A Possible Design of Large Angle Beamstrahlung Detector for CESR

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1 Introduction

Beamstrahlung radiation occurs when high energy electron and positron beams collide head-on. Inside each beam, a magnetic field is generated by the moving charges. When the other beam passes through the magnetic field, it will emit beamstrahlung radiation. This radiation is a direct monitor of the beam-beam collision . To achieve the best alignment of the two colliding beams, a beamstrahlung detector will be helpful.

Bonvicini and Welch have proposed a beamstrahlung detector [1] for CESR to monitor the beam-beam collision conditions. The chosen wavelength for detection is in the visible region. Red light polarized in $\vec{x}$ and $\vec{y}$ direction will be our signal, and unpolarized blue light will be used to substract background. Radiation can be emitted anywhere within a region about $20mm$ long, $2mm$ wide, and $0.1mm$ high. The proposed position of the detector is about $5m$ away for the collision point, so the signal light has an angle of $6.2 \pm 1.0mrad$ from the $\vec{z}$ direction.

The largest source of background is expected to be the synchrotron radiation from the quadrupole, which is $5.64m$ away from our detector, and about $1.5m$ long. Most of the synchrotron radiation is at zero degrees. However, there will be some electrons away from the center line and radiating directly into our detector.

This paper is devoted to a possible design of a beamstrahlung detector. First we discuss the entry optics of several designs, then the separation of signal and background, and in the end we will study the Beamstrahlung signal separation by using time-resolved optical pulse detection with streak camera.

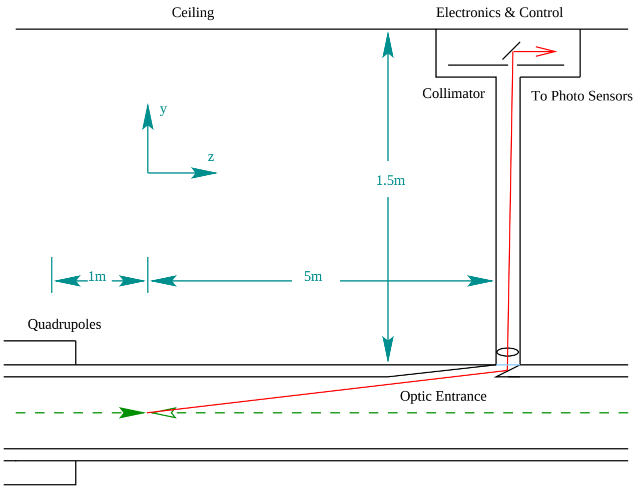

Figure 1: Entry Optics Design 1 – One lens and one moving collimator

2 Primary Design for Entry Optics

The first design uses a flat mirror to collect the signal. At the position of the detector, we can drill a hole on the beam pipe, mount a metal reflector on the surface of the hole, and seal the entrance with a transparent Beryllium film, as in Fig.1. A metal pipe is used to conduct the optical signal up to the photo sensor system on the ceiling. A lens is used to focus light from the collision point to a collimator, which is movable to accommodate the change of the position of beam-beam collision.

In order to separate the signal light ($6.2 \pm 1.0mrad$) and the major background (synchrotron from the quadrupole), we need an acceptance of less than $1mrad$. From Rayleigh's criterion

$$\theta_c = \frac{1.22\lambda}{a_{min}},$$

and considering red light, the aperture of the mirror should be larger than $0.8mm$.

