BEAMSTRAHLUNG AS AN OPTICS TUNING TOOL AT THE SLC IP*

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ABSTRACT

The phenomenology of beamstrahlung radiation is discussed, with an emphasis on its application to extracting the beam sizes from the observed signals and on monitoring the beam-beam collision in a nondisruptive manner. The calculations used include such effects as unequal beam sizes and aspect ratios, beam-beam offsets and beam orientation. Techniques for finding the beam parameters in both the cases of beams that are round or elliptical in the transverse plane are also discussed. .

1. INTRODUCTION

Beamstrahlung is a form of synchrotron radiation in which the collective electromagnetic fields of one beam bunch deflect the particles contained in the colliding bunch and cause them to radiate. Synchrotron radiation formulas are used as the starting point in all the calculations described below. These calculations are performed using the following assumptions, which are justified under the current operating conditions of the Stanford Linear Collider (SLC):

1. Negligible beam disruption.
2. Negligible quantum effects.
3. The charge density of each bunch is Gaussian in shape in all three dimensions.
4. The radial width of the beam is much less than the longitudinal width.
5. The beams are ultrarelativistic.

Note that the results obtained in this paper are for the properties of beamstrahlung radiation itself; the detector effects have not yet been folded in. The beamstrahlung detector in use at the SLC is a Cherenkov device with an energy threshold. So, if a substantial portion of the beamstrahlung spectrum is below threshold, much of the following would have to be modified. This is the case currently at the SLC, but as the luminosity of the collisions increases, the threshold effect should become less important.

2. ROUND BEAMS

In the case of round beams in the transverse plane colliding head-on, the total energy emitted in beamstrahlung radiation by one beam is:

$$U_1 = \frac{4}{3\sqrt{\pi}}\left(\frac{N_1 N_2^2 r_e^3 \gamma^2 mc^2}{\sigma_{1r}^2 \sigma_{2z}}\right) \ln\left[\frac{(1+B_r^2)^2}{1+2B_r^2}\right] \quad , \qquad (1)$$

and the luminosity of the collisions is:

$$\mathcal{L} = \frac{N_1 N_2 f}{2\pi(\sigma_{1r}^2+\sigma_{2r}^2)} = \frac{N_1 N_2 f}{2\pi\sigma_{1r}^2}\left(\frac{B_r^2}{1+B_r^2}\right) \quad . \qquad (2)$$

Where N_1 and N_2 are the beam intensities of the "probe" and "target" beams, respectively, σ_{1r} is the radial size of the probe beam, σ_{2z} is the length of the target beam, B_r is the ratio of the probe beam size to the target beam size, m is the mass of the electron, c is the speed of light, γ is the Lorentz factor, f is the collision frequency, and r_e is the classical radius of the electron.

As shown in Eqs. (1) and (2), for head-on collisions, both the luminosity, $\mathcal{L}$, and the total energy emitted in beamstrahlung by one beam, U_1, have a $1/\sigma_{1r}^2$ dependence and a weaker but monotonically increasing dependence on B_r. Thus, as luminosity increases, so does U_1. Therefore, U_1 can be used as an unobtrusive way to monitor any changes in the luminosity. However, U_1 alone contains no information on what caused the luminosity change, and, in general, depends on the beam intensities, beam widths, and beam sizes; any one of which could cause a change in luminosity. Extracting any of these parameters requires the study of offset beam collisions.

