission can be observed. (figure 3) Focusing the lens on infinity, the image represents angular distribution of the emission, which gives information about the energy and the divergence of the beam. (figure 4)

Experiments for the OTR beam monitor were carried out using a 15MeV electron linear accelerator at Nuclear Engineering Research Laboratory University of Tokyo. Figure 5 shows a schematic experimental setup. Two experiments have been performed. We used a Kapton foil as an OTR screen in the preliminary experiment and then a $1\mu m$ aluminized synthetic quartz screen in this experiment. The OTR screens were set at 45° to the beam line and the backward emission at 90° to the beam line was observed with an I-CCD camera.(figure 6)

A ceramic screen (Desmarquest AF995R) and a He-Ne laser were used for the alignment of the camera. Steering coils before the first screen were installed for the fine control of electron beam trajectory.

The image data from the camera were stored in a video frame memory and transmitted to the control room for on-line image processing and recording.[7]

Trigger signals both for the accelerator and for the measurement systems were generated with proper delays respectively, so that data acquisitions were synchronized with the beam macropulses, and thus quantitative analyses were guaranteed. The system allowed the measurement of a single macropulse for the reduction of radiation damage to the optical instruments.

The accelerator was operated with 12MeV in energy, 250mA of peak current in a $7\mu s$ long macropulse of 6.25pps repetition. These are almost as same as parameters for the projected UT/FEL experiment.[8]

The experimental procedure was:

1. To measure the beam position on the ceramic screen (S1) with the CCD camera (C1),
2. To retract S1 away from the beam line and then to measure the beam position on the OTR screen,
3. To align the He-Ne laser path on the electron beam trajectory by watching the laser spots on each screen,
4. To align the camera (C2) to the laser beam reflected on the OTR screen,
5. To measure the spatial distribution of the OTR radiation with focusing the lens (L2) onto the OTR screen,
6. To measure the angular distribution of the OTR radiation with focusing the lens on infinity.

The gain of the image intensifier was carefully adjusted not to saturate the CCD camera.

3 Results and Discussions

Figure 7 shows a result of the preliminary experiment: an image obtained with focus of the lens onto the screen. The image does not represent the spatial profile of the beam but is disturbed with background light. The background is considered as stray lights which derive from both forward emission from the guaranteed. The system allowed the measurement of a single macropulse for the reduction of radiation damage to the optical instruments.

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OTR screen and backward emission from the titanium foil at the duct terminal. Figure 8 shows how the stray lights come in the camera. The intensity of the stray lights is larger than the objective emission, because the forward emission is larger than the backward emission as described before.

The OTR image pattern the theory predicted was not observed, nevertheless it was confirmed that the gain of the image intensifier we used was large enough to detect the OTR emission for our beam parameters. Another important instruction was that we should pay much attention to the stray light which disturbed the measurements.

In the second experiment, the OTR image pattern was observed. Figure 9 shows an example of observed OTR images on the aluminized synthetic quartz screen, which represents beam spatial distribution. Although there was stray lights from the aluminum frame, the beam profile was clearly observed. The cross sections of the spatial profile for both x and y directions are shown in figure 10. These results show that the measurement of beam profile using an OTR monitor is of practical use, especially for high spatial resolution measurements.

In the measurement of the OTR angular distribution pattern, an aperture was inserted in front of the view port to reduce the disturbance of the stray lights from the aluminum frame. The inner diameter of the aperture was experimentally determined in trade-off for the divergence of the OTR.

An image of the OTR angular distribution pattern is presented in figure 11 and a comparison between theory and observation is shown in figure 12. Although the quartz screen interrupted the background light, the stray lights from the aluminum frame still disturbed the measurements. The image would have been a perfect hollow circle, if there were no stray light. The excess images besides a hollow circle in figure 11 are considered as the stray lights from the frame.

The measured divergence shows the difference from the calculated curve;

experimental one is falling-off at the outside of the lobe in figure 12. This is considered as the effect of the aperture.

The polarization of the emission, a positive proof of the OTR, was observed by setting a polarizer plate as shown in figure 6. Figure 13 is an OTR image obtained with the polarizer.

