Experimental investigations of backward transition radiation characteristics in extreme ultraviolet region

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ABSTRACT

This report summarizes the results of an experiment dedicated to the observation of backward transition radiation in the EUV spectral region. This radiation was generated by an 855 MeV electron beam at a molybdenum target. The radiation characteristics in the EUV region are compared to those in the optical region. It was shown that the radiation measured in the EUV region was more intense than theoretically predicted. As a result the EUV radiation yield seems to be sufficient for standard beam profile diagnostics.

Keywords: EUV, Transition radiation, Beam diagnostics

1. INTRODUCTION

Transverse profile diagnostics in modern electron linear accelerators as FELs or injector linacs is mainly based on optical transition radiation (OTR) as standard technique which is observed in backward direction when a charged particle beam crosses the boundary between two media with different dielectric properties. Advantages of OTR are the radiation generation directly at the screen boundary in an instantaneous emission process, a linear response, and the rather high light output emitted in a small lobe with an opening angle defined by the beam energy. However, there are two physical limitations that make the method ineffective for modern beam diagnostics.

The experience from modern linac based light sources showed that OTR diagnostics might fail even for high energetic electron beams because of coherence effects in the OTR emission process. Cause of this coherent emission is the Microbunching Instability, i.e. some unstable micro structures in the electron bunch that compromise the use of OTR monitors as reliable diagnostic and may as well interfere with the FEL process in a malfeasant way. Coherent OTR (COTR) was observed e.g. at the Linac Coherent Light Source LCLS in Stanford (USA)¹ and at the free-electron laser FLASH at DESY in Hamburg (Germany).² As consequence for the new 4th generation light sources as the European X-FEL which is currently under construction in Hamburg³ new reliable tools for transverse beam profile measurements are required.

The second physical limitation is connected with the spatial resolution and imposed by the diffraction limit. It is impossible to measure a transverse bunch profile which is smaller than a radiation wavelength. The smallest bunch size that was measured using OTR diagnostics in standard configuration was about 5 μm (rms) in the vertical plane.⁴ This value was far beyond the diffraction limit, but for smaller bunch sizes one may obtain not a bunch profile but the point spread function that results in a bunch size, but not in a transverse bunch profile. Recently A. Aryshev et al. obtained a point spread function at the KEK-ATF2 extraction line and estimated the vertical bunch size as small as 1.8 μm (rms).⁵ This method may be useful even for sub-micron bunch sizes. However, for the mentioned KEK-ATF2 facility the planned goal is to achieve vertical beam sizes as small as 37 nm (rms).⁶

In a previous paper⁷ it was proposed to use backward transition radiation (BTR) in the Extreme Ultraviolet (EUV) region ($\hbar\omega \simeq 90\text{ eV}$) as possible tool for transverse bunch profile diagnostics. In this case it seems to be possible to overcome both limitations mentioned above. Since the radiation wavelength in the EUV region

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is much smaller compared to the optical one, coherent radiation effects should be suppressed. In addition, the smaller wavelength in EUV region reduces the threshold imposed by the diffraction limit and allows in principle to measure with sub-micron resolution.

In this paper we report about the first observation of BTR in the EUV region. The angular distribution of the radiation was measured in different geometries and compared for the optical and the EUV region. A simple model of backward transition radiation based on the interaction of a charged particle with a tilted target of arbitrary permittivity was applied to explain the experimental results.

2. THEORETICAL MODEL

In our theoretical estimations we follow a simple method of transition radiation that is generated at an ideally reflecting target. In this case the radiation field is expressed using the projection angles θ_x and θ_y that are counted from the specular reflection direction:⁸

$$\mathbf{E}(\theta_x, \theta_y) = \frac{e\beta}{\pi c} \frac{1}{\beta^2 \cos^2 \theta_x \cos^2 \theta_y - 1} \frac{e^{i\mathbf{k}\mathbf{r}}}{r} \left\{ -\cos \theta_x \sin \theta_x \cos \theta_y, -\cos^2 \theta_x \cos \theta_y \sin \theta_y, \sin^2 \theta_x + \cos^2 \theta_x \sin^2 \theta_y \right\}. \quad (1)$$

e is the electron charge, β the electron velocity, c the speed of light, $\mathbf{k}$ the wave-vector of the emitted photon, $\mathbf{r}$ the detector coordinate, and $r = |\mathbf{r}|$. The real optical properties of the target are taken into account using the Fresnel reflection coefficients R_σ and R_π . In this case the spectral-angular density of the radiation is expressed as:

$$\frac{d^2 W}{\hbar d\omega d\Omega} = \frac{cr^2}{\hbar} \left[|R_\sigma E_y|^2 + |R_\pi|^2 (|E_x|^2 + |E_z|^2) \right], \quad (2)$$

with $\hbar$ the Plank constant.

