Beamstrahlung Calculations

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Abstract

In the ongoing quest for higher luminosity, focusing the electron/positron beams becomes an increasingly greater priority. In order to properly focus the two beams, however, we must have a tool with which we monitor the beams. Such a tool, we predict, is beamstrahlung radiation. To give credibility to our prediction, we must strengthen our hypothesis with data. At this time, the data comes from a computer simulation program designed to interact electron/positron beams. Thus far, the results of said program point in the desired direction.

Introduction

In the current world of high energy physics, luminosity is cherished like no other quantity. In equational terms, the luminosity for two Gaussian beams of equal sizes colliding head-on is

$$L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y} \tag{1}$$

where f is the bunch collision frequency, $N_{1(2)}$ is the number of particles per bunch in beam 1(2), and $\sigma_{x(y)}$ is the horizontal(vertical) beam size [1]. But very roughly, we can say luminosity is the number of electron/positron collisions per unit collision area per unit time. The conditions for which Eq.(1) holds are termed "perfect collision". Since these collisions are essential to event (factory) production, high luminosity is obviously needed to produce a substantial number of events.

Maintaning high luminosity is a challenge since the machine has some degree of asymmetry between the positive and negative beams. The asymmetry stems from various misalignments of the machine components as well as changing beam energies; beam energy is lost continuously but replenished at only certain locations in CESR. The resulting asymmetric orbits cause the beams to lose focus. Losing focus, in turn, causes the collision area to increase, or the beams to miss one another, thus decreasing luminosity. Therefore the beams must be continuously refocused in order to maintain high luminosity. In order to properly focus the two beams, we must have a tool with which we monitor the beam pathologies. Our proposal for such a tool is a beamstrahlung radiation monitor.

Before we build such a monitor, however, we must be certain that the project is worth undertaking. We must validate our hypothesis with meaningful data and figures. Therefore we must travel to the world of Beamstrahlung Calculations.

We begin our exploration of the world of beamstrahlung calculations with a brief journey into the physics of beamstrahlung. We will then continue to the land of computer simulation, where I currently hold a summer residence. Our tour will conclude in the stunning sea of glorious results.

Beamstrahlung

Beamstrahlung is a form of synchrotron radiation emitted when particles of the first, or radiating, beam are deflected by particles of the second, or target, beam. If we consider low energy conditions as well as the conditions stated for Eq.(1), we get that the beamstrahlung energy radiated by beam 1 in one crossing is [2]

$$U_1 = g(r) r_e^3 m_e c^2 \gamma^2 \frac{N_1 N_2^2}{\sigma_x \sigma_y \sigma_z} \tag{2}$$

where U_1 is the energy radiated per collision. Here r_e is the classical radius of the beam particles, m_e is the mass of each particle, γ is the relativistic factor, N_2 is the number of particles in beam 2, and σ_x,σ_y,σ_z are the dimensions of the beam in x,y,and z respectively. $g(r)$ is a dimensionless factor obtained through integration over space-time. It is maximal for round beams ($r = 1$), at 2.735..., and for flat beams (r small, as in CESR) it can be approximated as follows

$$g(r) \sim 11.4r.$$

In the flat beam limit, σ_y cancels in Eq.(2) and the dependence of U_1 on beam parameters becomes

$$U_1 \propto \frac{\gamma^2 N_1 N_2^2}{\sigma_z \sigma_x^2}. \tag{3}$$

The energy of the emitted light is not the only information given to us by beamstrahlung, however. The emitted light propagates with its electric field parallel to the charged particle's acceleration vector. If the collision is perfect, there will be no polarization since the charged particles accelerate equally in the x (horizontal) direction as in y (vertical direction)[2]. We will see this is not the case for other pathologies when we arrive in the results section.

Computer Simulation

Since the CLEO Collaboration does not approve people drilling holes in the beampipe to test unfounded theories, we must lend credibility to our hypothesis. We have done and continue to do so via data from computer simulation.