The factor of polarization has been determined as

$$\frac{I_{\|} - I_{\perp}}{I_{\|} + I_{\perp}} \simeq 0.6 \quad , \tag{3}$$

where $I_{\|}$ and $I_{\perp}$ are the intensity of the image in the direction parallel and perpendicular to the polarizer respectively.

Dose measurements were also performed to compare the amount of X-ray radiation from the aluminized synthetic quartz OTR screen of 1mm thick and the ceramic screen of 1mm thick at the camera position with pocket-chambers and radiochromic films. The results showed that the difference in dose rate was less than the statistical error. This is because the amount of the X-ray depends on the thickness of the target and both screens have almost the same thickness. Thinner screens are preferable for the low X-ray generation. It will be easily achieved by using OTR monitors made of submillimeters or thinner metal foils.

4 Conclusions

The electron beam diagnostics with the OTR monitors have been carried out and an experimental technique has been established. The OTR images of both spatial profile and angular distribution have been observed with an image intensified CCD camera. The OTR intensity is independent of the screen thickness. If we use OTR screens of metal foils as thin as submillimeters or less, simultaneous monitoring of beam profile on several positions in the beam line is available and the amount of X-ray can be reduced. The OTR beam experimental one is falling-off at the outside of the lobe in figure 12. This is considered as the effect of the aperture.

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The observed OTR angular distribution patterns showed good agreement with the theoritical ones. This confirmed that the OTR monitors is useful for the measurement of energy and emittance.

The measurements of the OTR angular distribution pattern were found to have some difficulties concerned with the stray lights. However, the stray lights can be intercepted by appropriate arrangement of the optical instrument.

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[9] J.Sasabe, R.Hajima, T.Ueda, Y.Yoshida: 1990 JAERI Annual Report.

