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Beam Emittance From Coherent Cherenkov Radiation in a Solid Dielectric*

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DRAFT

Abstract

We report experimental results of a technique for direct measurement of the emittance in high energy beams. This technique is analogous to the well known "pepper pot" masking approach, but with no upper limit on particle energy. Single shot emittance profiles were obtained on the 10 kA, 4 MeV SNL electron Recirculating Linear Accelerator showing agreement with theory and with alternate emittance measurements. Coherent (i.e., not strongly scattered or diffused) Cherenkov radiation from a flat, transparent, range-thin dielectric foil was split by an array of mirrors in order to view the emission profile up to a divergence angle of 70°. The mirrors were imaged by a distant telescope attached to an intensified, 2 ns video framing camera. The relative intensity profiles of the multiple images were unfolded using the properties of classical Cherenkov emission and geometric optics to obtain directly, without precise knowledge of other beam parameters, the transverse velocity distribution in the viewing plane. In our case the rms emittance was directly proportional to the product of the beam diameter and the transverse velocity spread. This and prior research efforts indicate applicability over a wide range of high energy beam parameters.

I. INTRODUCTION AND BACKGROUND

Understanding the transport properties of high current (several kA), high energy (several MeV) electron beams is complicated by difficulties in experimental measurement of the beam phase space parameters. At sufficiently low currents and energies, for any particle beam, techniques based upon masking the beam and measuring the spatial distribution of expanding beamlets can be used to probe the phase space density at a high resolution¹. From such data one can obtain the local beam emittance which is a critical parameter in the focusing and transport. Alternatively, as is frequently done in the high energy accelerator community, the emittance may be inferred directly from beam profile measurements in a well defined optical system.

These emittance measuring techniques work best with repetitively pulsed or cw beam sources. Furthermore, for masks and aperture plates to perform well requires that the particle range in the mask material be small compared to the working aperture size and the beam transverse temperature be low enough to avoid collimation errors. Under these constraints successful measurements have been made² on single pulse electron beams using slit masks with pinhole detection.

Our research was motivated by the need for a diagnostic which could potentially operate at energies into the 100 MeV range and beyond, provide local measurements of emittance with nanosecond time resolution, and be minimally perturbing to the beam. We also expected to encounter difficult experimental conditions. High density plasma backgrounds, rotating hollow beams, and beams with large amplitude collective instabilities are examples of such conditions.

Conceptual design studies completed in 1985 showed that classical Cherenkov radiation, emitted in the visible band as the beam passes through a thin transparent film, contains sufficient information to unfold the transverse velocity distribution in one plane. We shall term this type of emission as "coherent" even though it is really semi-coherent as in a collimated broadband light source. In non-fluorescing materials Cherenkov emission dominates other radiation processes such as bremsstrahlung and transition radiation and has a time response on the order of the particle transit time through the material, i.e. less than one picosecond. For range-thin converter foils there is minimal perturbation to the beam. A 3d optical ray tracing computer code was written to investigate the effect of rotating and oscillating beams on the Cherenkov emission patterns. This code helped predict limitations under these conditions and provided quantitative guidelines for unfolding the beam emittance.

Basic feasibility tests were carried out on intense relativistic electron beam (IREB) machines operated jointly by Sandia National Laboratories (SNL) and the U.S. Air Force. These experimental investigations verified the predictions of the theoretical and conceptual design work. Kapton, quartz, and FEP Teflon radiators were initially tested. The transparent FEP Teflon material was chosen for further study due to its excellent performance as an optical Cherenkov radiator, its availability in large area thin films, and its relative ease of mechanical workability in stretching and mounting. The optical emission in the range of 400-700 nm from 2 mil thick foils exhibited the following properties:

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- 1) Strong peaking at the nominal Cherenkov angle
- 2) Broadband spectrum biased toward the blue
- 3) Negligible emission in the back direction
- 4) Time dependence which tracked the beam current
- 5) No evidence of beam induced fluorescence
- 6) No evidence of dose related radiation darkening

These results were obtained over a range of beam current densities from 1 kA/cm^2 to 20 kA/cm^2 and pulse lengths from 20 to 50 ns. Survivability of the converter foil is ultimately limited by the temperature rise due to the particle fluence (for single pulse machines).

