

Incoherent and coherent beamstrahlung at the ILC

Classification (subsystem)

Beam-beam collision monitoring.

Personnel and Institution(s) requesting funding

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Project Overview

We request a one year grant, in view of foreseen developments this year that will lead to a substantial three years request next year. As discussed in the “Activities” Section below, we will concentrate on extracting a signal from the existing CESR device (to be fully installed around Memorial Day 2005). We will also design a device to measure coherent beamstrahlung (CB) at CESR, for which equipment money will be requested next year.

It has become generally accepted that the beam-beam collision (BBC) has a very large number of degrees of freedom (over twenty, of which at least fifteen can affect the luminosity at the 10% level), and that measuring as many of them as possible is crucial to the success of the ILC. The measurement and control of beam-beam jitter, and the direct measurement of wake field effects at the Interaction Point (IP) are the largest issues in the minds of many, but there are many other potential effects. Just by looking at SLC history one finds a host of unforeseen problems which include unexpected beam lengths and single-arm faulty beam optics.

The benefits of a very thorough measurement of the BBC are at least threefold:

1. the shape, size and relative location of each beam at the IP are the ultimate figure(s) of merit of the ILC. Advances in luminosity will be possible only if the beam-beam mismatches are correctly diagnosed. If not, operators will have to try blind optical tuning which, given the complexity of the machine, is probably hopeless.
2. the possibility to correlate precise beam-beam observables to various machine or magnet variables should tremendously simplify machine development. Correlation coefficients between BBC observables and machine variables can be computed directly and automatically, and high correlations are then flagged by the software. That allows intervention on the correct machine components, and it also allows the machine simulation software to be vastly simplified.
3. a precise measurement of the beam geometrical parameters (their 3-D sizes, and possible non-gaussian components) predicts the beamstrahlung and disruption parameters precisely. These in turn provide fundamental input to the detector (by providing a precise prediction for the dL/dE tail) and the downstream part of the machine (by providing the angular divergence of the disrupted beam).

A proper understanding of the potential of each BBC detector is also of primary importance at the planning level. Should we demonstrate, for example, that fifteen independent measurements are feasible for the BBC, that detection is fairly straightforward, and what they are sensitive to, these findings would cascade through the entire ILC organization, and provide basic input to other working groups such as the wake field group.

Studying the BBC is not only central to the ILC effort, it is also very complicated. Serious developers should accept that studying the BBC at the ILC will be a real time analysis effort, with a devoted analysis group, rivaling in complexity and manpower the most complex data analyses of a particle physics experiment.

The effort of our group, if fully successful, will provide about half of the possible independent data, and of course the attendant hardware and software. The two methods of BBC detection discussed here are conceptually new compared to the methods established at the SLC, detecting the beam-beam deflection[1] and studying the high energy beamstrahlung component[2].

Wayne State is the sole institution in the world developing detectors and methods to study the low energy component of beamstrahlung[3] – [8]. The advantages of using low energy components, compared to the classical, high energy part of the spectrum, are:

1. the possibility to use the larger angular divergence of low energy beamstrahlung compared to low energy synchrotron radiation. Data from our R&D effort at CESR already indicate that this method works well.
2. the possibility to measure the radiation polarization (in practice, in the visible or near infrared), which already enables powerful diagnostics[6], by measuring four independent degrees of freedom.
3. the very high signal-to-background ratio in the microwave region, when the two beams are offset[7], due to the onset of coherence.
4. the direct measurement of each beam length, in the microwave region[7]. The microwave part of the spectrum provides at least another four degrees of freedom, of which at least three are independent of those provided by the visible part of the spectrum.
5. we believe that there are more independent observables to be had from imaging the microwave part of the spectrum. A definitive conclusion about this needs detailed simulation.

We are advancing in our understanding of the CESR visible/infrared beamstrahlung detector, and the beam currents are right now getting to where we expected to establish a first signal (80mA per beam). Because the signal is proportional to the cube of the current, even a factor of two matters (see Figs. 6 and 7 below). We have also been slowed down by instabilities in our infrared photomultipliers which are currently under study. In view of our well-established measurements of backgrounds and pointing capability, we are proceeding with the construction of the full detector (the present system has 1/2 the optics and 1/4 the phototubes).