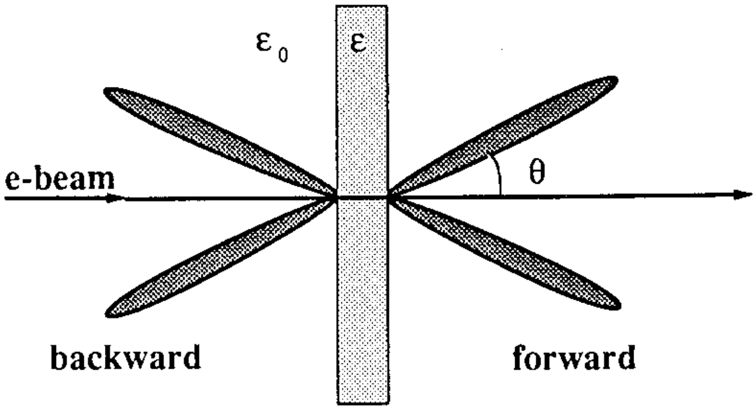

Figure 1. A schematic representation of OTR

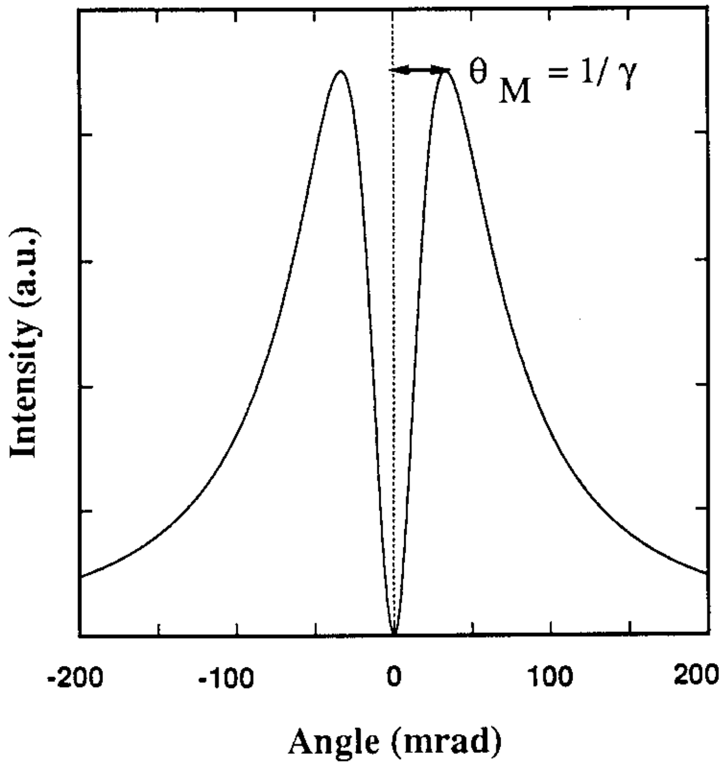

Figure 2. OTR angular distribution pattern ($\gamma =$

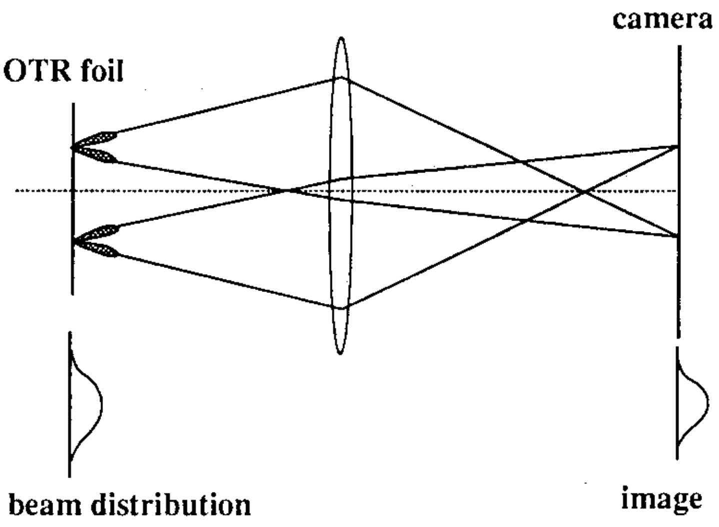

Figure 3. OTR image of spatial distribution (focus on the foil)

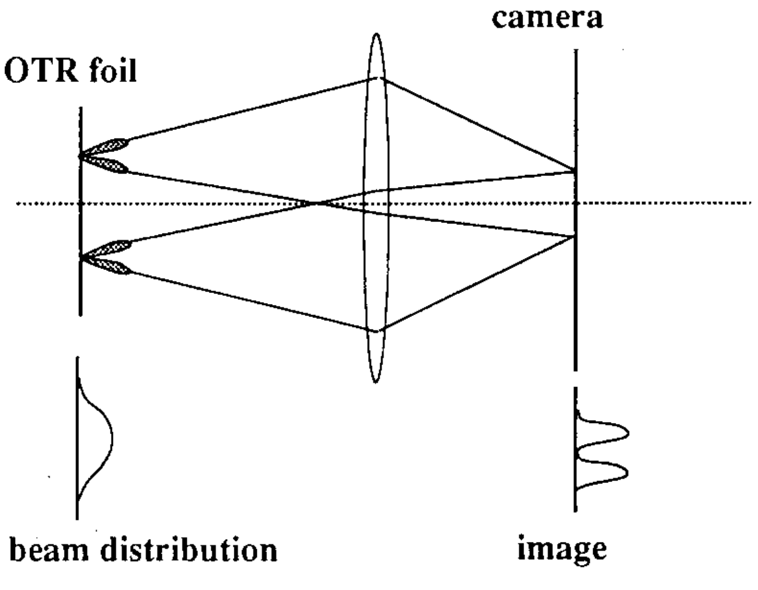

Figure 4. OTR image of angular distribution (focus on infinity)