In an equivalent picture, BTR is treated as reflection of virtual photons connected to an initially charged particle at a target which acts as a mirror.

If the target permittivity ε is known, the Fresnel coefficients can be expressed as⁹:

$$R_\sigma(\alpha) = \frac{\cos(\pi/2 - \alpha) - \sqrt{\varepsilon - \sin^2(\pi/2 - \alpha)}}{\cos(\pi/2 - \alpha) + \sqrt{\varepsilon - \sin^2(\pi/2 - \alpha)}} \\ R_\pi(\alpha) = \frac{\varepsilon \cos(\pi/2 - \alpha) - \sqrt{\varepsilon - \sin^2(\pi/2 - \alpha)}}{\varepsilon \cos(\pi/2 - \alpha) + \sqrt{\varepsilon - \sin^2(\pi/2 - \alpha)}} \quad (3)$$

Here α is the grazing angle of electron incidence, see Fig. 1. Applying these equations it is possible to calculate the characteristics of BTR.

Because of the high reflectivity of molybdenum in the photon energy range of 30...100 eV for grazing angles $\alpha \leq 30^\circ$, a silicon target with a thin molybdenum surface layer was used for the experiment. The molybdenum permittivity in the photon energy range of 1...30 eV was taken from Ref.¹⁰ in the range of 30...150 eV anomalous scattering factors $f_1(\hbar\omega)$, $f_2(\hbar\omega)$ tabulated in Ref.¹¹ were used to recalculate ε according to

$$\varepsilon(\hbar\omega) = \left[1 - \left(\frac{\hbar\omega_p}{\hbar\omega} \right)^2 \frac{1}{2Z} (f_1(\hbar\omega) + i f_2(\hbar\omega)) \right]^2 \quad (4)$$

with ω_p the plasma frequency and Z the atomic number.

The results of this calculation are shown in the following together with experimental results.

Figure 1. Experimental scheme. The y -axis is perpendicular to the drawing plane and points to the reader.

3. EXPERIMENTAL SETUP

The experiment was carried out at the 855 MeV electron beam of the Mainz Microtron MAMI (Institute of Nuclear Physics, University of Mainz, Germany). Fig. 1 shows the scheme of the experimental setup. The electron beam with average beam current of 52 nA was used in macropulse operation, i.e. with a pulse duration of 0.8 sec and 3 sec spacing. The BTR target was mounted onto a goniometric stage together with wire scanners for transverse beam size diagnostics.

The BTR target was made of a 50 nm thin molybdenum layer (surface roughness better than 0.5), evaporated onto a 0.5 mm thick silicon substrate (dimension 40 mm $\times$ 10 mm). During the course of the experiment, it was oriented under two different grazing angles: $\alpha = 28.07^\circ$, $\theta_D = 2\alpha = 56.14^\circ$ (so-called “forward” geometry) and $\alpha = 67.5^\circ$, $\theta_D = 2\alpha = 135^\circ$ (so-called “backward” geometry).

The experiment was carried out using different beam sizes by changing the focusing lengths of upstream quadrupoles. Beam sizes were determined based on wire scanner measurements, the corresponding sizes (FWHM) are listed in Table 1. Almost all beam profiles were fitted by ordinary Gaussians except for beam configuration No.3 (obtained while all upstream quadrupole magnets were switched off). For this configuration, the horizontal beam profile fit function was $a \exp[-0.5 (\frac{x-x_0}{\sigma})^c]$ with $c = 8.97$. This configuration was used only for $\alpha = 67.5^\circ$.

The resulting transition radiation angular distributions were recorded with a scientific grade CCD camera (ANDOR DO434-BN-932) with 1024 $\times$ 1024 pixels and a pixel size of to 13 $\times$ 13 μm^2 . Special feature of this CCD camera was the comparable high sensitivity in the photon energy range of 1 eV up to 10 keV.