This proposal could have looked a lot different if it could have been sent to the funding agencies in september. For the time being we request funding for one year only. We planned, in summer 2005, to have an all out effort to detect visible beamstrahlung for the first time, and to study the feasibility of a coherent beamstrahlung detector for CESR. Some activities

may have to be anticipated to the spring in view of a possible summer CESR shutdown. On successfully completing those tasks, we will request a substantial, three years grant.

The activities for the next year will be listed in the appropriate Section below. In the next two Sections we wish to give an idea of what is needed (for each detector) to achieve a stage of development that the global ILC community would consider sufficient for immediate design and construction of the two ILC detectors. A third Section is devoted to the development of a BBC simulation program to simulate at once all the components of beamstrahlung, a piece of software that we find absolutely necessary. The funding agencies can get an idea of the effort and support that will be needed to see these potentially crucial devices to a successful conclusion.

Visible beamstrahlung detector (VBD).

The basic phenomenology of this device is well understood[6]. By using the favorable polarization pattern at large angle, one detects observables which are sensitive to the geometrical shape of the BBC.

The CESR activities are discussed in the “Results from Previous support” Section below, and the next year’s activities are discussed in the “Activities” Section below. At this time it is clear that, once the full detector is installed in May 2005, we ought to fully concentrate on understanding the infrared photomultipliers and extracting a first signal. Therefore in this Section we concentrate on the activities which are ILC-specific.

We have a preliminary design for the VBD at the ILC, by I. Avrutsky, shown in Fig. 1. It is meant to occupy the entire angular region between 1 and 2 mrad and to measure the beamstrahlung ring. We believe that higher angles will be suitable as well to detection of visible beamstrahlung.

The main features of the device are shown also in Fig. 1. They include excellent angular resolution, about 0.12 mrad, because the large ring diameter produces a small diffraction limit and also because of the CCD small pixels. The fast CCD should also allow imaging of the entire ring. The projected signal is plentiful (3×10^6 photons per BBC at nominal ILC conditions). There are no limitations as to which wavelength should be used.

Over the next four years we need to answer the following questions:

- are the ILC backgrounds in that angular region acceptable? This is the major feasibility question. Preliminary estimates, using simulation results by T. Maruyama for that region[9], showed backgrounds well below the signal, at least for NLC conditions (10^4 photons or less). The estimate was obtained by scaling x-ray rates in the region to visible wavelengths. A proper simulation of the ILC visible backgrounds should use the current ILC parameters[10] and make use of the large angle synchrotron radiation algorithm developed in Ref.[8].
- which background reduction techniques are available at the ILC? This question should be a straightforward extension of the methods discussed in Ref.[5]. First the imaging affords a very clean background subtraction procedure since the azimuthal dependence of the signal is known and the background is measurable directly and expected to have over 90% radial polarization[5]. Secondly, radiation reflected off the beam pipe is a concern. Simple methods for making the beam pipe non-reflective are discussed in Ref.[5].

Hollow mirror imaging system for detection of beamstrahlung radiation

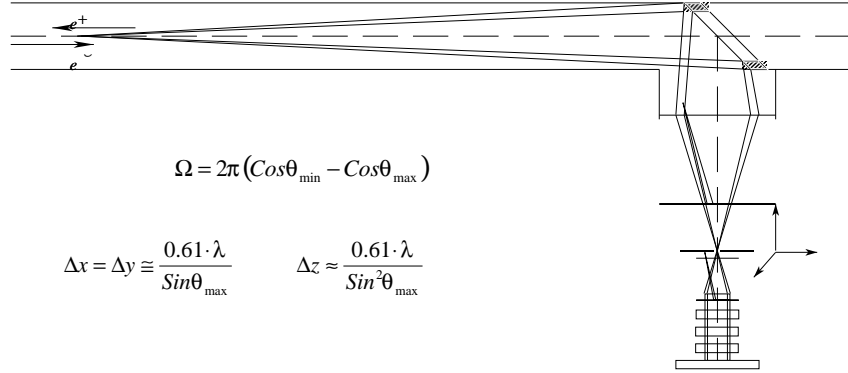


Figure 1: Schematic of the ILC large angle beamstrahlung detector.