The program we use interacts one bunch of electrons and one bunch of positrons while keeping track of the emitted energy and polarization. We originally began using an already existing beam-beam Fortran program from the early 1980's which used the popular "cloud-in-cells" approximation. As time passed, however, it became brutally apparent that this would not serve our purposes as cloud-in-cells is best-suited for simulating round beams. This resulted in the creation of a new technique[3]. This new system for simulating beam-beam interactions allowed us to simulate flat beams by treating each cell as a line, or "matchstick". After conquering that territory, we once again traveled into uncharted waters as we dared to write code which would simulate the various beam pathologies. The program was written so that beams could be allowed to evolve, in response to the attraction from the other beam, or maintain their shape (stiff beams).

Results

There are several ways in which beams can be out of focus. This is apparent in Fig. 1. We can see that the beams can be offset along the y-axis as well as the x-axis, rotated with respect to one another, different sizes, or any wild combination of these. By studying the energy and polarization of the emitted light, we can distinguish what type of beam pathology we have. Thus we present our data in a diagram where the energy emitted by each beam in both x and y are plotted. Thus each beams becomes an arrow in the first quadrant of (x, y).

For perfect collisions, and perfectly rigid beams, we expect arrows of equal length at 45 degrees. The results are presented starting with simulations of rigid beams. In Fig. 1 we see defining characteristics for each pathology.

We observe that for beams with a y offset, the ratio U_y/U_x is the same for both beams. But also, the energy emitted in y is greater than that emitted in x. Analyzing the other pathologies similarly, we notice that for the rotated beam, U_y is still greater than U_x for both beams, but the ratio U_y/U_x differs considerably from beam to beam. For the fattened beam pathology, we see $U_y > U_x$ for the bloated beam and $U_y < U_x$ for the correct (non-pathological) beam. Also with the bloated beam we see that the vector corresponding to the pathological beam is longer. Interestingly enough, in each case, the pathological beam has the greater energy emitted in y. This is extremely useful in deciding which beam to adjust.

In the third column of Fig.1, we see plots which pit various asymetry variables against the ratio L/L_0. Essentially, these plots show us the sensitivity of the asymmetry variables to shifts in luminosity. We notice immediately that the vertical offset and the beam fattening asymmetry variables are the most sensitive with the rotation variable being the least. Regardless, by monitoring these quantities and keeping shifts to less than a few percent, we can keep luminosity shifts to less than a few percent [4].

In Fig.1, we considered only stiff, or non-disrupted beams. Ofcourse, in reality, CESR suffers from beam disruption. In Fig.2 we take these conditions under consideration. Happily, we observe that the new dynamic nature of the beams had little effect on our pathology characteristics. Infact, even with the addition of beam dynamics, our normalization constants U_{y0} and U_{x0} changed by only a few parts in one thousand [5]. Therefore, with even greater dynamic beta effects, we still expect all conclusions to hold.

A perfectly valid question to ask is what happens when more than one problem occurs. Fig.3 diplays for us the situation in which the beams become offset in the x (horizontal) direction by a distance of 17.5 microns. Properly, the x-offset has only passive effects on the results. This is expected since such an offset would vary the luminosity ratio $L/L0$ by only .06 percent. Fig.4 gives us something a little more informative. As stated before, the rotation has the least effect on the beamstrahlung characteristics as both the y-offset and the bloated beam dominate vectors shared with the rotation. Furthermore, the y-offset dominates the bloated pathology.

The Virtual Operator

So far we have experienced many different pathologies and we have learned the various characteristics of each. Now is the time to put what we learned to the test. We must become...The Virtual Operator.