The focal length f of the lens is determined by the object distance a (the collision position here) and the image distance b (the length from the

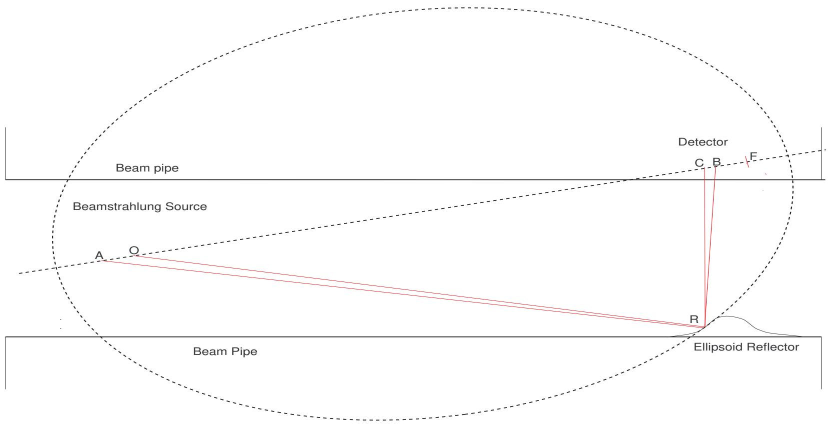

Figure 2: Idea of an ellipsoid reflector

lens to the collimator)

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}.$$

Here we have $a \approx 5.0m$, $b \approx 1.5m$, and $f \approx 1.2m$. The lens should be an achromatic combination designed for blue and red light.

The linear magnification will be $m = b/a \approx 0.3$. Since the source region is about $20 \times 2 \times 0.1mm^3$, the image region will be $6 \times 0.6 \times 0.03mm^3$. Two stepping motors can be used to move the collimator on a surface for best signal selection, with a hole of $1.2mm$ diameter. The motors will allow for changes in the IP, as well as corrections for various sources of misalignment, including thermal effects.

3 Ellipsoid Mirror

The second design involves building a smooth ellipsoid mirror on the inner surface of the beam pipe, like in Fig.2. For an ellipsoid mirror, light from one focus point of the ellipsoid will be reflected to the other focus point, and the length is the same for any path. At all frequencies the light from the ideal collision point will be focused on the detector. This mirror will also dramatically reduce the heat load, due to the irregularity resistance of the beam virtual image on the inner surface of the beam pipe. Since the radius of the beampipe is $3cm$, a $0.5cm$ high structure may be possible.

What is the spatial resolution of an ellipsoid reflector? Suppose point O is the ideal collision point and also one focus point of the ellipsoid, point C is the center point of the photon detector plane and also another focus point, OA is half the length of the beamstrahlung source, and CB is the image of OA produced by the ellipsoid reflector. Then angle ARO should be equal to angle BRC. So in millimeter we have

$$|BC| \approx 60 \times \left(\frac{30}{5000} - \frac{30}{5000 + x} \right).$$

Here we have put in the diameter of the beam pipe ($60mm$), the position of the ideal collision point($5000mm$), and x stands for the distance form a radiation position to the point O. So for $x = OA = 10mm$, $|BC| \approx 0.72\mu m$. For points about $1m$ away from the ideal collision point, such as the synchrotron radiation from the quadrupole, the separation will be $60\mu m$. If the detector aperture is several μm, such as a single-mode fiber, signal and background can be well separated.

So we have a quite open frequency window and a practical spatial resolution. However, as in the first design, the disadvantage of this design is we have to build some structure inside the beampipe.

4 Grating Reflectors

4.1 Basic Idea

A grating can be used as a reflector, as in Fig.3. The grating reflectors can be built with holographic methods. A laser with the same wavelength as the signal light is used to construct the grating. One laser beam will be separated into two paths, one is diverged from the the center of the collimator to the grating position, and the other from the ideal beam collision position. A standing wave pattern will be exposed to the polished inner surface of the beam pipe which is coated with photo-resist. Each pattern is a grating reflector, and when light of the same frequency as the holographic laser comes from the same position as the corresponding collision point, it will be reflected exactly to the collimator center.

