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**TITLE: INITIAL OPTICAL TRANSITION RADIATION
MEASUREMENTS OF THE ELECTRON BEAM FOR THE
BOEING FREE-ELECTRON LASER EXPERIMENT**

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**Initial Optical Transition Radiation Measurements of the Electron Beam for the Boeing
Free-Electron Laser Experiment***

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ABSTRACT

The potential for characterization of electron beams at ~ 100 MeV at the Boeing Free-Electron Laser (FEL) facility by optical transition radiation (OTR) techniques has been demonstrated as an important complement to other diagnostic means. Electron beam properties such as spatial profile and position, current intensity, emittance, and energy were made accessible in an on-line manner. Initial examples including transport through the 5-m wiggler and the resolution of Cerenkov radiation and spontaneous emission radiation competitive sources are discussed.

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I. INTRODUCTION

During the past year we have tested and implemented optical transition radiation (OTR) techniques [1, 2] for characterizing the ~110-MeV electron beam of the Boeing visible Free-Electron Laser (FEL) experiment. These techniques have been demonstrated to be an important complement (or replacement) to other diagnostic methods [2-7]. Electron beam properties such as spatial profile and position, divergence, current intensity, emittance, and energy were accessed in an on-line manner in most cases.

Due to the e-beam energy-dependencies of OTR, the potential advantages of OTR-based systems over the reference fused silica plus polished aluminum mirror or phosphors include: an improved effective spatial resolution, reduction in beam scattering and Bremsstrahlung radiation, on-line divergence measurements, single axial position e-beam pointing information, and elimination of a superimposed Cerenkov source image. In the latter case, our data show that at these energies, with the specified converter assembly geometry, and for fused silica 125- μm thick, the OTR intensity from the aluminum mirror is comparable to the fused silica sources (Cerenkov plus OTR). Therefore interpretation of observed spot sizes using both sources must be done carefully.

We have used self-supporting, polished aluminum mirrors oriented at 45° to the beam direction at beamline locations in a straight section after accelerator #6, before the wiggler, within the wiggler, and after the wiggler. These were basic single foil experiments in which the camera focus was adjusted to provide beamspot sizes. The OTR angular distribution measurements with a two-foil interferometer and preliminary emittance measurements will be discussed also in Section III.

II. EXPERIMENTAL CONSIDERATIONS

For completeness, a few brief comments about the OTR mechanism and the Boeing facility's electron-beam properties are provided in this section.

Optical transition radiation was first predicted by Ginzburg and Frank in 1946 [1], but its practical usefulness as an e-beam diagnostic was not explored/demonstrated until 1975 by Wartski [2]. Optical transition radiation is generated when a charged particle beam crosses the interface, or transition, between two media of different dielectric constraints. Its angular distribution pattern can be exploited to measure e-beam divergence and energy, although these two parameters are somewhat convoluted. One of its more useful features is that the backward lobes of radiation are emitted around the angle of specular reflection so that a foil at 45° to the beam emits at 90° to the beam, the standard port geometry for accelerator beamlines (see Fig. 1). The angle integrated brightness of the OTR is much less than Cerenkov light, but at higher e-beam energies, the emission opening angle of $1/\gamma$ leads to a localized photon/steradian brightness that is comparable to or exceeds Cerenkov light. Another important feature is that effective spatial resolution limit in diagnostics becomes the optical sensor, and one is no longer limited by thickness of the fused silica or phosphor.

The experiments as implemented at Boeing were worked into several locations along the beamline. The schematic of the beamline is shown in Fig. 2 where the principal targets are the straight section after the last accelerator (A-leg), the straight section before the wiggler (C-Leg), the wiggler itself with eleven viewing stations separated by 0.5 m, and a position 1.2 m after the wiggler just before the e-beam spectrometer. This is somewhat the chronology of introduction into the system except the wiggler screens were changed after some experiments were done at the station 1.2 on after the wiggler where spontaneous emission source competed with the OTR.