One technique to obtain additional information about the beams is moving one beam in small steps (usually 2 μm) across the other beam.[1] Measuring the beamstrahlung signal at each position of the scan results in a U_1 vs. impact parameter distribution. In the case of round offset beams, the total energy emitted is:

$$U_1 = \frac{8}{3\sqrt{\pi}}\left(\frac{N_1 N_2^2 r_e^3 \gamma^2 mc^2}{\sigma_{1r}^2 \sigma_{2z}}\right) \int_0^\infty \frac{1}{x}(1-e^{-B_r^2 x^2})^2 e^{-(x^2+\xi^2)} I_0(2\xi x)\, dx \quad , \qquad (3)$$

where $I_0(x)$ is the modified Bessel function of the first kind of order 0, and ξ is a dimensionless impact parameter equal to $a/\sqrt{2}\sigma_{1r}$, where a is the actual impact parameter. This integral must be done numerically. Plots of U_1 vs. impact parameter show two classes of shapes. If B_r is greater than 1.23, the curve has one peak centered at zero offset. If B_r is less than 1.23, the curve has two peaks with a local minimum at zero offset (see Fig. 1).

The extraction of the beam parameters from the U_1 vs. ξ distribution would require a 7-parameter fit involving an online numerical integration and would therefore be slow. Instead, each of the beam parameters except N_1 and N_2 can be found by studying the shape of the distributions. The widths of the U_1 vs. ξ distributions depend only on the radial sizes of the beams and not on the beam intensities or lengths. If one defines this distribution width as the full width at half the radiated energy at zero offset (see Fig. 1), the U_1 vs. ξ distribution width scaled by the probe beam sigma is a function of B_r alone (see Fig. 2). The ratio of the U_1 vs. ξ distribution widths of the two beams is also a function of B_r (see Fig. 3). By combining both graphs, one gets a relationship between the ratio of the widths and the scaled width of one of the beams (see Fig. 4). By measuring the widths of the U_1 vs. ξ distribution for both the electron and positron beams, both beam sizes can then be extracted.

The lengths of the beams can then be extracted in a similar manner. The full width, defined above, multiplied by U_1 at zero offset is a function of the intensities, the beam lengths and B_r. But B_r is known from the ratio of the U_1 vs. ξ distribution widths. If one knows the intensities from another source, the beam lengths can then be extracted.

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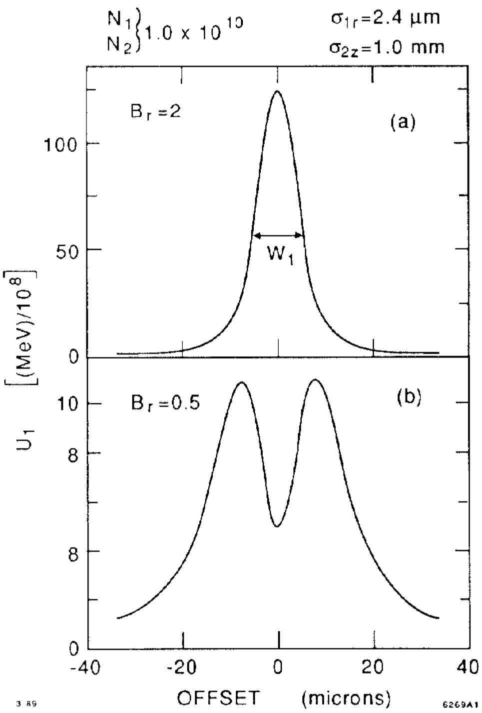

Fig. 1: The total energy emitted for round beams in beamstrahlung radiation by one beam vs. impact parameter, for N_1 and N_2 equal to 10^{10}, σ_{1r} equal to 2.4 μm, σ_{2z} equal to 1 mm, and B_r as indicated. W_1 is the width of the distribution.

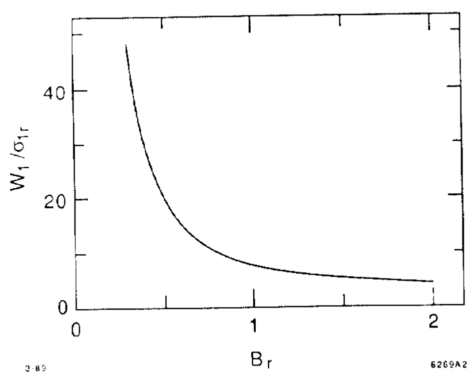

Fig. 2: U_1 vs. the impact parameter distribution width (W_1) scaled by the probe beam width as a function of B_r for round beams.