The distance from the target to the camera amounted 1010 mm. The camera collected light during 1 sec: 0.1 sec before start of the the macro pulse, 0.8 sec during macro pulse duration, and 0.1 sec after the macro pulse. A filter set mounted on a movable holder was installed between target and camera. The filter characteristics are listed in Table 2. Filter transmission coefficients together with the CCD quantum efficiency are shown in Fig. 2. The data for the optical filters and the CCD were taken from the manufacturers, the ones for the aluminum

Table 1. Beam sizes in the interaction point

No.	Vert. FWHM, μm	Horiz. FWHM, μm
1	64.3	533
2	542	365
3	247	6111

Table 2. Filter characteristics

No.	Type
1	Aluminum foil, 1.3 μm (2 layers of 0.65 μm foil)
2	Aluminum foil, 1.8 μm
3	Fused silica, 3 mm

Figure 2. Transmission coefficients of the filters and CCD quantum efficiency (black curve). Filter No. 1 – green curve, No. 2 – pink dashed curve, No. 3 – red curve.

foils from Ref.¹¹ Because of the aluminum L-edge ($\hbar\omega \approx 72$ eV) the aluminum foils (No.1 and No.2) acted as low-pass filters.

The detection system was operated under vacuum. The CCD was cooled down to about -40° C in order to decrease the dark current. The images obtained using filters No. 1 and 2 were averaged over 200 shots, the ones obtained with filter 3 over 20 shots. The CCD noise was obtained without beam and averaged over 100 shots.

In the following the photon spectral region expected in the experiment will be explained: the lower limit is defined by the CCD quantum efficiency and is believed to be about 1.2 eV. The upper limit is determined by the filter in use. In Fig. 2 the photon energy range ends at a photon energy of about 150 eV because the reflectivity of the single molybdenum layer at grazing angles used in the experiment drastically decreases at high energies. Characteristic X-ray absorption edges of both the molybdenum layer (L-edges in a range of 2520...2865 eV and M-edges in a range of 228...506 eV) and the silicon substrate (K-edge at 1839 eV and L-edges in the range of 100...150 eV) can be detected by the camera. Hence, they can influence the obtained images. However, the spatial distribution of characteristic X-ray is isotropic and one may be able to separate backward transition radiation.

4. EXPERIMENTAL RESULTS

All results presented in this section were calculated resp. normalized for a total number of electrons of $N_e = 10^{10}$ (usual bunch population of modern accelerators). In addition, they will be presented in the unit CCD counts per pixel, i.e. N_{ph}^{pix} . This quantity was obtained according to

$$N_{ph}^{pix} = N_e \int d\Omega \hbar d\omega \frac{d^2 W}{\hbar d\omega d\Omega} E_{CCD}(\hbar\omega) T_i(\hbar\omega) \quad (5)$$

with $E_{CCD}(\hbar\omega)$ the CCD quantum efficiency and $T_i(\hbar\omega)$ the transmission function of the i -th filter (see Fig. 2). The solid angle $d\Omega$ is defined by the pixel size and the target-detector distance. The following values are compared for the theoretical and the experimental distributions: distance between maxima, number of CCD counts, and distribution asymmetry. The latter is obtained according to:

$$A = \frac{I_l - I_r}{I_l + I_r} \quad (6)$$

with I_l and I_r the intensities of the left and right distribution maxima, respectively.

As a first step, the angular distributions of BTR in the optical spectral region were obtained. Fig. 3 shows recorded BTR for a grazing angle of $\alpha = 28.07^\circ$ with filter No. 3. Fig. 4 shows the experimental and theoretical cross sections along the θ_x ($\theta_y = 0$) resp. the θ_y ($\theta_x = 0$) directions.

Figure 3. Spatial distribution of backward transition radiation obtained with filter No.3.

Figure 4. Cross sections along θ_x ($\theta_y = 0$) (upper) and θ_y ($\theta_x = 0$) (lower) directions obtained with filter No.3 (blue dots). Theoretically predicted distributions are shown by red lines and divided by a factor of 2.

Table 3. Characteristics of optical transition radiation for different beam shapes obtained with filter No. 3.

