Ti Foil Light in the ATA Beam

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ABSTRACT

An experiment is in progress to characterize the visible light produced when a Ti foil is immersed in the ATA 2 kA, 43 MeV beam. Results obtained to date indicate that the optical condition of the foil surface is a critical determinant of these characteristics, with a very narrow angular distribution obtained when a highly polished and flat foil is used. These data are consistent with the present hypothesis that the light is produced by transition radiation. Incomplete experiments to determine the foil angle dependence of the detected light and its polarization are summarized and remaining experiments are described.

Introduction

Visible light produced by electrons striking titanium and carbon foils is used to determine the primary current density profile in the Advanced Test Accelerator (ATA) and Experimental Test Accelerator (ETA) at the Lawrence Livermore National Laboratory. An image of the visible light is formed using conventional optics and TV cameras, and the image intensity is assumed to be proportional to the current density[1,2]. The mechanism of light generation at the foil surface has not been clearly established and there is some concern that its intensity may not be a reliable monitor of primary current density under the conditions of the ATA beam, i.e. 2-10 kA current, up to 100 kA/cm^2 current density, and 40-50 MeV electron energy. Consequently, experiments have begun to identify the light generation mechanism(s) and determine the reliability of foil light for diagnostic application on ATA.

Light produced by electron beams at foil surfaces has been studied since the early days of vacuum tubes. "Lilienfeld light"[3] was commonly observed at the anode of discharge tubes. Fluorescent processes were often suspected, but careful studies showed that low energy electrons (up to a few hundred keV) produce plasma oscillations among conduction electrons both at the the surface and interior of metals. These oscillations produce radiation in a broad spectrum about the plasma frequency, which is often in the visible or UV regions in low Z metals. "Lilienfeld light" later became known as "plasma radiation" or "plasmon light". Its abundance and properties depend on the optical attenuation and dielectric properties of the medium as well as electron energy. Good reviews of the literature are found in references 4-8.

Frank and Ginsburg[9] showed that a more abundant "transition radiation" is produced by relativistic electrons and hundreds of papers have confirmed this experimentally. Good reviews appear in references 7-8 and 10-17. Transition radiation is observed whenever relativistic charged particles pass through the dielectric interface at the surface of dielectric or metal foils. This phenomenon has been used successfully to determine the current density profile and energy of accelerator beams by Wartski[14,17,18] and that application has been reviewed in references 16-21.

Plasma radiation, Cerenkov radiation, and transition radiation are closely related. Plasma radiation is important as a light source for low energy electrons accompanying the beam. It is emitted in a very broad angular distribution from both surfaces of the foil[4,5,12,22-24]. The angular distribution varies with photon wavelength, peaking near the foil normal at long wavelengths and along the foil at short wavelengths. At intermediate wavelengths where the light frequency is twice the plasma frequency, the peak occurs at 45° to the foil normal. This mechanism could play an important role when a foil is at 45° to the beam and light is detected normal to the beam. Cerenkov radiation is generated within the foil and is usually unimportant in metal foils due to attenuation. In addition, it is emitted only in the forward direction and at small angles to the beam in the case of 40-50 MeV electrons in metal foils whose dielectric constant is near unity.

Transition radiation is emitted from both surfaces of a foil and the yield per electron increases rapidly with electron energy. Its spectrum is a broad continuum but the light is emitted into a narrow conical shell from each surface which peaks at $\theta=1/\Gamma$ and is $1/\Gamma$ in width where Γ is the electron energy in units of the rest mass. Light emitted in the forward direction (from the electron exit surface) is symmetrical about the beam and independent of foil angle. Backward radiation (from the entry surface)

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is emitted into a conical shell whose axis lies in the direction of specular reflection of the beam and its apex angle is the same as the forward cone[7,17]. Wartski[17] simplifies the predicted yield by:

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2}{4\pi^2}\frac{\sin^2\theta}{(1-\beta\cos\theta)^2}\left|\frac{\epsilon^{\frac{1}{2}}-1}{\epsilon^{\frac{1}{2}}+1}\right|^2 \qquad (1)$$

where θ is the angle between the line of observation and the direction of specular reflection of the beam, $\beta=v/c$, and ϵ is the complex dielectric constant of the foil at the radiation wavelength. Thus the light detected normal to the beam from the back of the foil will vary with the foil angle relative to the beam.