3. ELLIPTICAL BEAMS

For elliptical beams, all calculations become more complicated. One now has a σ_x and σ_y instead of just a σ_r. Also, there are two new angle parameters which determine the orientation of the two beams relative to each other and to the scan direction. The U_1 vs. ξ distribution has the same two classes of shapes as those for round beams, if the center of the probe beam passes through the center of the target beam during the scan. If the beam centers miss each other, one may also obtain single-peaked curves that are offset from zero and double-peaked asymmetric curves. It also is no longer completely true that the total energy emitted always increases as the luminosity increases. An example of this happens when the beams are colliding head-on. The maximum of luminosity occurs when the angle between the major axis of the two bunches is zero, and the minimum occurs when this angle is 90°. For the emitted energy, this is reversed.

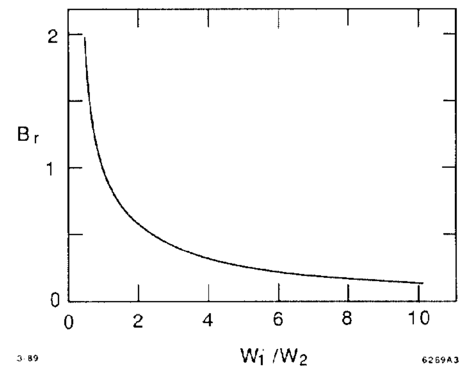

Fig. 3: The ratio of the widths of both beams as a function of B_r for round beams.

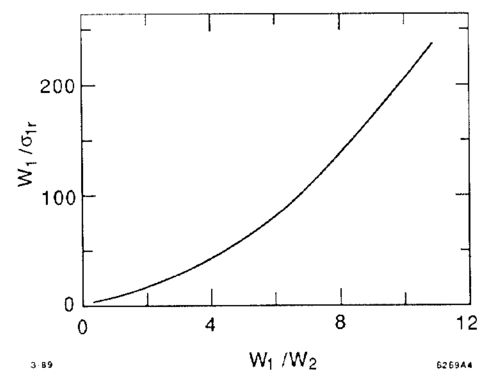

Fig. 4: U_1 vs. the impact parameter distribution width (W_1) scaled by the probe beam width vs. the ratio of the widths of both beams.

Also, there is no longer a simple relationship between the U_1 vs. ξ distribution widths and the radial beam sizes. But a scan along the x-direction is much more sensitive to σ_{1x} and σ_{2x} than to σ_{1y} and σ_{2y}. So, if one does an x-scan and measures the U_1 vs. ξ distribution widths and extracts the beam sizes in the same way as in round beams, one gets answers that are within 15% of the correct σ_x's, provided that neither of the beams have aspect ratios greater than 2, and that the major and minor axes of the two beams are aligned with each other and with the scan direction. We expect that these conditions will hold for most of the 2-beam tuning work at the SLC. This is not a perfect method for monitoring changes in the beam sizes since changes in the σ_y's do affect the value found for the σ_x's. It may be possible to extract the correct σ_x's and σ_y's for each beam by matching these four widths to the four U_1 vs. ξ distribution widths from the two orthogonal scans via a look-up table, but this has not yet been demonstrated. When there is an angle between the major and minor axes of the two beams, extracting the beam parameters may require a third scan not along either the x or y directions.

In conclusion, beamstrahlung does show promise as a technique to monitor the beam collisions at the SLC. But more work needs to be done to fully integrate the effects of the detector threshold and to understand the relationship between the beam parameters and the U_1 vs. ξ distribution shapes for elliptical beams.

REFERENCE

1. P. Bambade *et al.*, SLAC-PUB-4767 (January 1989), submitted to *Phys. Rev. Lett.*