We used both the standard vidicon cameras at the beamline positions and gated, intensified charge-injection device (CID) cameras. As will be shown later, we could saturate a standard video camera viewing a beamspot by integrating over the broadband OTR and the e-beam macropulse. In cases involving spectral filtering, polarization filtering, angular distribution measurements, and/or anticipated sampling of a portion of the macropulse, the intensified camera sensitivity was needed.

The electron-beam parameters that we addressed were: spatial position and profile, current intensity, divergence, pointing, emittance, energy, and micropulse duration (potential). Samples of results are given in the next section.

III. EXAMPLES OF RESULTS AND DISCUSSION

A number of very graphic examples of the improvements in diagnostic capabilities via OTR techniques is presented below. First, it would be appropriate to briefly discuss the reference fused silica and polished aluminum mirror-assembly that has been used for beam profile and position measurements at the Los Alamos and the Boeing FELs. Figure 3 shows a schematic of such an assembly at the Boeing facility. There are a number of sources related to the incidence of the e-beam including OTR from interfaces #1, 2, and 3 and the Cerenkov light generated in the volume of the fused silica screen. In addition to the scattering of the e-beam by the silica and refraction of the light, alignments and depth of field problems could lead to broadened beamspots as will be shown below [5]. In the fused silica screens and the alumina screens in the wiggler the e-beam interaction throughout the volume causes a thickness-dependent resolution which was limiting operations in dealing with sub-millimeter radius beams.

The A-leg diagnostic station was the least interfering to operations so initial experiments were done there. Very simply, at a station with a dual actuator the reference assembly was compared to an aluminum mirror only. Figure 4 shows that even when viewed with a standard vidicon camera, the beamspot image of 160 micropulses at 1.5 nC/micropulse could saturate the video. A subtlety here is that the calculated profiles were very similar in the x-direction, but the reference assembly result measured to be about 25% broader at full width at half maximum than the OTR-only measurement of 2.0 mm. As a point of reference Fig. 5 shows data from a Los Alamos experiment at 20 MeV where the mirror only signal was about one fourth of the total signal when a 0.5-mm thick fused silica screen was involved. Since this screen was four times thicker than the reference Boeing sample, the Cerenkov radiation from the latter

would be reduced by four. Therefore schematically we expected something like Fig. 6, where the two displaced spots would be almost equal in intensity. Indeed, when in later operations a FODO array after accelerator #6 was used to produce a smaller spot, the assembly at the A-leg showed a doublet separated by about 1.3 mm on the y-axis as seen in the upper half of Fig. 7. In the lower half of the figure, the aluminum mirror only (hence OTR only) image shows a single spot. So the quartz screens were removed from this viewing station and subsequently from the two screens in front of the wiggler on the C-leg. The resultant improved spatial resolution helped in matching to the wiggler.

Having established the source intensity and the Al mirror survivability, we completed our plans for the OTR interferometer experiment on the A-leg. Figure 8 shows a schematic of the beamline that we eventually installed. As the e-beam comes from the right, it is aligned to a reference HeNe laser line for the two stations about 2.2 meters apart. Optical transition radiation single-foils in the first and second stations can serve as beamspot monitors for a two-station emittance measurement or the variable quadrupole-variable spot size measurement at either screen. At the second station, the OTR interferometer can be used to generate both the beamspot and the e-beam divergence information as discussed previously [2-4]. The experiment was done just after the conference and an initial interference image and fringe pattern is provided in Fig. 9. The fringe visibility is quite good, the rings are symmetric, and the measured divergence was about 0.4 ± 0.1 mrad. Full analysis of the data and comparison of all three techniques' results to each other and to PARMELA calculations will be reported at a later time [8]. We believe these interferometer data are for the highest electron-beam energy (highest gamma charged-particle beam) reported to date. The higher energy also allowed a larger foil spacing in the interferometer so that we viewed directly the formation regime on the second foil. We therefore avoided optical contributions from a first clear foil as discussed by Rule, et al. [9].