Transition radiation is polarized in the radiation plane (defined by the electron velocity and the viewing axis) and its intensity passes through zero at the cone axis. On the back side of the foil the radiation plane is defined by the foil normal and the electron velocity. The observation plane defined by the viewing axis and the foil normal may not coincide with the radiation plane. When the incident beam is divergent or misaligned, some electrons have non-zero velocity normal to the observation plane and generate light which is not polarized in that plane. The net polarization, defined by eq. 2 below,

$$P = \frac{(I_\parallel - I_\perp)}{(I_\parallel + I_\perp)} \qquad (2)$$

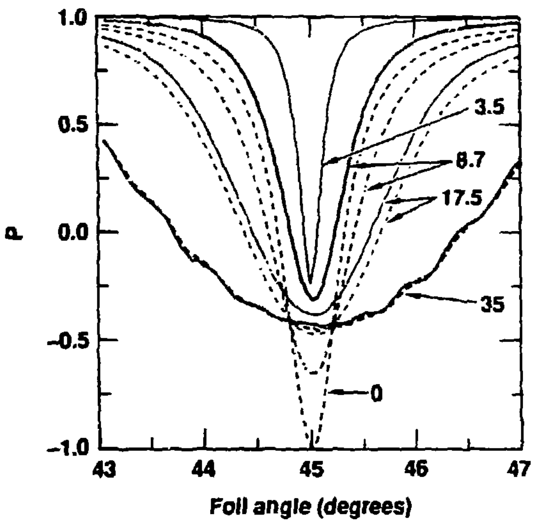

Figure 1. Predicted net polarization vs. foil angle. Curves correspond to beams with divergence 0, 3.5, 8.7, 17.5, and 35 mrad divergence. Solid curves show predictions when the beam is in the observation plane and dashed curves show predictions when the beam is inclined at an angle of 17 mrad to that plane.

is less than 100% and the angular distributions of the parallel and perpendicular polarized components of the light are distinct. The parallel component tends to peak away from the specular reflection axis at an angle 1/Γ and pass through a minimum at the axis. The perpendicular component peaks at the specular axis and its magnitude is very sensitive to the beam divergence and misalignment. In both cases the dependence of detected light on foil angle is very sensitive to the angular divergence of the beam and/or the angle between the radiation and observation planes, i.e. the beam misalignment. Thus the net polarization, P, is a sensitive function of beam divergence and foil angle. Yield of parallel and perpendicular polarized transition radiation as a function of foil angle has been calculated for Ti foils in the ATA beam based on the formulas of Ter-Mikaelian[8]. Calculated yields at 500 nm were convoluted with divergent incident electron distributions assumed to be Gaussian with 1/e angles in the range 0-35 mrad. These results will be discussed later with the experimental data obtained to date. Net polarization was also determined from eq. 2 for the calculated profiles. Results are shown in Figure 1. Two sets of calculations are shown corresponding to divergent beams aligned with their axes in the observation plane and inclined at an angle 10 mrad to the plane.

Experiment

Limited access to the ATA beam made it necessary to view Ti foil light normal to the electron beam. Figure 2 shows the experiment configuration. Background light sources due to the electron injector, fluorescence in benzene gas used for beam transport, and the KrF laser used to ionize the benzene are hidden from view by the offset in the beamline. The foil used was a 0.76 mm thick disk of Ti backed up by a 1.5 mm thick disk of carbon to protect the wiggler in case of foil failure. Rotation through 180° allows carbon foil light to be studied as well. Both foils were approximately 25 mm diameter and large compared to the usual 5-10 mm diameter beam spot. Light produced at the foil was transported through a quartz vacuum window and through air over four large mirrors to a small periscope at a distance of 11 m. The 1 cm² periscope aperture determines the angular acceptance in the experiment. The periscope had a rotatable polarizer and provision for wavelength filtering but no filtering was used in the experiments thus far.

During the experiment the foil angle (angle between the beam and the foil normal) was varied while the viewing axis remained normal to the beam. A polarizer in the optical path transmitted light polarized either perpendicular or parallel to the observation plane. Experiments were also carried out while the polarizer was rotated at fixed foil angle. Beam current and centroid position were monitored using wall current monitors. One pair of monitors was located on either side of the foil as shown in Figure 2, and one pair was located immediately upstream from the foil. Beam position determined at two