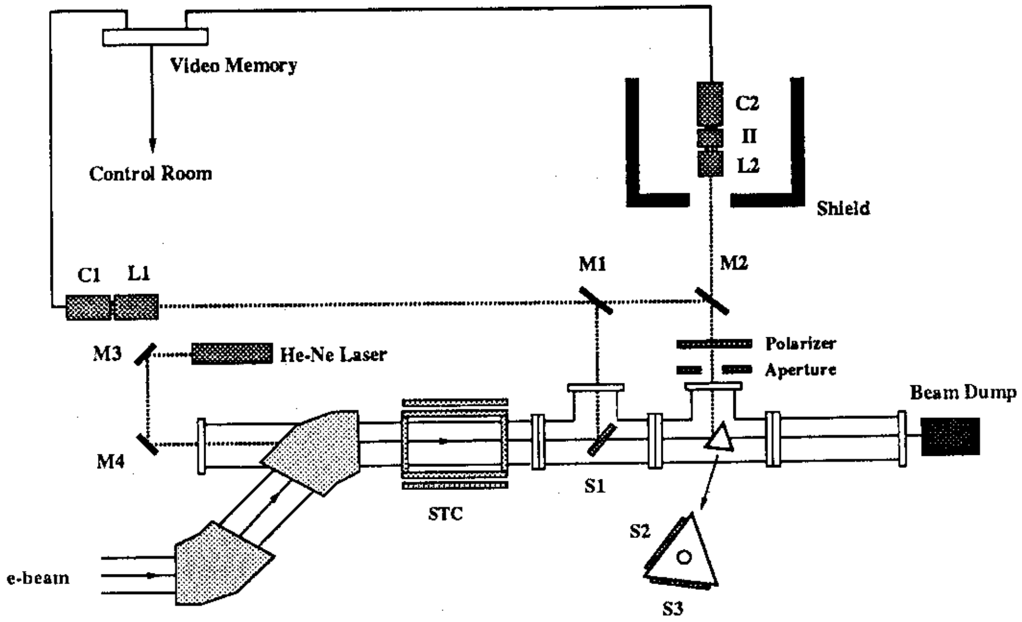

Figure 5. A schematic experimental setup

C1: CCD camera (Omron), L1: lens (f=2000mm), C2: CCD camera (Hamamatsu C3077), L2: lens (Victor 75mm F1.8), II: image intensifier (Hamamatsu C4237), M1~4: mirror, S1:ceramic screen, S2:OTR screen(quartz mirror), STC:steering coils

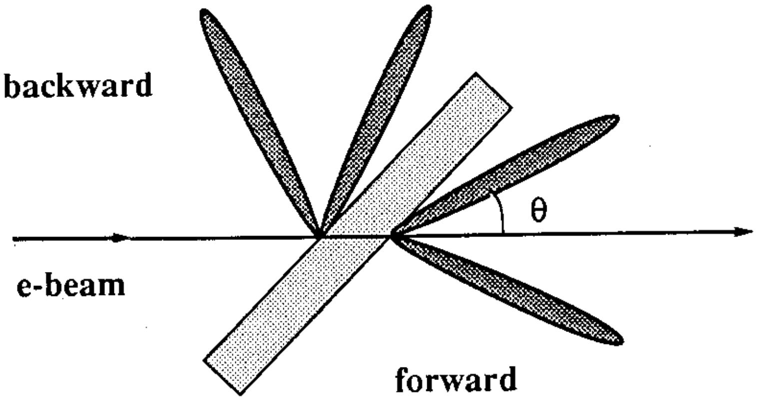

Figure 6. OTR radiation pattern for oblique incidence.

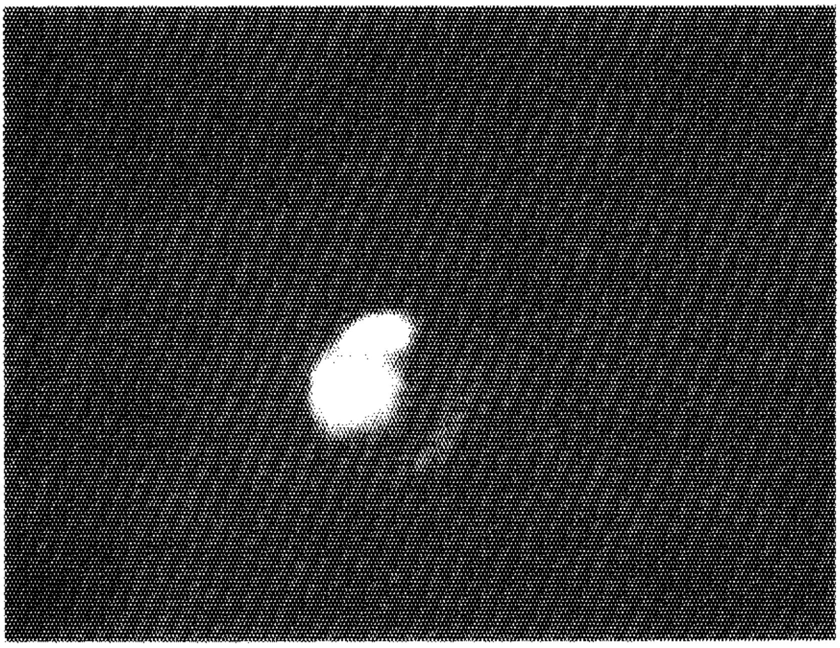

Figure 7. An observed OTR image.