The initial conceptual design and experimental studies have been summarized in a Final Report³ to the U.S. Air Force. Unfortunately, circumstances prevented the full implementation of an emittance diagnostic during this time period and work was suspended in 1987. Not until 1990 did an opportunity arise to test a prototype emittance measurement diagnostic on a pulsed IREB experiment. The tests were performed on the SNL Recirculating Linear Accelerator (RLA) injector in support of an ion focused regime transport experiment. The RLA injector, referred to as IBEX, nominally produced a 10 kA, 4 MeV, 20 ns electron beam with a 1-2 cm radius at the measurement point. Emittance data were collected after 2m and 5m of linear transport along the ion focusing channel.

These data were in good agreement with theoretical predictions of the emittance growth and also with emittance estimates obtained from a vacuum expansion technique. While Cherenkov witness plates have been used in other laboratories as optical current meters or as beam profile diagnostics⁴, to the authors knowledge, this represents the first emittance diagnostic for an IREB based entirely upon the directional properties of Cherenkov radiation.

II. DESCRIPTION OF THE DIAGNOSTIC

A. Essential properties of Cherenkov radiation

For a charged particle traveling at velocity v in a straight line through a dielectric medium with refractive index n , Cherenkov radiation is emitted in a thin cone centered on the trajectory with opening angle θ_c given by

$$\cos \theta_c = \frac{1}{\beta n},$$

where $\beta = v/c$ is the usual relativistic factor. The basic properties of this radiation are well described in the literature^{5,6}. An electron radiates an energy per unit path length in a dielectric as a function of wavelength given by (Gaussian units)

$$\frac{dW}{dx} = 4\pi e^2 \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^3} \left[1 - \frac{1}{\beta^2 n^2} \right] d\lambda,$$

where it is always assumed that $\beta n > 1$. This integral may be rewritten to express the radiation power per kiloampere of current per millimeter of dielectric thickness in the visible spectrum $\lambda_1 = 400\text{ nm}$ to $\lambda_2 = 700\text{ nm}$ as $P \approx 58 \text{ kW/kA-mm}$, where βn was chosen to be 1.4. Since this power is radiated

into a solid angle small compared to 4π , the observed intensities can be quite strong even with very inefficient light collection optics. In the case of the feasibility experiments mentioned above it was found that the Cherenkov emission from a 2 mil FEP Teflon converter was 500 times more intense than the plasma fluorescence generated by a 30kA IREB traveling in full density air.

Inside a linear, isotropic optical medium the angular thickness of the Cherenkov cone is determined mainly by coulomb scattering and by the optical dispersive properties of the dielectric. Variation of θ_c due to slowing down of the particle may be neglected for range-thin converters. In this case it can be shown that the Cherenkov cone is broadened by less than a few milliradians in the visible spectrum for most optical materials. Now consider the radiation pattern, still within the dielectric, produced by a monoenergetic beam having a transverse temperature characterized by a thermal velocity $\beta_{\perp} = v_{\perp}/c$. We will use the following approximations: $\beta_{\parallel} \approx 1$ and $\tan \phi_i = \beta_{\perp i} / \beta_{\parallel} = \phi_i$, where the component $\beta_{\perp i}$ is the instantaneous transverse speed for the i th particle in the beam as the particle passes through the converter. Hence, there is a one-to-one correspondence between the the distribution function of transverse velocities and transverse angles. The accuracy is better than two percent for $\beta_{\perp} < 0.2$. Since the Cherenkov cone angle is the same for all particles, the angular distribution of Cherenkov radiation intensity in a plane perpendicular to the beam cone will be directly proportional to the beam transverse velocity distribution. This simple result provides the basis for the emittance diagnostic.

Outside the dielectric the physical and geometric optical properties of the converter will change this simple proportionality relation. Diffraction in thin films can significantly broaden the radiation cone divergence. When combined with the effects of Coulomb scattering, the optimum radiator thickness, all other considerations aside, can be determined from the theory of diffraction modified scattering⁷. For the FEP Teflon material, and electron energies of 4 MeV, this broad optimum is on the order of 0.08 mm. For reasons of convenience and availability, 2 mil (0.05 mm) thick film was chosen for the experiments. Other effects such as internal interference and temperature induced changes in the refractive index may be neglected for this application.