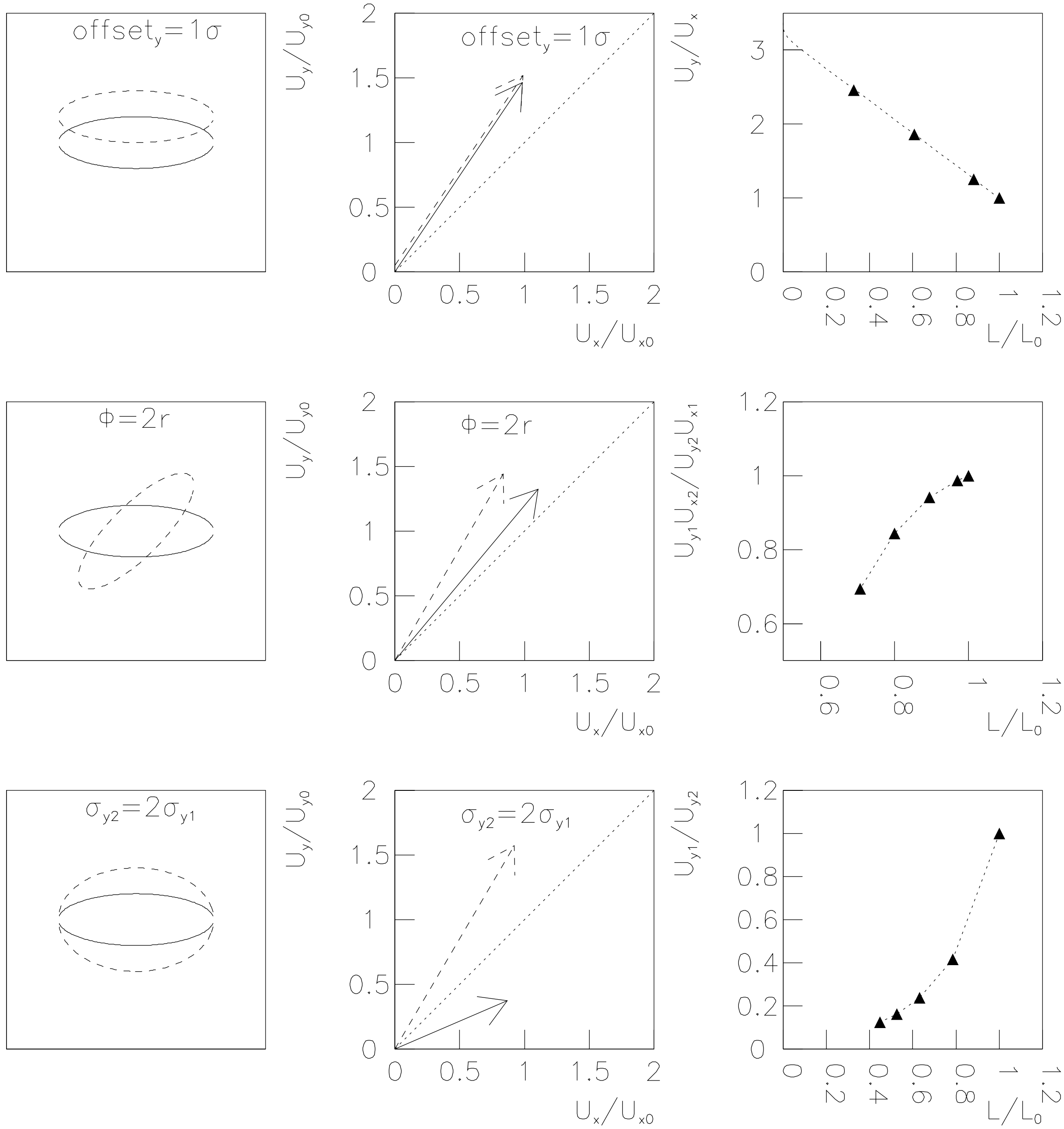

FIGURE 1. Energy vectors and asymmetry variable plots for stiff beams (tips of vectors in y-offset case are displace for display purposes). The normalization constants U_{x0} and U_{y0} are equal and representent the energies emitted in x and y respectively during perfect head-on collision.

We begin with our beams badly out of focus. Looking at Fig.5 we see that our vectors show us two separated vectors of different length above the 45 degree reference line. At this point, it is completely up to the operator's discretion what to fix first. In this case, I will begin with adjusting the aspect ratio of beam 2 in order to get the vectors to equal lengths.