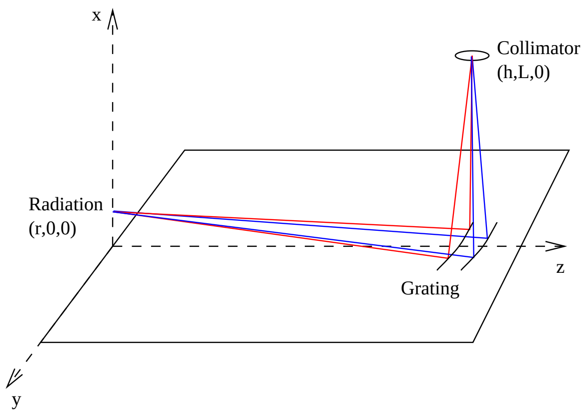

Figure 3: Basic Idea for Grating Reflector

We have blue and red light for detection, so we need gratings for both of them. Two methods exist: using separated gratings for blue and red, or using one grating built twice with blue and red laser independently, which is called a multiplexer. Which one is better can be measured experimentally.

Since our light source is not a point source, but a distribution around the ideal collision point, and one grating reflector can monitor only one point of the source (see next section for the calculation), we need a series of gratings, as in Fig.4. The beam is about $18mm$ long, and the effective beamstrahlung radiation source length is about $6.4mm$ (see section 6). Currently there is a $40mm$ long pipe avilable for the detector at CESR, and suppose each grating needs to be $5mm$ wide, an array of 80 gratings can be built. We can have a spatial profile of 20 points of the beamstrahlung source.

The greatest advantage of this method is no moving part involved, and almost no irregular pattern needed on the inner surface of the beam pipe. Transparent Beryllium film can be used to cover the collimator hole. Since the refractive index of a conductor is normally less than one, $n < 1$, most background radiation which is almost parallel to the beam pipe will be blocked by total reflection from the film.

The grooves are curves on a cylindrical surface of the beam pipe. From the ideal source point to the collimator, light reflected from any point of one particular groove should have the same path. We can say that a groove is the intersection of the inner surface cylinder of the beam pipe and the

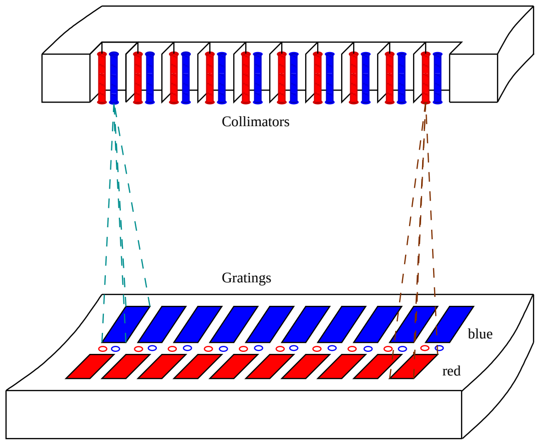

Figure 4: Grating Reflectors Array

ellipsoid focused on the ideal source point and the collimator.

If grooves have the same length, then each groove reflects the same amount of signal light, but with a different phase. For a light source at the ideal source and the center point of the collimator, the path difference between two successive grooves will be exactly one wavelength. No other point on the collimator plane satisfies such a condition. Therefore most light will be reflected to that point, just like any other grating.

When we build a grating with holographic method, the grooves will be in the shape of a sinusoid wave. In fact since the grating is far away from the beamstrahlung light source ($5m$), the grooves are almost straight lines. Because the incidence angle is about $6.2mrad$, the separation of two grooves in a grating will be about one wavelength. For $650nm$ red light, $5mm$ width means about 7700 grooves.

4.2 Spatial and Frequency Resolution of the Grating Reflector

At the center of the collimator, the reflected signal field will be:

$$\mathrm{E} = E_0 + E_1 cos\delta_1 + E_2 cos\delta_2 + E_3 cos\delta_3 + ... \quad (1)$$

$$= \sum_{n=0}^{N} E_n cos\delta_n \quad (2)$$

Here E_n is the reflected field from each groove, δ_n is the phase difference from the first groove. Suppose each groove has the same length and reflects the same amount of light, $E_n = E_0$, and the phase differences of the nth groove is simply $n\delta$ – as long as the groove separation is far less than the source distance ($5m$). In this case, we can make a simplification as:

$$\begin{aligned} \mathrm{E} &= E_0 \sum_{n=0}^{N} cos(n\delta) && (3) \\ &= E_0 \left(\frac{1}{2} + \frac{sin((n+1/2)\delta)}{2sin(\delta/2)} \right) && (4) \end{aligned}$$

$$I = I_0 \left(\frac{1}{2} + \frac{sin((n+1/2)\delta)}{2sin(\delta/2)} \right)^2 \quad (5)$$

$$\delta = \frac{2\pi\lambda_g}{\lambda} \left(\frac{L^2 + r_b^2}{(r_b + x)^2 + (L+z)^2 + y^2} \right)^{\frac{1}{2}} \quad (6)$$

Here $r_b = 30mm$ is the radius of the beam pipe, $L = 5000mm$ is the $\vec{z}$ value of the first groove, λ_g is the wavelength of the laser which built the grating, λ is the signal wave length, and N is the total groove number. In the following figures, spatial and frequency resolution are calculated. For the calculation of the spatial resolution, each time we change one variable and keep others as constants of the ideal situation. For the frequency resolution, we choose a source point at $(2mm, 0.5mm, 0)$ which is about the edge of the collision region, and all other points within the source region have almost the same distribution.

We can see that in $\vec{x}$ and $\vec{y}$ directions, the detector accepts a wide range. In $\vec{z}$ direction, the grating is very selective, $\sigma_z \approx 0.3mm$. The frequency window is also very narrow, $\sigma_\lambda \approx 0.1nm$. Considering the effective beamstrahlung radiation region is about $6.4mm$ long, and the red light signal is from $625nm$ to $700nm$, only about 0.0063% of the red signal will finally come to our detector.

5 Separation of Polarization and Color

The beamstrahlung detector measures the intensity of $\vec{x}-$ and $\vec{y}-$polarized red light and unpolarized blue light.

To separate two different polarizations, a double refraction crystal can be used, as in Fig.10. When unpolarized light shines normally on one face of the