A series of experiments were also performed at a station 1.2 m after the 5-meter wiggler. Because of this location, there was a significant contribution from the wiggler's

spontaneous emission radiation. A ten-position, remotely actuated filter wheel was placed in front of the camera viewing this polished metal mirror oriented at 45° to the e-beam direction. Figure 10 shows a series of images for three bandpass filter selections of 400×40 , 500×40 , and 600×40 nm. In all cases, the analyzing polarizer was in place with its polarization axis parallel to the beamline. Hence, it should significantly block the transversely polarized fundamental and any components of the second harmonic in that same plane. The central spot is the OTR light which is broadband and radially polarized. As one selected longer wavelengths, the observed ring of radiation grew in diameter as expected from calculations. Profiles taken through these images are shown in Fig. 11 and are displayed somewhat more quantitatively in Fig. 12. The approximate half-angle increased from about 3 to 6 mrad as one sampled from 400 to 650 nm. The lower portion of Fig. 12 shows the peak OTR counts where the $1/\lambda^2$ dependence has been dominated by the rapid response roll-off at shorter wavelengths of the Sh_2S_3 -targeted vidicon tube. The fundamental wavelength of 650 nm was also attenuated by the polarizer. When the polarizer was removed and the 650×50 nm filter was selected, the fundamental saturated the camera badly and dominated the OTR contribution. However, we were able to detect the steering of the e-beam just after the wiggler by using the filter combinations in Figs. 10 and 11. It should be noted also that the beamline expands in diameter from the 4.7-mm diameter wiggler gap to the about 100-mm diameter in this region.

The next major effort was the replacement of the nine inner wiggler screens of the eleven screen set [10]. Diagnostic stations had been provided every 0.5 m in the 5-meter wiggler in its initial construction. It had been suggested that a natural wavelength gap would exist between the fundamental and off axis, long-wavelength shifted second harmonic radiation as discussed elsewhere in this conference [11] (see Fig. 5 of Ref. 11).

However, the narrow bore of the wiggler, the 4.7 mrad opening angle of synchrotron radiation, the mixing of polarization in the off-axis angles and reflections in the bore combined to produce a very poor signal to background for the initial OTR

measurements. The problem was resolved by adding an optical mask (a thin metal foil), just before the OTR screen that blocked the spontaneous emission but not the electron beam. Using this system and the two OTR screens just before the wiggler, the e-beam was matched and emittance of $180\text{-}200\text{-}\pi\text{-mm mrad}$ was measured before the wiggler and in transport through the wiggler. The results are shown in Fig. 13. The horizontal axis of the figure is referenced to the wiggler entrance. One can see that for both the horizontal and vertical planes, the beamspot radii at these locations were about $1/2\text{-mm}$. The wiggler number eleven screen (W11) shows an almost 60% larger spot than the OTR screen. This comparison graphically illustrates the improvement in spatial resolution of perhaps a factor of five attained from the OTR screens. Subsequent measurements of small-signal gain also showed improvement so that the higher resolution screens may have allowed a better spatial overlap of the e-beam to the laser reference axis. The importance of matching and this diagnostic improvement is discussed in more detail by Dowell, et al. [10].

IV. SUMMARY AND CONCLUSIONS

In summary, the OTR-based techniques applications to the Boeing FEL experiment have been very successful. At these beam energies and peak currents, the OTR source is sufficiently bright for most beamline applications. The easily obtained improvements in diagnostic system spatial resolution by removing the fused silica at the A-leg and C-leg stations and replacing the aluminum screens in the wiggler have resulted in more accurate emittance measurements using both standard and new techniques, better matching into the wiggler, and better alignment within the wiggler (overlap). Further application to energy measurements either by focal plane "detector" replacements or interferometer fringe variation is in progress. Development work is needed when there is a competitive source involved in the image scene. It has been demonstrated that OTR techniques can play an important role in the characterization and optimization of the e-beam and in the concomitant improvement in FEL performance.

V. ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

- Fig. 1. Schematic of OTR radiation patterns.
- Fig. 2. Boeing FEL beamline schematic showing the accelerators, A-leg, bend, C-leg, and wiggler.
- Fig. 3. Schematic of reference fused silica and mirror assembly sources involved in beamspot images.
- Fig. 4. Initial OTR measurement of beamspot vs. Cerenkov and OTR obtained on the A-leg.
- Fig. 5. Beamspot data from reference assembly at 20 MeV using 0.5-mm thick fused silica.
- Fig. 6. Schematic representation of fused silica sources and OTR mirror source in beamspot imaging.
- Fig. 7. Beamspot doublet in y-plane discerned at A-leg station when the spot is focused smaller than in Fig. 4.
- Fig. 8. Schematic of A-leg two-foil OTR and two-station emittance measurement experiments.
- Fig. 9. Initial interferometer image (top) and fit to its horizontal profile (bottom).
- Fig. 10. Images of OTR and spontaneous emission contributions under polarization and wavelength filtering.
- Fig. 11. Profiles of the images in Fig. 10 showing the central OTR spot and ring of spontaneous emission.
- Fig. 12. Graphical display of the second harmonic ring angle location vs. wavelength (upper) and OTR intensities vs. wavelength (lower). The Sb_2S_3 vidicon tube response has not been removed.
- Fig. 13. Plot of spot sizes obtained before and within the wiggler.

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OPTICAL TRANSITION RADIATION PATTERNS

CHERENKOV RADIATION PATTERN ($\theta \sim 46^\circ$)

Fig. 1

VISIBLE FEL EXPERIMENT

Fig. 2

Fused Silica Plus Metal Mirror Assembly Can Lead to Broadened Beamspot (scattering and alignment)

Fig. 3

Optical Transition Radiation Produces Sufficient Light for E-Beam Profile Measurements

OTR

$Q = 1.5 \text{ nC/micropulse}$

$\tau = 40 \text{ } \mu\text{sec}$

$\text{FWHM}_x = 2.3 \text{ mm}$

$\text{FWHM}_y = 2.0 \text{ mm}$

Quartz

$Q = 1.5 \text{ nC/micropulse}$

$\tau = 40 \text{ } \mu\text{sec}$

$\text{FWHM}_x = 2.4 \text{ mm}$

$\text{FWHM}_y = 2.5 \text{ mm}$

FEL PR-12/20-DY-5

Fig. 4

20-MeV E-Beam Case Shows Double Spot Onset

Fig. 5

**Quartz Plus Mirror Assembly Shows
“Double Spot” Image at 110 MeV
(Schematic)**

Fig. 6

REFERENCE SCREEN ASSEMBLY PRODUCES BEAMSPOT "DOUBLET"
IN IMAGE FOR WELL-FOCUSED BEAM AT A-leg
($E_B = 109 \text{ MeV}$)

FUSED SILICA PLUS
Al MIRROR ASSEMBLY

(CHERENKOV
PLUS OTR)

Al MIRROR ONLY

(OTR)

Fig. 7

Schematic of OTR Setup on Boeing FEL for Emittance Technique Comparisons

- TWO-SCREEN
- VARIABLE QUAD
- OTR BEAMSPOT AND DIVERGENCE

Fig. 8

a)

b)

Fig. 4

**E-BEAM GENERATED IMAGES SHOW OTR AND SPONTANEOUS
EMISSION SOURCES AT STATION 1.2M AFTER WIGGLER**

Wavelength Dependence of Spontaneous Emission
and Optical Transition Radiation

Both OTR and Spontaneous Emission Sources Compete at Station 1.2 m after Wiggler

Fig. 12

Electron Beam Matching to Wiggler