- will the new device be intrinsically more powerful than the CESR device? By that it is meant, will it be sensitive to new observables, beyond those discussed in Ref.[6], that correlate favorably with a beam-beam mismatch.
- will the device suffer significant backgrounds from the low energy, large angle pairs (and slow electrons) which emerge from the BBC? While these, in principle, contribute to the signal, their polarization information is likely to be different from that of beamstrahlung itself. This is important, because the predictive power of this device comes primarily from the measurement of the polarization.

The latter questions will need to be addressed with software that does not exist now and that is discussed below. Other questions will no doubt surface as we advance through our CESR data analysis, and of course questions about the DAQ need to be addressed (if no satisfactory CCD can be found, which can be read every 337nsec, we will use a diode matrix instead).

Coherent beamstrahlung detector (CBD).

In the last two years, we have developed the concept of a device looking at the microwave part of beamstrahlung[7]. The interest of this part of the spectrum is that, if the beams are offset and one observes them at a wavelength exceeding the length of the beam, coherence will develop. Fig. 2 shows that the coherent enhancement can exceed 10^{10} at the ILC. The observation of this effect should be available as soon as the ILC is turned on.

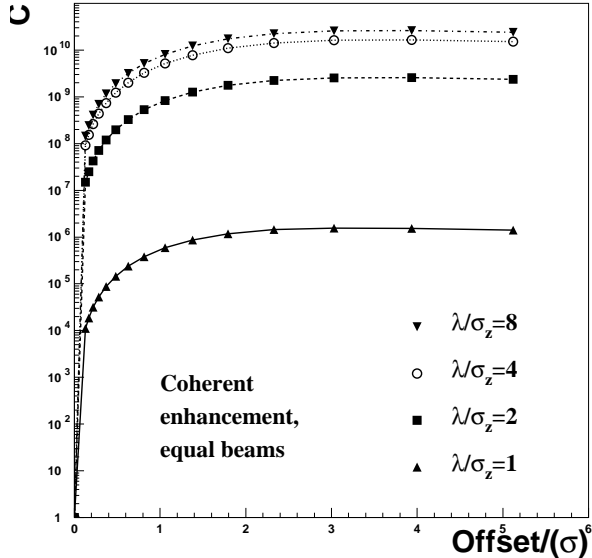


Figure 2: CB yield as a function of the beam-beam offset. The simulations were done with ILC "weak beam" conditions ($N = 0.3 \times 10^{10}$, $\sigma_y = 19\text{nm}$). Plots are shown for four different wavelength-beam length ratios. The markers locate the points where the simulation was performed.

The particular and unique phenomenology of CB results in four independent observables. These are:

- the beam-beam offset, assumed to be in practice the vertical offset. Because the signal varies so strongly with the offset (Fig. 2), measurement of the (crucial) beam-beam jitter at the 0.1 nm level will be possible even when the beams are tens of nanometers wide. Therefore diagnosis and remediation of the jitter can start long before the beams are made small, improving the efficiency of the whole project.
- both beam lengths, σ_z . Fig. 3 shows the ratio of the coherent powers radiated by each beam when the two beam lengths are unequal.
- the ratio of the beam heights σ_y . Fig. 4 shows the different coherent enhancements when the beams have unequal height.

This is already a phenomenon with powerful insight in the BBC, but there is one potential breakthrough beyond the simple analysis of Ref.[7]. At microwave wavelength, and for very modest beam-beam offset, the recorded microwave radiation is in fact the image of the BBC, with expected negligible backgrounds. The image could, potentially, produce several more observables of interest. There is no software available to study these phenomena, which is why in the next Section we propose to write some.