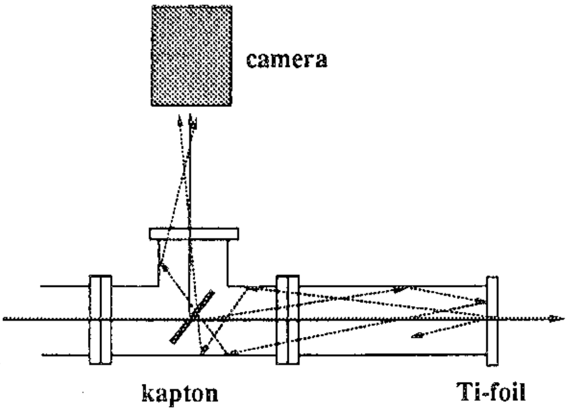

Figure 8. Forward emission from the kapton and backward emission from the titanium foil disturb the measurement.

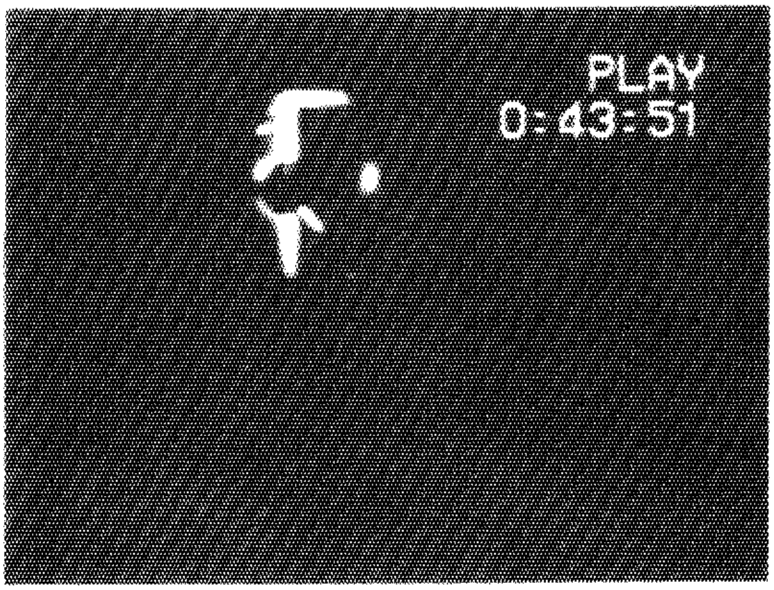

Figure 9. OTR image corresponding to the spatial profile of the beam.