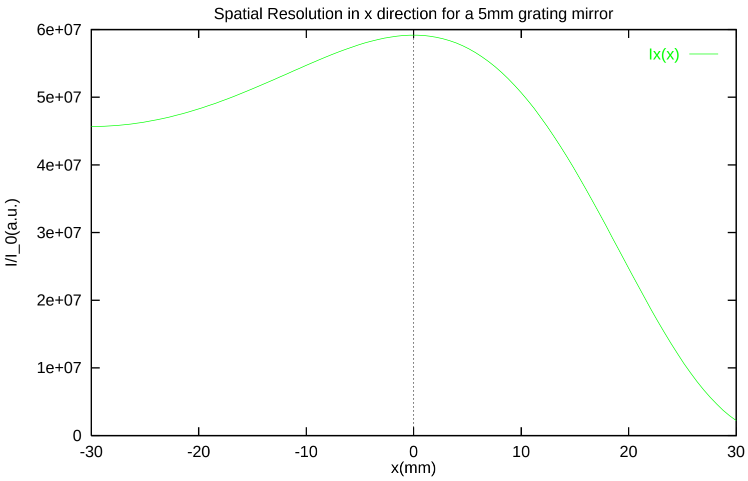

Figure 5: Spatial Resolution for a Grating Reflector in X direction

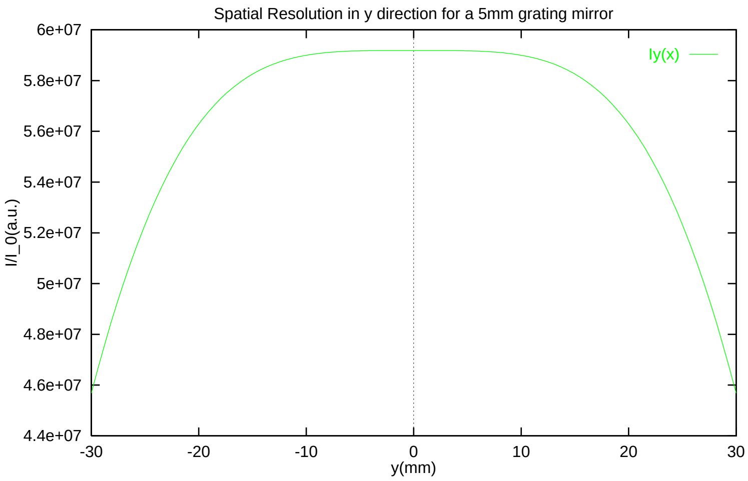

Figure 6: Spatial Resolution for a Grating Reflector in Y direction

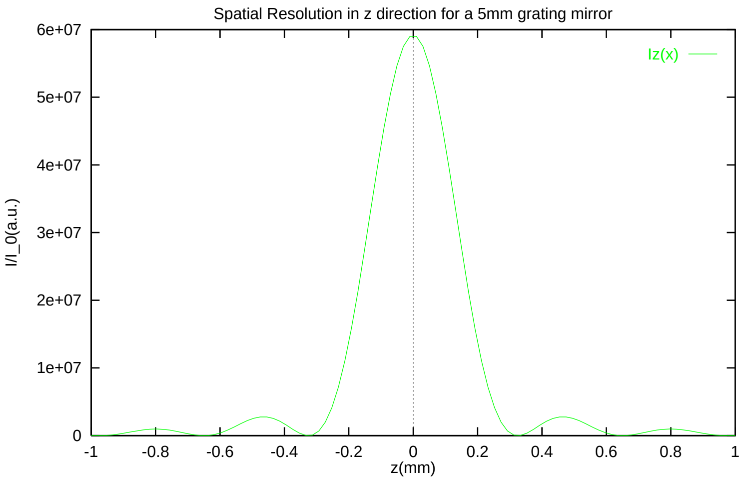

Figure 7: Spatial Resolution for a Grating Reflector in Z direction

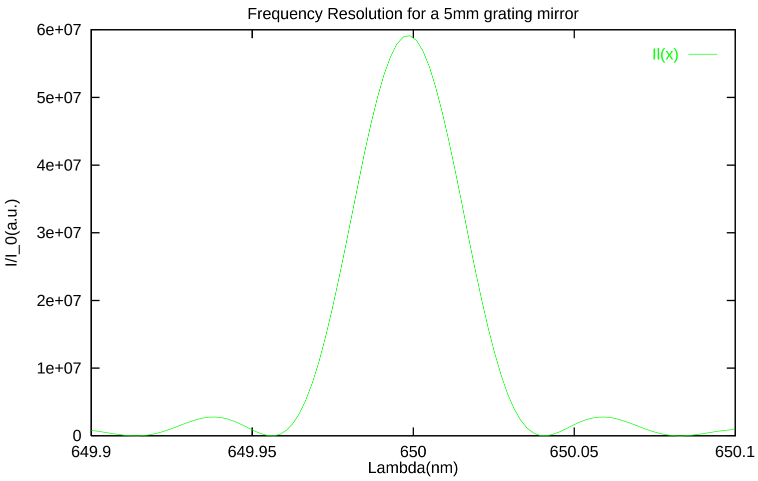

Figure 8: Frequency Resolution for a Grating Reflector

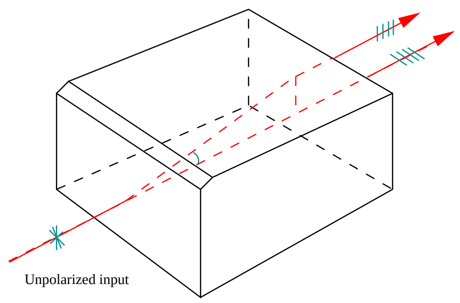

Figure 9: Beam Displacing Prisms

crystal, it will separate into two plain polarized beams whose polarizations are at right angle. One beam (extraordinary beam) deviates from the other. Upon exit, the extraordinary beam will be again parallel with the input and the ordinary beam, but with a lateral displacement.