An image of the BBC can be obtained from the high energy part of the radiation, however there are severe constraints due to high power, extreme radioactivity, the interference with the beam dump, a mission-critical device, and the uncertainties inherent to measuring the

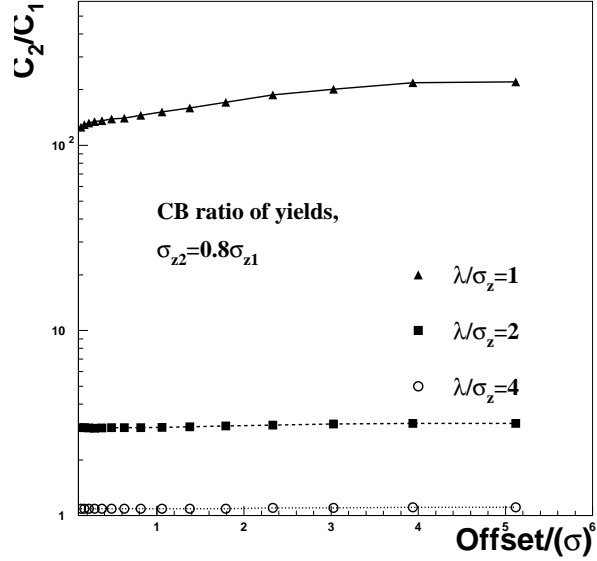


Figure 3: CB ratio of yields (beam 1 versus beam 2) as a function of the beam-beam offset. The simulations conditions are described in Fig. 2, but $\sigma_{z2} = 264\mu\text{m}$.

radiation within some sort of calorimeter. Also the sensitivities to beam-beam parameters are very different.

At this time the most urgent step is to assess the feasibility of a microwave detector at CESR, to prove the principle. Ref.[7] forecasts a large signal for wavelengths between 2 and 5 cm. The only problems which are seen at this time concern how to minimally shield from the RF noise by the beam. This step of feasibility study will be taken in Summer 2005.

Simulations.

The existing software to simulate the BBC and attendant beamstrahlung, GUINEA PIG and CAIN, is of little use for our project. Both programs, however, provide a platform for development of a software that would provide predictions for all the phenomena through which the BBC can be observed.

The development of such a software goes well beyond our specific needs, and would in fact serve the community at large. Firstly, with such a software one would be able to assess the projected knowledge of the BBC interaction. It is important, for example, to let the wake fields working group know that the beam tail will (or will not) be measured directly in the BBC.

Likewise, the community has been supportive of multiple measurements of the same BBC quantity (say, the beam-beam vertical offset) on general principles. But the real interest of multiple measurements is that they have somehow different sensitivities to the same quantity when the beam shape changes. Wake fields, if significant, are bound to produce a wealth of complex beam shapes. So the hypothesis of different sensitivity (which is just an hypothesis right now) needs to be evaluated thoroughly.

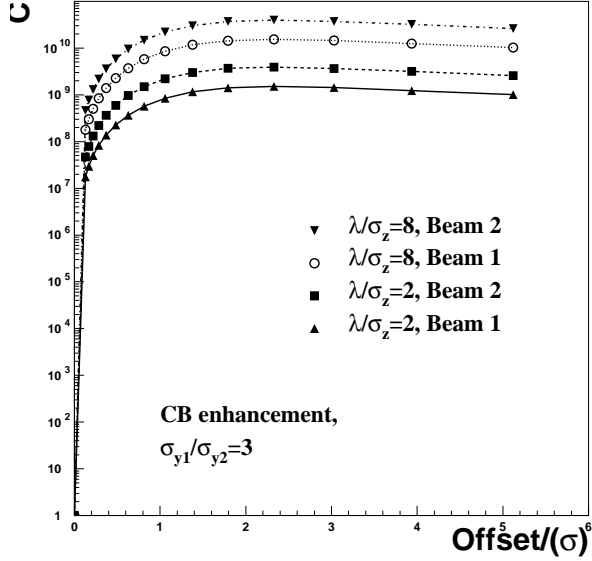


Figure 4: Same as Fig. 2, but $\sigma_{y1} = 57\text{nm}$.