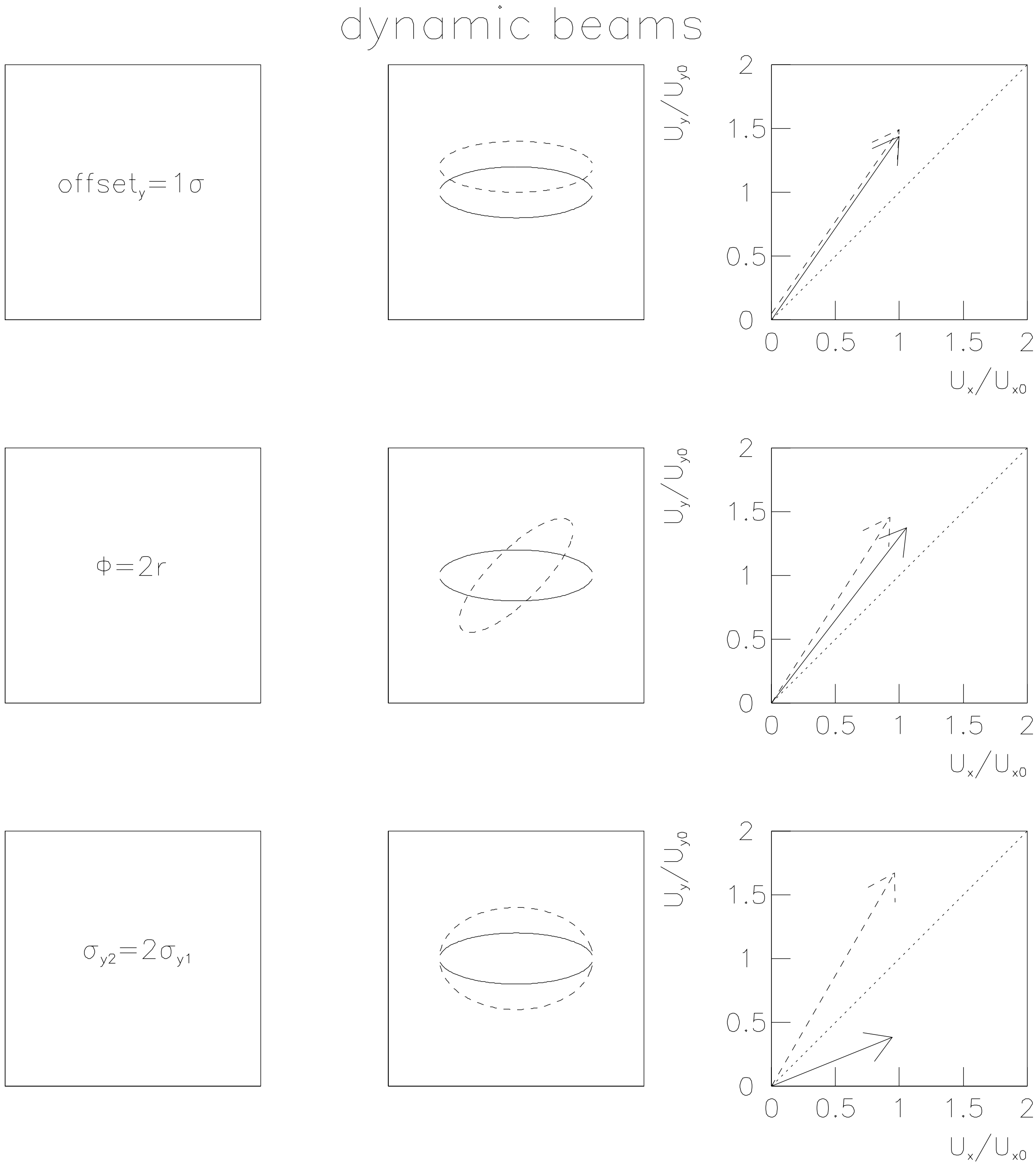

FIGURE 2. Energy vectors for dynamic beams. (tips of vectors in y-offset case are displace for display purposes)

Now that I have done this, I have two vectors of equal lengths still separated by an angle and still residing above the 45 degree reference line. Once again, what to do now is up to the operator. Since I am presently operating, I elect to fix the rotation. We now have a single vector (actually two identical vectors) resting above the reference line. Adjusting for the obvious offset in vertical, we get a focused beam. Success!