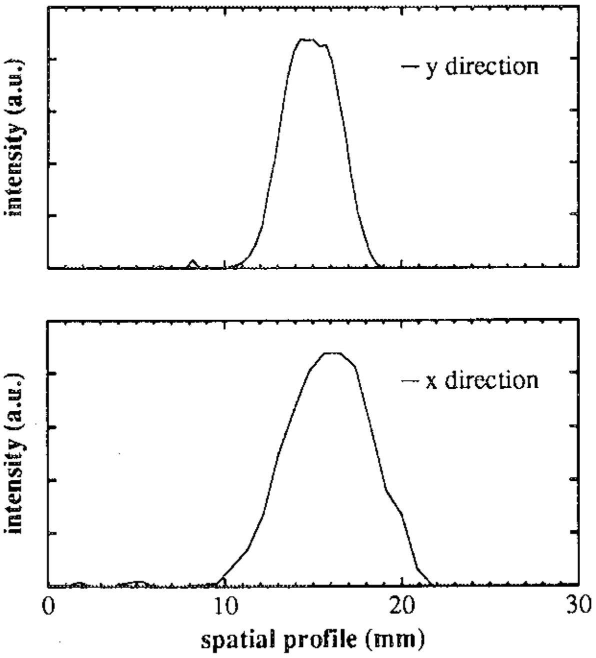

Figure 10. measured spatial profile of the beam

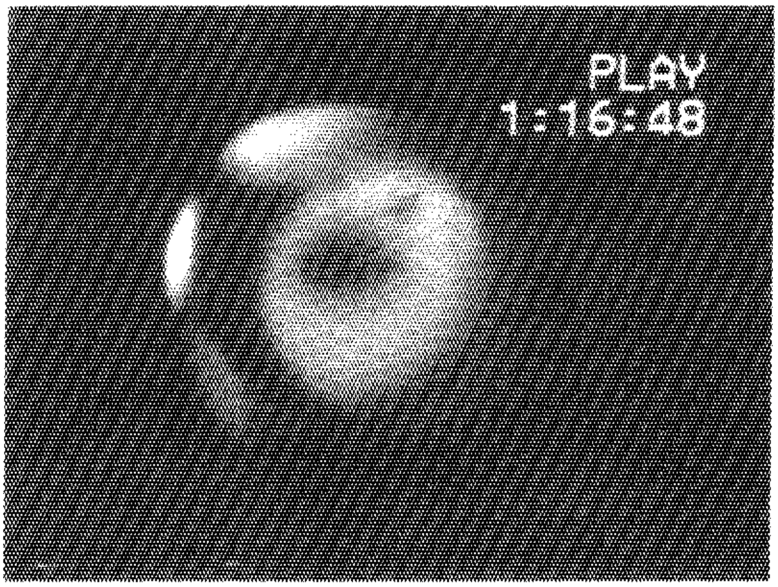

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Figure 11. OTR image of angular distribution

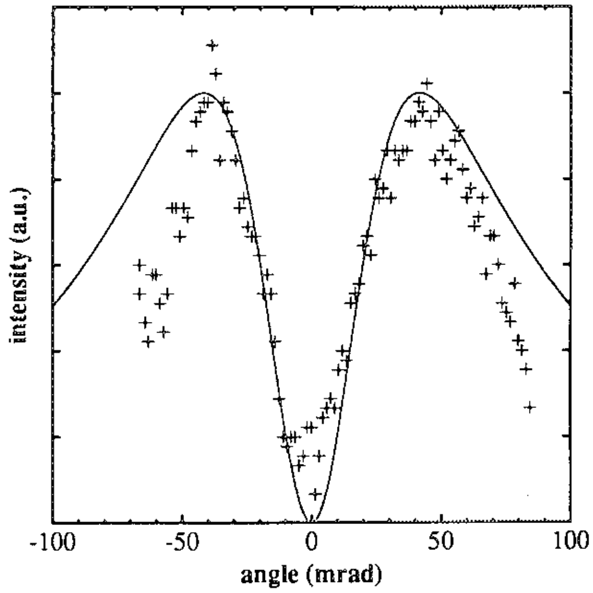

Figure 12. A comparison of divergence data from figure 12 to a calculation (12MeV).

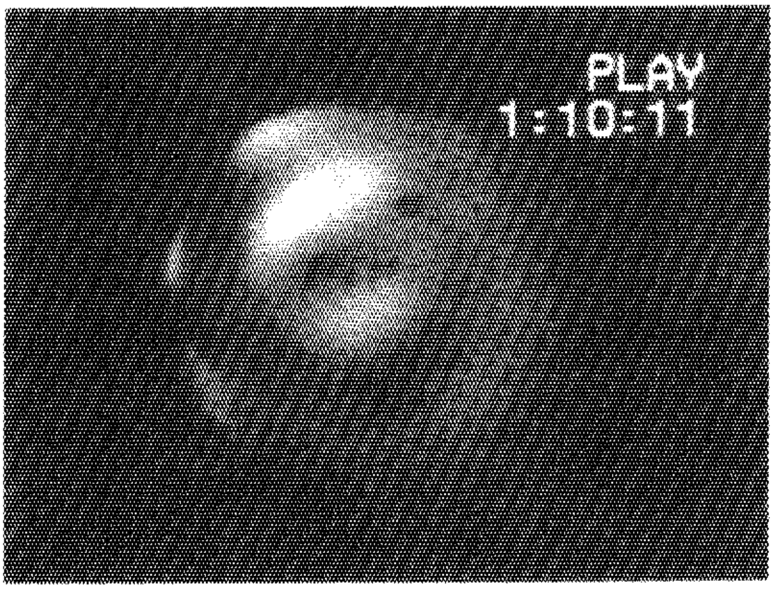

Figure 13. OTR image of angular distribution with a polarizer.