Therefore we will eventually propose to develop such a program and to obtain the the following results:

- what information can be extracted from the possible imaging of the BBC in the microwave part of the spectrum?
- how do low energy particles (pairs created by beamstrahlung, and particles that lost much of their energy to beamstrahlung radiation) affect the low energy signals?
- finally, when everything else is in place, we will evaluate how the many observables of the BBC relate to specific beam-beam configurations. Because most observables are non-linear with respect to beam-beam parameters, even assuming only three lattice points per d.o.f., one arrives at a minimum grand total of 3^{15} simulations. While some simplifications will be necessary, this is a large amount of work. It will, though, provide answers to questions such as: how can we monitor wake field effects? Which aspects of the BBC that may affect luminosity are not detectable? In turn these conclusions would spawn a debate, within the community, at a much deeper level than in the recent past.

Technically, the difference between low energy and high energy beamstrahlung is that, for high energy, one generates the photons (in one of the programs above, exactly parallel to the instantaneous particle direction) and let them fall where they may. For the VBD, one needs to specify the detector pixel, compute the angle between particle, its plane of curvature, and the pixel, compute (and add up) the intensity at the pixel. Algorithms for this, which include a choice of spectral distributions, were introduced in Ref.[8]. For the CBD, one needs to specify the angle, compute (and add up) the amplitude, and square at the end. G. Bonvicini and N. Delerue at Oxford, himself a proposer of a beamstrahlung detector for the high energy part of the spectrum[11], have begun investigating how to modify the existing software.

Broader Impact

Beamstrahlung is a terrific topic for young students. They only need to know electromagnetism at the undergraduate level to grasp the fundamental issues of the project. The small size of the project also invites student participation. The student can contribute while avoiding the intimidation and hierarchical structure intrinsic to a large collaboration. In the last six years REU students E. Luckwald, N. Detgen, N. Powell, and E. West have participated in beamstrahlung activities, all of them for six months at least (three months in the summer and three months to a year during the academic year). Three of them won competitive undergraduate research awards, three of them published papers (Refs.[6], [5], and[7]), two of them are in Graduate School in Physics, one obtained a Masters (not in Physics), and one attempted graduate school in Physics. Their research reports can be found at our REU website[12]. K. Korbiak also collaborated with Prof. Cinabro for two years on characterizing the BBC using the silicon vertex detector of CLEO[13]. She is in Graduate School in Physics as well. Four of these five are “first generation students” (first in their family to attend college).

Since it is clear that there are another four years of work ahead before the R&D can be successfully completed, undergraduate students will continue to work in this project and find projects that are accessible, significant, and can be done while working elbow-to-elbow with a scientist. Future projects which are suitable for undergraduates include:

- the analysis of available CESR large angle data, including doing their own data taking.
- the assembly of a possible coherent beamstrahlung detector for CESR;
- the simulation of special aspects of beamstrahlung, such as, for example, the unpolarized signal in the ILC VBD from stray particles.

Results of Prior Research

In 2001, we obtained a three year MRI grant (NSF-PHY-0116058, \$312361) to build the CESR large angle beamstrahlung device. Part of it is built, installed and working as advertised. At CESR, data have been taken lately at 1.8 GeV in the infrared, in the red, and in the visible. The data for a very recent day (red and visible only) are shown in Fig. 5, while Fig. 6 shows the beam currents for the day. The current detector sees the electron radiation, so that an eventual beamstrahlung signal (expected to be almost exclusively in the infrared) would be proportional to $I_- I_+^2$. Our beam finding capability is excellent, and Fig. 7 gives an idea of the dark noise of each PMT as well as the angular resolution of our optics. The final pieces of the full detector are under construction at WSU and will be installed at CESR during the shutdown starting in late May 2005..

In September 2004, we obtained a one year grant (DOE-FG02-04ER4, \$6000) to study beamstrahlung. In the last four months, we firstly concluded that there was no real possibility to test CB at the FFTB at SLAC. We then chose to concentrate on feasibility studies at CESR.