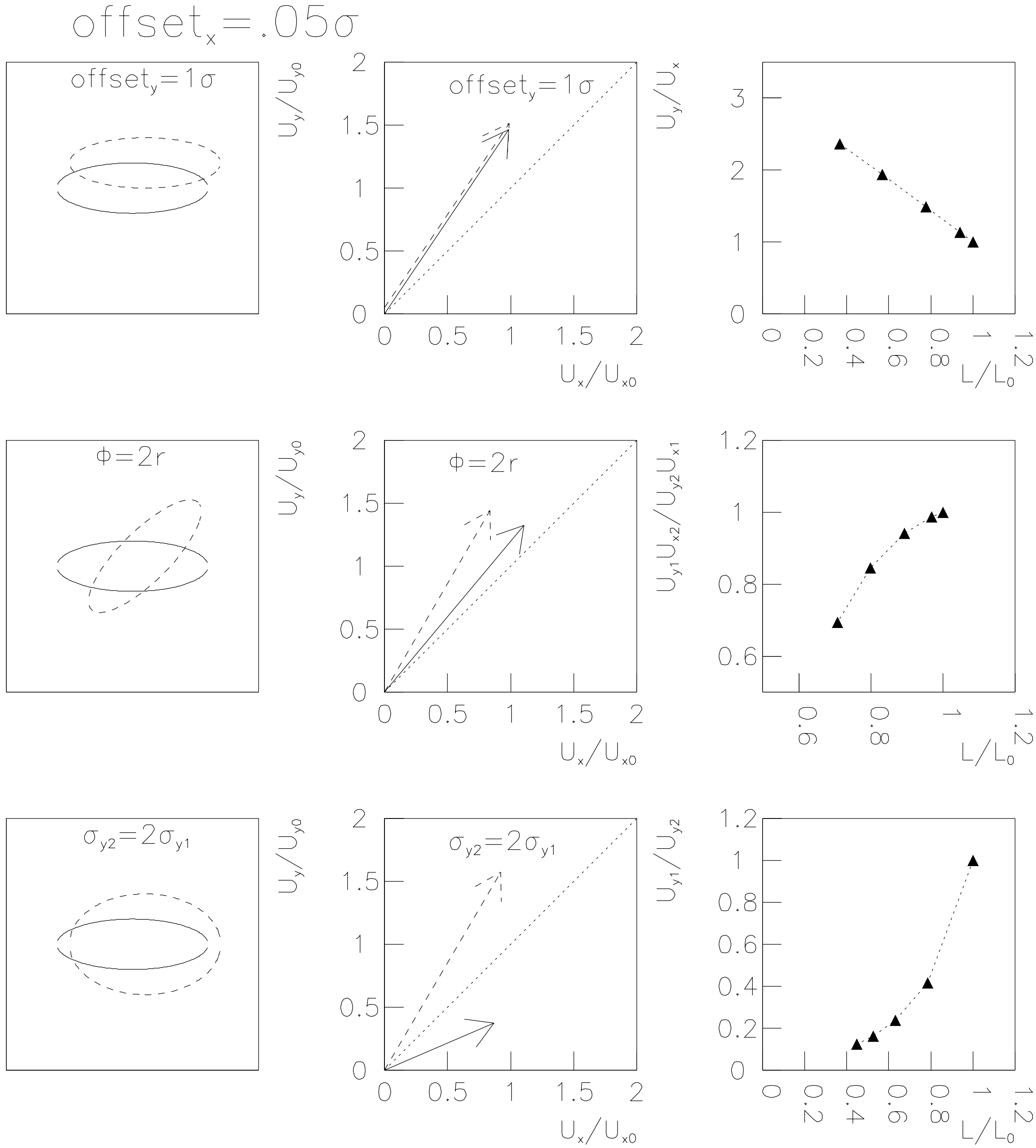

FIGURE 3. Energy vectors and asymmetry variable plots for stiff beams with a horizontal separation of 0.05σ (17.5μm).(tips of vectors in y-offset case are displaced for display purposes)