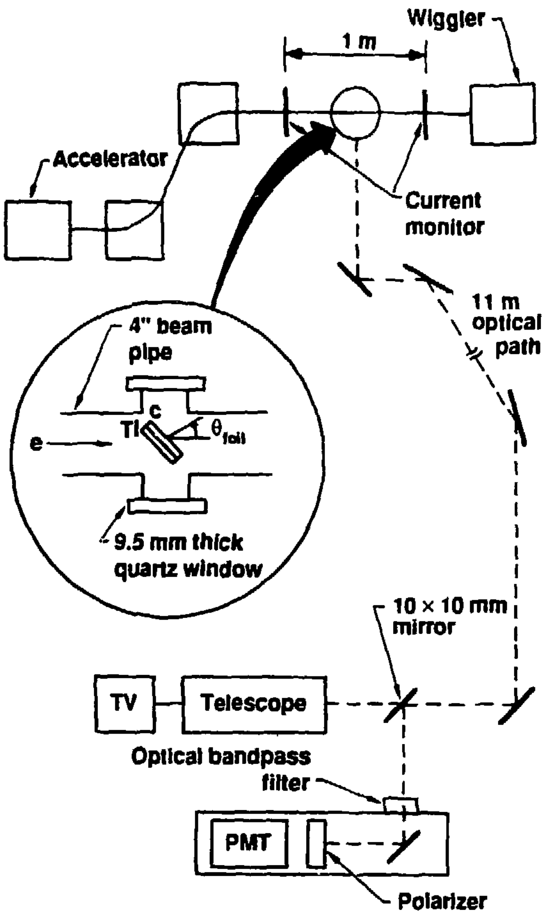

Figure 2. Experiment configuration for foil light measurements in the ATA beam.

adjacent monitors was used to monitor the beam alignment. The visible beam spot was simultaneously observed using a TV camera focussed on the foil. The electron beam was aligned with the beamline axis using positions indicated by the wall current monitors with the foil removed. This procedure insured that the observation and radiation planes were nearly coincident and that the maximum angle between them was 5 mrad. In all of the data reported below the signal detected at the photomultiplier was integrated over time and normalized to the integral of the total beam current indicated by the wall current monitors.

Results

Variation of detected light with foil angle depends critically on the condition of the foil surface as shown in Figure 3. Two scans were taken using a Ti foil whose surface was unpolished and which produced very diffuse reflected images of light sources held near the surface. Another scan was taken with a polished Ti foil. The surface of this foil was tested by reflecting a HeNe laser beam from it and determining the divergence of the reflected light, which was generally about 1 mrad. In the data shown the absolute intensity was not determined, but the photomultiplier detection efficiency and gain were not

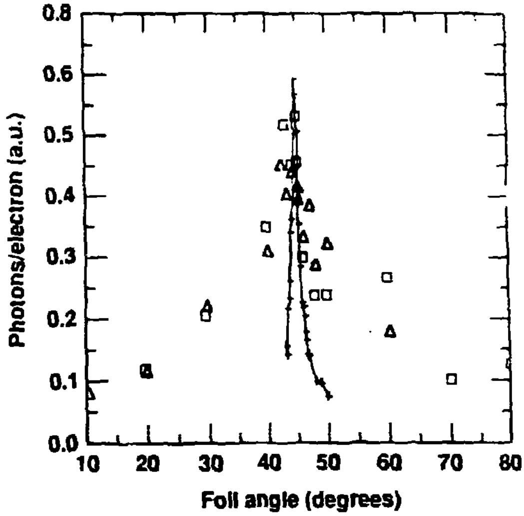

Figure 3. Comparison of polished (solid curve) and unpolished Ti foil (triangles and boxes). Data show detected light vs. angle between the beam and the foil normal. Triangles show data for perpendicular polarized light and boxes the parallel component. Solid curve shows perpendicular component for polished foil.

changed between scans. It appears that the polished foil does not generate a brighter source of foil light.

Relative intensity normal to the beam varies with foil angle as predicted for transition radiation when the foil is polished to a reasonably good optical quality. Figure 4 shows the experimental data obtained for the perpendicular component superimposed on several predicted distributions for transition radiation. Predicted yield was calculated according to Ter-Mikaelian[8] as before. The several curves in the figure show that agreement between the observed foil angle dependence and the transition radiation prediction is good when the beam is assumed to have a Gaussian angular distribution with 1/e angle 15-30 mrad. The experimental yield data has not been determined absolutely, so for purposes of comparison in Figure 4, the experimental data and the transition radiation calculations have been re-scaled to a maximum value of unity.

Foil angle dependence for the parallel polarized component has not been determined as yet. These data should provide an interesting test of the transition radiation hypothesis. Figure 5 shows calculations of the parallel polarized transition radiation intensity normal

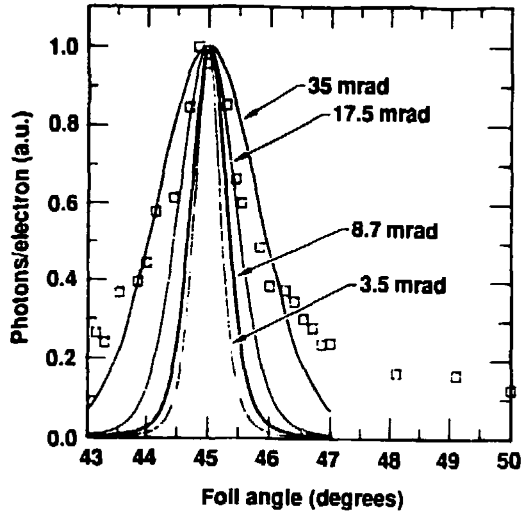

Figure 4. Foil light polarized perpendicular to the observation plane. Boxes show the experimental data while predictions for transition radiation at 500 nm are indicated by solid curves.