To separate blue and red light, a simple way is using bandpass interference filters, based on Fabry-Perot interfometers. Two parallel surfaces of high reflectance ($> 95\%$) define a cavity and make multiple reflections of the incident signal light. If the distance between the two surfaces is half-integral times of the signal wavelength, due to the constructive interference, the signal light will transmit about 100%. Light with other frequency will be totally blocked by the two highly reflective surfaces.

6 Temporal Profile of the Signal Pulse

e Now let's look at the time structure of the beamstrahlung radiation. Suppose the radiating beam is beam 1 and the target beam is beam 2. The beamstrahlung radiation power is proportional to the magnetic field squared of beam 2, $W_1 \sim B_2^2$, and $B_2 \sim E/c$. If each beam has a Gaussian charge distribution, then the z profile of the electric field is also gaussian:

$$E_2(x, y, z, t) = E_2(x, y) \times e^{-\frac{(z \pm ct)^2}{2\sigma_z^2}},$$

and the dependence of the radiated power on z will be:

$$W_1(z) \sim E_2^2(z) \sim e^{-\frac{(z \pm ct)^2}{\sigma_z^2}}.$$

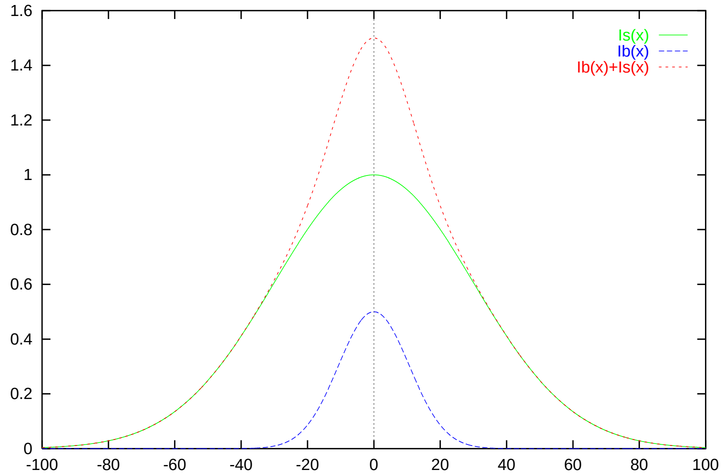

Figure 10: Time Structure of Beamstrahlung and Synchrotron Radiation. (Is = Signal intensity Ib = Background intensity)

This means the paulse length of the radiation or of the electric field squared is $1/\sqrt{2}$ of the beam size. Also since the two beams are colliding head-on at almost twice the speed of light, the interaction length is half of each beam [6], then the total reduction factor is $1/2\sqrt{2}$. We know that each beam is about $18mm$ long at CESR, or $\tau = 18mm/c = 60ps$. So each pulse of the beamstrahlung radiation is about $\tau_b = 60/2\sqrt{2} = 21ps$ long.

For synchrotron radiation from the quadrupole, the magnetic field is at rest and much larger than the beam, the pulse length is of the same length as the beam, $60ps$. Other background radiation will be $60ps$ or longer (e.g., reflected radiation inside the beam pipe).

So a time-resolved measurement of the pulse profile can distinguish the beamstrahlung signal, like in Fig.11. Streak camera is a possible candidate. With multichannel streak camera which is commercially available for $0.5ps$ temporal resolution [5], several inputs can be tested at the same time. We can test the synchrotron pulse with one beam first, and then test the sum of beamstrahlung and synchrotron radiation with two beam collision. With a 2-Gaussian fit, we can find our beamstrahlung signal. For fast reaction, the fitting can be done online.

If a streak camera cannot be used, the standard choice for light detection are photomultipliers. Special selection should be made to suit the visible light detection.

7 Acknowledgment

I have discussed with Giovanni Bonvicini the design many times. Without his ideas and help this design would not have been possible. Prof. David Cinabro has also given me a lot of instructions about the beam structure and the reflector design.

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