Beam	α , deg	Distance between maxima, γ^{-1}	A, %	Total exp. CCD counts,
No.1	28.07	x : 3.7	x : 0.6	$8.85 \cdot 10^6$
		y : 2.6	y : 23	
	67.5	x : 3	x : 3.3	$10 \cdot 10^6$
		y : 2.6	y : 26.8	
No.2	28.07	x : 2.3	x : 2.8	$7.14 \cdot 10^6$
		y : 2.6	y : 9.5	
	67.5	x : 2.4	x : 6.3	$7.45 \cdot 10^6$
		y : 2.7	y : 9.3	
No.3	67.5	x : 2.8	x : 0.9	$6.92 \cdot 10^6$
		y : 2.4	y : 1.1	

Figs. 3 and 4 demonstrate that the distribution recorded experimentally in the optical spectral region deviates from the theoretically predicted one in shape and intensity. The experimental distance between the maxima along the θ_y axis is equal to about $2.6\gamma^{-1}$, along the θ_x axis to about $3.7\gamma^{-1}$, while the theory predicts $2\gamma^{-1}$. The vertical asymmetry is equal to $A_y = 23\%$, the horizontal one to $A_x = 0.6\%$, while theoretical distributions are symmetrical. The most significant reason for such asymmetry seems to be synchrotron radiation from upstream quadrupole magnets. In order to investigate the origin of such discrepancy in standard OTR configuration, quadrupole currents were changed in order to obtain beams of different shape and measure the characteristics of transition radiation. The results are listed in Tab. 3.

The intensity of the theoretical distribution is twice higher than experimentally measured. We believe that this was caused by the thin molybdenum layer which decreased the target reflectivity. The total number of CCD counts calculated theoretically in the angular range $-4.56\gamma^{-1} \leq \theta_x \leq 4.56\gamma^{-1}$, $-4.56\gamma^{-1} \leq \theta_y \leq 4.56\gamma^{-1}$ is equal to $2 \cdot 10^7$ for $\alpha = 28.07^\circ$ and $2.1 \cdot 10^7$ for $\alpha = 67.5^\circ$. From Tab. 3 it is possible to see that while switching off all upstream quadrupole magnets (beam No.3) we had an almost symmetrical angular distribution. However, the distance between the maxima in the distribution is still larger than $2\gamma^{-1}$ which may be caused by a pre-wave zone effect.¹²

Figure 5. Spatial distribution of backward transition radiation obtained with filter No.1.

Figure 6. Cross sections along the θ_x ($\theta_y = 0$) (upper) and the θ_y ($\theta_x = 0$) (lower) direction, obtained with filter No.1 (blue dots). Theoretically predicted distributions are shown by red lines and multiplied by a factor of 6.

Table 4. Characteristics of EUV transition radiation for different beam sizes obtained with filter No. 1.

Beam	α , deg	Distance between maxima, γ^{-1}	A , %	Total, exp CCD counts
No.1	28.07	x : 2.3	x : 8.3	$3.57 \cdot 10^6$
		y : 2.2	y : 5	
	67.5	x : 1.7	x : 1.3	$0.45 \cdot 10^6$
		y : 2.1	y : 3.3	
No.2	28.07	x : 1.7	x : 1.9	$2.44 \cdot 10^6$
		y : 2.2	y : 5.9	
	67.5	x : 1.4	x : 0.7	$0.38 \cdot 10^6$
		y : 2.5	y : 0.1	
No.3	67.5	x : 2.1	x : 2.9	$0.40 \cdot 10^6$
		y : 2.1	y : 1.5	

Fig. 5 shows an example of an experimentally obtained BTR angular distribution for the grazing angle $\alpha = 28.07^\circ$ with filter No. 1, using beam configuration No. 1. Fig. 6 shows experimental and theoretical cross sections along the θ_x ($\theta_y = 0$) and θ_y ($\theta_x = 0$) directions.

Figs. 5 and 6 demonstrate that the measured angular distribution in the EUV region is close to the theoretical one with respect to the shape. The measured distance between the maxima along the θ_y axis is about $2.2\gamma^{-1}$, along θ_x axis about $2.3\gamma^{-1}$ while the expected one amounts to $2\gamma^{-1}$. The vertical asymmetry is about 5.1%, the horizontal one about 8.3%, while from theory it is expected to be symmetrical. The characteristics of the images obtained with filter No. 1 using different beam sizes are listed in Tab. 4. According to this table it is also possible to see that angular distributions in the EUV spectral region are more symmetrical than the ones in the optical spectral region. This may be explained by the fact of a suppressed contribution of synchrotron radiation from the upstream magnets at higher photon energies.