The main distortion of the radiation distribution in the laboratory is due to simple geometric optics effects. Figure 1 illustrates the geometry by considering the ray optics of an optically flat slab converter. The converter plane is shown tilted with respect to the particle trajectory to include this option explicitly in the analysis. Using Snell's law the observed angle of emission with respect to the beam axis is related to the angle of emission in the dielectric by the expression

$$\theta_o = \theta_f + \sin^{-1} [n \sin(\theta_c - \theta_f)],$$

where θ_o , θ_f , and θ_c are the observation, converter plane tilt, and Cherenkov angles, respectively. Internal reflection can become significant as the internal angle of incidence approaches the total reflectance angle given by $\theta_{\max} = \sin^{-1}(1/n)$. FEP Teflon has the desirable property of a low index of refraction of 1.345 which yields $\theta_c = 42^\circ$ and $\theta_{\max} = 48^\circ$. For

ideal observation conditions the foil is tilted such that $\theta_c = \theta_f$ and the observation angle is equal to the principal Cherenkov angle, and this angle is normal to the foil surface. We use the term principal Cherenkov angle to refer to the angle of emission for a particle in the beam having $\beta_{\perp} = 0$. In the converter, by our approximations, the average angle of emission in the plane perpendicular to the beam cone is always the principal angle. The intensities must also be corrected for internal reflection effects. Cherenkov radiation is polarized with the polarization vector normal to the cone surface and to the direction of propagation. Hence, the p-wave transmission reflection coefficient given by

$$R = \frac{\tan^2(\theta_r - \theta_i)}{\tan^2(\theta_r + \theta_i)},$$

where θ_i is the internal angle of incidence and θ_r is the external angle of refraction, is appropriate. Summing the infinite series for total forward transmitted power yields

$$P_{\text{forward}} = \frac{P_0}{1+R}.$$

B. Measurement technique

Transverse emittance ϵ_x may be defined to be $1/\pi$ times the area in xx' phase space, where x is a transverse coordinate and $x' = dx/dz$ is the conjugate angle. Of more utility for pulsed beams is the rms emittance defined to be⁸

$$\epsilon_{\text{rms}} = 4 \left(\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \right)^{1/2},$$

where the factor of four is dependent on the area definition adopted. For beams having azimuthal symmetry such that the emittance is at most a function of radius, the rms emittance may be written

$$\epsilon_{\text{rms}} = 2a\beta_{\perp}.$$

That is, the rms emittance is directly proportional, with proportionality constant fixed by the definitions used, to the product of the beam radius a and the transverse thermal velocity.

There are two basic approaches an experimenter might take in collecting the angular intensity profiles. Discrete optical detectors, appropriately collimated to provide angular resolution, may be placed in the observation plane at several angles. This approach is attractive, but is subject to stray light contamination and does not provide any spatial resolution of the beam profile. The preferred method is to image the converter foils at different angles and use the intensity ratio of the images to unfold the Cherenkov angular distribution inside the dielectric. The most attractive feature of this approach is that each point on the converter image at one view can be compared to the same point on the image at another view. Stray light sources such as intense sparks can easily be identified in this manner. Unfortunately, this complicates the data collection process, mainly due to the cost of the equipment. Fast framing cameras or fast gated video cameras are required. Computer based image data acquisition and analysis systems are recommended. In order to obtain an angular discrimination of a few mrad the camera(s) must be placed at a large distance D from the converter such that $[2a+d]/D < 10^{-2}$, where d is the effective camera aperture size.

Rather than placing N imaging camera systems at N angular locations, the Cherenkov radiation lobe in the viewing plane was split into seven different angular slices by using flat mirrors placed near the converter foil. Figure 2 shows the mirror and converter foil layout for the IBEX RLA measurements. Six mirrors were placed at 10° intervals for observation angles θ_j of $22^\circ, 32^\circ, 42^\circ, 52^\circ, 62^\circ$, and 72° , for $n = -2, -1, \dots, 3$. The view at $90^\circ, j=4$, was on the line-of-sight of the camera. Imaging was provided by a gated, microchannel plate intensified video camera located 30m from the converter foil. The mirror holder consisted of an aluminum block with interference fit grooves machined at the correct angles to position each mirror in the array. This holder turned out to be a robust design and could be removed and replaced many times without loss of relative alignment. The mirror/foil setup was aligned by illuminating the center of the foil at the expected beam intersection point with a HeNe laser and adjusting for focusing and optimum image position on the video camera by moving the foil axially and the mirror array radially. The entire arrangement was designed to fit inside a standard 8 inch vacuum cross. A 10 inch lucite flange served as the vacuum window.

Using a 600 mm focal length $f/5.6$ lens on the camera gave an angular resolution for this system of about 5 mrad which is on the order of the diffraction modified Coulomb scattering limit of the 2 mil FEP Teflon foil and is much less than the expected >200 mrad divergence of the refracted Cherenkov lobe.