We also arrived at a simple but effective design for the CBD, shown in Fig. 8. The device makes use of the beam dump window as the primary mirror, with a secondary mirror located some 26 meters away from the beam dump. By this method, the detector is completely isolated from the many problems (RF noise, real estate conflict, and radiation damage) associated with the beam line. The second mirror bounces the radiation away from the beam line to a grating which is used to spread the radiation in wavelength. In view of the very strong signal, the detectors contain each several fast microwave detectors, of a type that saturates for large pulse heights, and with different attenuators, to cover an expected dynamic range

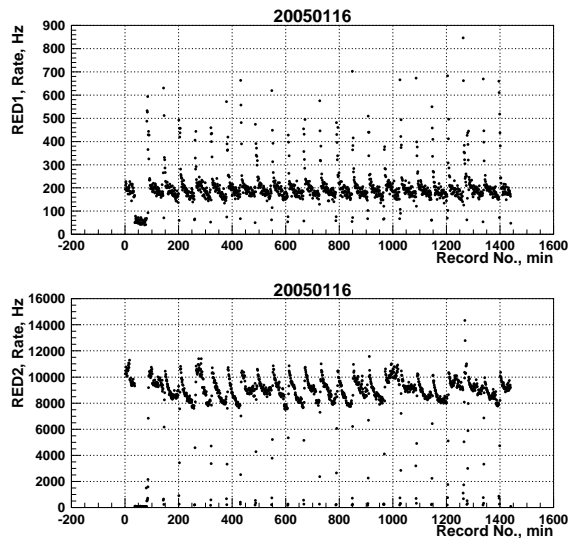


Figure 5: Data for two red PMTs, taken last Sunday.

of order 10^{10} . The detector features are discussed in greater detail in Ref.[7]. This simple device should deliver the four observables presented in Figs. 2-4.

Facilities, Equipment and Other Resources

WSU owns a high quality Machine Shop, where many high energy physics devices have been built. These include the hadronic calorimeter of experiment E-864 at Brookhaven, the electromagnetic calorimeter of STAR, the current CLEO Beam Pipe and attached equipment, and the CESR beamstrahlung monitor. Our group owns 15 Linux boxes and has access to hundreds more.

FY2005 Project Activities and Deliverables

In spring and summer 2005 we will pursue two things.

First, by then the CESR device will be completely installed and calibrated. We will therefore try to extract a first signal. Expected signals are of order a 100 Hz at $I_+ = I_- = 80\text{mA}$. There are a few handles to establish the signal uncontroversially. The first is to monitor any hypothetical signal and see that it decreases like $I_+^2 I_-$ as the run progresses.

The second is to compare results from three different bands (infrared, red, and visible above yellow). No signal in the visible is expected, and the red and infrared signals are expected to be in the ratio of about 16. This seems marginal, considering that the infrared signal is already so weak, but in fact the dark noise of our red PMTs can be made as small as 30Hz with cooling. In time, with the beam currents improving, this method will become feasible.

The third and most important way to establish the signal is to have specialized runs with a shorter CESR beam length. Going from 9 to 8 mm changes the expected signal by a factor

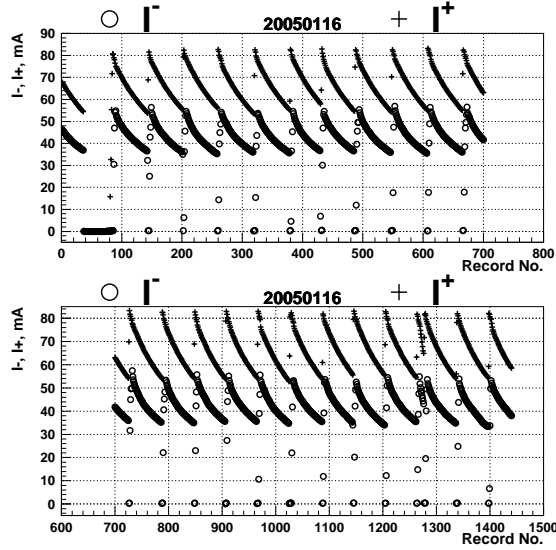


Figure 6: CESR beam currents corresponding to the data of Fig. 5.

of 5 in the red and a factor of 4.2 in the infrared, while obviously the backgrounds remain constant.