The total number of CCD counts simulated theoretically in the angular range $-4.56\gamma^{-1} \leq \theta_x \leq 4.56\gamma^{-1}$, $-4.56\gamma^{-1} \leq \theta_y \leq 4.56\gamma^{-1}$ is equal to $0.58 \cdot 10^6$ for $\alpha = 28.07^\circ$ and $6 \cdot 10^4$ for $\alpha = 67.5^\circ$. From theory the intensity should be six times smaller than the one measured experimentally for beam No. 1 (comparing the total number of CCD counts), and a factor of 4.2 times smaller for beam No. 2. The measured intensity is even

Figure 7. Difference images for grazing angles of $\alpha = 28.07^\circ$ and $\alpha = 67.5^\circ$ in the optical (left) and the EUV spectral region (right).

larger than the theoretical one if we assume that our target has reflection coefficients equal to one in the whole energy range. In this case the calculated total number of CCD counts would amount $1.75 \cdot 10^6$ and would not depend on the grazing angle α .

One explanation might be to assume that there was some optical background passing the filters. Filter No.1 was made of two layers of $0.65 \mu\text{m}$ thick foil, and each individual foil was transparent for optical light (because of pinholes). However, two layers were measured to be opaque which was verified before the experiment. To ensure that no optical radiation contributed to the measured intensity the number of photons collected by the CCD using filters No.1 and 2 will be compared. The latter one consisted of a single aluminum layer ($1.8 \mu\text{m}$) and was opaque for optical light. Let us compare the total number of CCD counts after both filters, and let us calculate additionally the ratio ($R = \frac{N_{o.1}}{N_{o.2}}$). The measured value is about $R = 2.14$, taking beam configuration No. 1 as a basis. From theory the number of CCD counts may deviate only because of a difference in the filter transmission coefficients. However, the measured ratio is rather close to the theoretical one of $R = 2.36$, obtained by integration over the filter transmission coefficients. As a result, filter No.1 should be opaque for radiation in the optical spectral region.

An additional possibility to verify that while using aluminum foil filters no radiation in the optical spectral region contributed to the measured intensity is to compare the measured angular distributions for the two grazing angles $\alpha = 28.07^\circ$ and $\alpha = 67.5^\circ$. In case of optical radiation contributions the difference should not be significant, but in case of radiation only in the EUV region the intensity should change drastically because of the photon energy dependence of the reflection coefficients. Fig. 7 shows the difference images for the optical (filter No.3) and the EUV spectral region (filter No.1). From Fig. 7 one may see that the intensity difference of optical transition radiation for grazing angles $\alpha = 28^\circ$ and $\alpha = 67.5^\circ$ is almost zero as expected besides some part that is caused by the difference in the reflection coefficients. The difference for EUV radiation results in a well-known transition radiation distribution which means that the radiation have a pronounced dependence on the grazing angle, and this is an additional proof of the spectral region from which the radiation originates.

5. CONCLUSION

As conclusion it is of importance to point out that the properties of measured BTR in the EUV region was observed reproducibly. The intensity of the measured radiation in this spectral region was higher than predicted from theory, and therefore an application as basis for transverse beam profile diagnostics seems to be realistic in modern accelerators. The yield of EUV radiation obtained for a grazing angle of $\alpha = 28.07^\circ$ together with

a $1.3\text{ }\mu\text{m}$ thick Al filter was smaller than the one obtained in the optical spectral region with filter No.3 by a factor of $2.4 \dots 2.9$, depending on the beam configuration. The results obtained for the molybdenum target at a grazing angle $\alpha = 28.07^\circ$ and $1.3\text{ }\mu\text{m}$ thick Al filter allow to give an estimate for the EUV BTR yield of $3.5 \cdot 10^{-4}$ photons/electron. The radiation measured in the EUV region is more symmetrical than in the optical spectral region, and it seems that the influence of parasitic synchrotron radiation is suppressed. This may be an additional advantage for a diagnostics based on transition radiation in the EUV region.

As the next step we plan to install a multi-layer focusing mirror that render it possible to obtain beam profiles using EUV radiation, and to investigate the possibility of beam profile measurements.

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