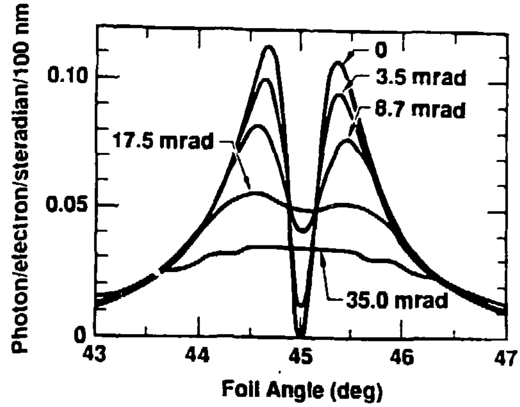

Figure 5. Calculated intensity of transition radiation normal to the beam for light polarized in the observation plane (parallel). The family of curves show the foil angle dependence for several assumed values of beam angular divergence.

to the beam as a function of foil angle. Beams with small divergence produce a node at foil angle 45°. Even when the divergence is as large as 20 mrad or so the foil angle distribution is flat or depressed near 45°. These characteristics are unique and, if observed, would rule out most other foil light generation mechanisms.

Foil light polarization experiments are in progress but are incomplete. Measurements at foil angles 45, 46, and 46.5° are expected to provide a clear test of the transition radiation hypothesis. Examination of Figure 1 shows that, for reasonable values of beam divergence, the net transition radiation polarization should be large and negative at foil angle 45°, but will shift to a large and positive net polarization at 46-46.5°. No other light generation mechanism will produce such a dramatic change in polarization direction with so small a change in foil angle.

Temporal dependence of the foil light detected by the photomultiplier is shown in Figure 6 and compared to the beam current indicated by the wall current monitor. The foil light follows the current trace closely with no indication of delayed emission or saturation. It appears to follow electron current linearly over the range 0-4 kA/cm².

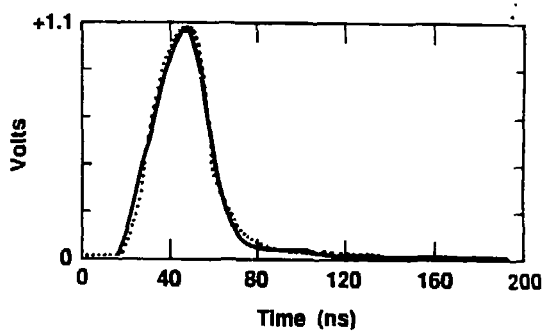

Figure 6. Foil light vs. time (solid curve) and beam current vs. time (dotted curve).

Discussion

Ti foil light observed on the electron entry side is seen to be prompt and has no observable delayed emission following beam passage through the foil. The angular distribution observed normal to the beam is very sensitive to the condition of the Ti foil surface. When the surface is polished sufficiently to provide good specular reflection, then the foil light observed has a very sharp angular distribution characteristic of transition radiation. The observed angular width is in good agreement with predictions for transition radiation, assuming the incident beam is slightly divergent.

The observed characteristics rule out significant contributions due to bremsstrahlung, Cerenkov, plasma, or fluorescent light. Reflections of background light from the foil surface are not entirely ruled out, but the source would have to be spatially small to produce the experimental data. Its angular size would have to be no larger than 15 mrad when viewed from the foil location.

Conclusions

Foil light experiments reported above are incomplete as yet and not conclusive. However, many hypothetical light generation mechanisms have been ruled out by the data obtained up to this point. Ti foil light on the electron entry side has characteristics completely consistent with transition radiation and is not consistent with fluorescence, bremsstrahlung, Cerenkov, or plasma light mechanisms. Its angular distribution is extremely narrow and it is linear with beam current at least up to current densities of 4 kA/cm². Since transition radiation yield increases rapidly with electron energy, this light source is not expected to be appreciably stimulated by secondary electrons or other charged species accompanying the beam. Nevertheless, its narrow and structured angular distribution make beam profile measurements based on polished Ti surfaces using small aperture optics an inherently unreliable procedure unless great care is taken. Only diffuse reflecting foil surfaces or large aperture optics obviate the difficulties inherent in a highly directional light source.

If the foil light is, indeed, produced by transition radiation it should be possible to infer the beam divergence from a measurement of the foil light angular distribution or polarization at a polished foil. Similarly, the foil light image produced on a diffuse surface foil should be a reliable monitor of the current density profile of the primary beam. Two such measurements, taken together, should be helpful in establishing the brightness of the electron beam.

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