Other tests are possible, such as running with offset beams, and they will be done as the analysis progresses. Because this program involves short, dedicated CESR runs, it is best done in the summer when the complete device is available and calibrated, and we can be continuously present at Cornell.

The second thing to be done this summer is to study the feasibility of a CBD for CESR. The intent is to build and operate a simple device provide a proof of principle for the method. There are no problems in detecting such a huge signal (expected to be of order 0.1W total microwave radiation when the beams are offset by 3σ). The only problem is to find a way to minimize the RF noise coming from the beam or its charge image, which is also known to be very large.

Budget justification:

Travel: overall traveling to Cornell totaling two months for the year. Graduate student: twelve months of graduate student support. The graduate student will run simple simulations and analysis programs to support the effort described above. These include analyses to evaluate the dependence of the signal on certain parameters of interest (such as the current or beam length), evaluate internal reflection and beam pipe absorption effects for the CBD, estimate RF noise for particular configurations, and predict properties of the signal.

One-year budget, in then-year K\$

Institution: Wayne State University

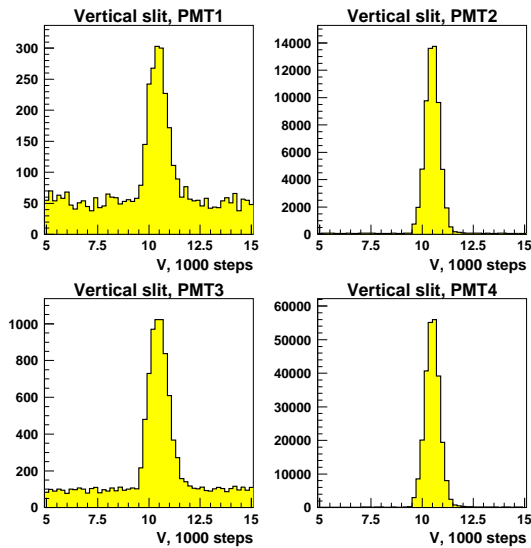


Figure 7: Vertical alignment scan for the detector optics.

Item	FY2005	Total
Other Professionals	0	0
Graduate Students	15	15
Undergraduate Students	0	0
Total Salaries and Wages	15	15
Fringe Benefits	4	4
Total Salaries, Wages and Fringe Benefits	19	19
Equipment	0	0
Travel	8	8
Materials and Supplies	0	0
Other direct costs	0	0
Total direct costs	27	27
Indirect costs(1)	14	14
Total direct and indirect costs	41	41

References

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- [2] G. Bonvicini *et al.*, Phys.Rev.Lett.62:2381,1989
- [3] The next five references are collected at the following website
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- [4] G. Bonvicini and J. Welch, Nucl. Inst. and Meth. 418, 223, 1998.
- [5] N. Detgen *et al.*, CBN-99-26.

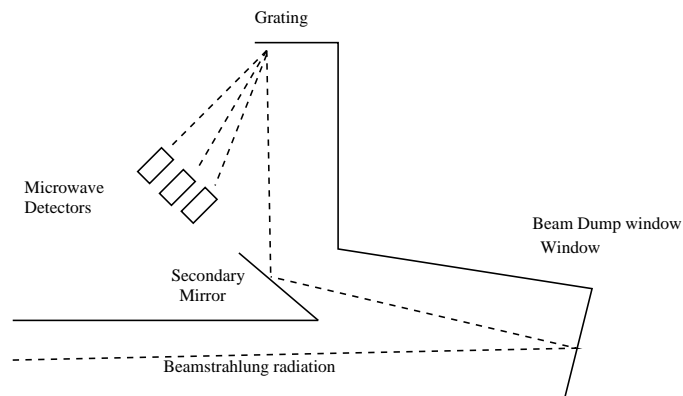


Figure 8: Basic CB detection: a) reflection off of slightly tilted beam dump window; b) extraction by a primary mirror at 26 meters; c) angular spreading by a microwave grating; d) detection by three microwave diode arrays.

- [6] G. Bonvicini, D. Cinabro and E. Luckwald, Phys. Rev. E 59: 4584, 1999.
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