C. data analysis

The basic approach in unfolding the data was to correct for geometric optics effects to obtain the Cherenkov intensity profile in the dielectric, and then fit the data to a Gaussian transverse velocity distribution. The Gaussian assumption is not necessary, but it turned out to be an excellent approximation in our case.

Solving for the emission angle in the dielectric φ_j in terms of the observation angle θ_j yields

$$\varphi_j = \theta_r + \sin^{-1} \left[\frac{\sin(\theta_j - \theta_r)}{n} \right].$$

In addition to the internal reflection correction we must also adjust the intensity for differential refraction in the viewing plane given by

$$\frac{d\theta_j}{d\varphi_j} = \frac{n \cos(\varphi_j - \theta_r)}{[1 - n^2 \sin^2(\varphi_j - \theta_r)]}.$$

Therefore the relative intensity I_j at the emission angle φ_j is related to the measured intensity F_j at the corresponding observation angle by the relation

$$I_j = F_j \frac{d\theta_j}{d\varphi_j} (1 + R_j).$$

The Gaussian distribution in transverse velocity φ (recall that $\varphi = v/c$) was assumed to be of the form

$$g(\beta_{\perp}, \varphi) \propto \exp \left[-\frac{\ln 2}{\beta_{\perp}^2} (\varphi - \theta_0)^2 \right],$$

where $2\beta_{\perp}$ is understood to be the FWHM. Fitting this functional form to the I_j data yields our measure of $\beta_{\perp}$.

III. EXPERIMENTAL RESULTS

For all of these measurements the gated video camera was operated at a gate width of ≈ 4 ns. This setting provided the best signal to noise ratio. Even at the 30m working distance, gain settings on the microchannel plate intensifier were in the lowest range. Since we could obtain only a single time point during the pulse, the delay system was set to trigger the gate at peak beam current.

Intensity profiles were taken after various lengths of IFR transport on IBEX. A profile was also obtained for the case of beam scattering through 1cm of graphite which produced a nearly isotropic velocity distribution. Figure 3 shows a raw image for a 5m transport case with the corresponding line intensity scan from the image processing system. Mirror positions are indicated on the intensity scan. Line scans for 1m of transport and for the scattering target are shown in Figure 4. The scattering data comparison shows that we are indeed viewing the transverse velocity distribution of the beam. The Gaussian fit results are shown in Figure 5 for both 2m and 5m. The values of $\beta_{\perp}$ obtained were 0.11 and 0.17, respectively. The combined error in this measurement technique is less than ten percent.

The main problem encountered in this diagnostic was background light in the chamber due to diffusely reflected Cherenkov light seen as higher than baseline intensities between the mirrors. As the emittance became larger this problem became more noticeable. While not tested on our experiment, it should be straightforward to reduce the background levels using baffles and low reflectance coatings.

IV. CONCLUSIONS

The angular dependence of Cherenkov radiation from range-thin, transparent, flat dielectric foils can be used to measure the transverse velocity distribution of a warm IREB

and therefore the emittance. This diagnostic is capable of giving the local beam temperature for each point on the beam/foil intersection plane to an accuracy better than ten percent. Detailed models or simulations of the beam transport conditions are not required. The beam does not even need to be monoenergetic as long as $\beta \approx 1$ at all times. Otherwise it is necessary to have time resolved data. There is essentially no upper limit to the beam particle energy in this application. We have completed a basic feasibility study and a series of experiments culminating with the test of a fully operational emittance meter on the IBEX RIA experiment. There are few difficulties involved in fielding Cherenkov diagnostics on IREB machines. The fundamental limit to the angular resolution is diffraction modified Coulomb scattering.

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BASIC OPTICS

Fig 1

Layout of Cherenkov Diagnostic

Fig 2

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DATA REDUCTION

Fig 3

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EXPERIMENTS CONDUCTED ON IBEX

(Beam temperatures for IFR transport)

Line scan intensities of the raw data for the cases:

- a) 2 meters of IFR transport (Beta-perp = 0.11)
- b) 5 meters of IFR transport (Beta-perp = 0.17)
- c) scattering through 400 mils of graphite (nearly isotropic velocity distribution)

Fig 4

Data for 2 meters of IFR transport

Fig 5 a)

Beam Temperature Estimate

- Measurement on IBEX beam (10 kA, 4 MeV) *San transport*

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Fig 5 b)

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