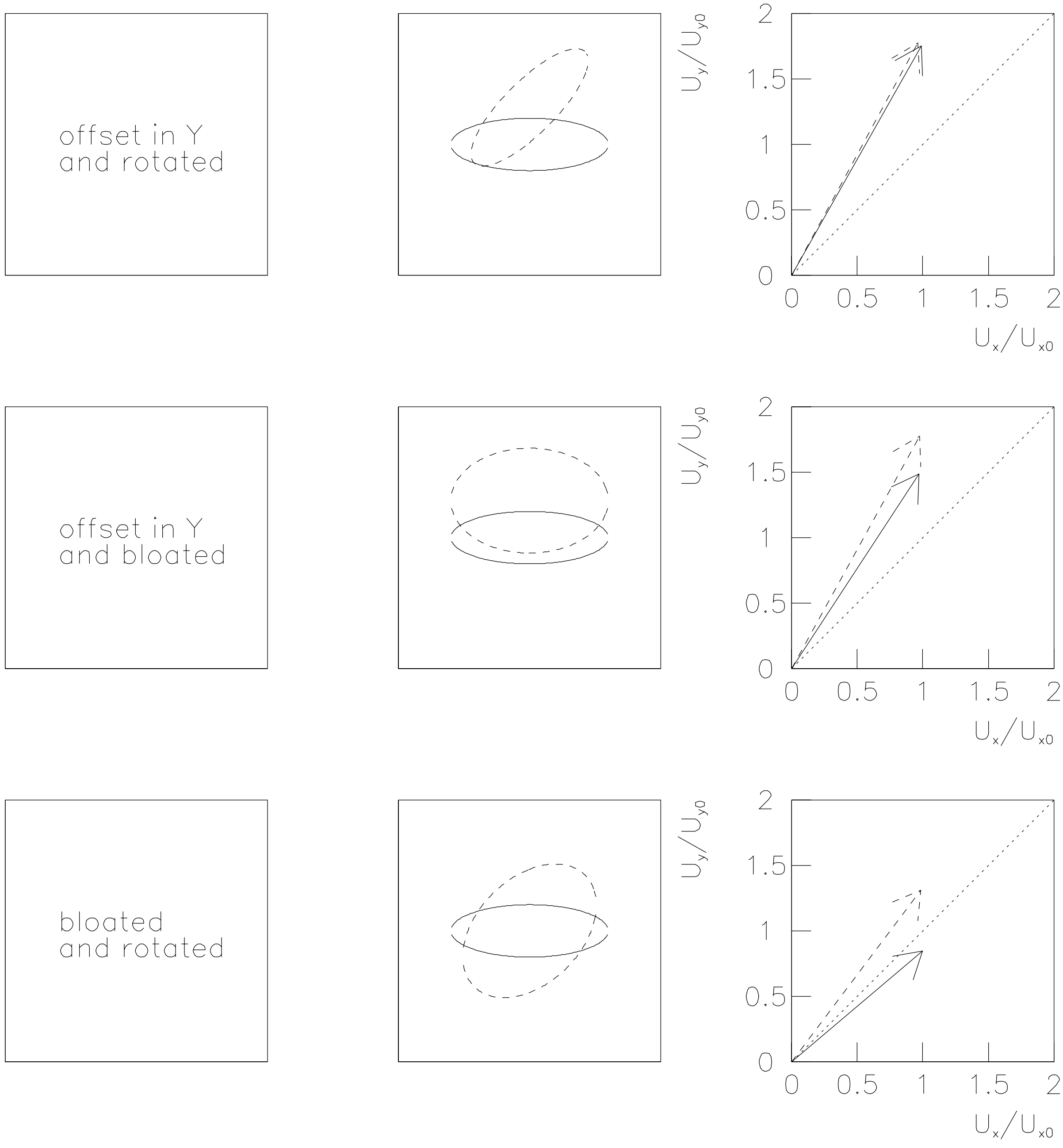

FIGURE 4. Energy vectors for dynamic beams with dual pathologies.

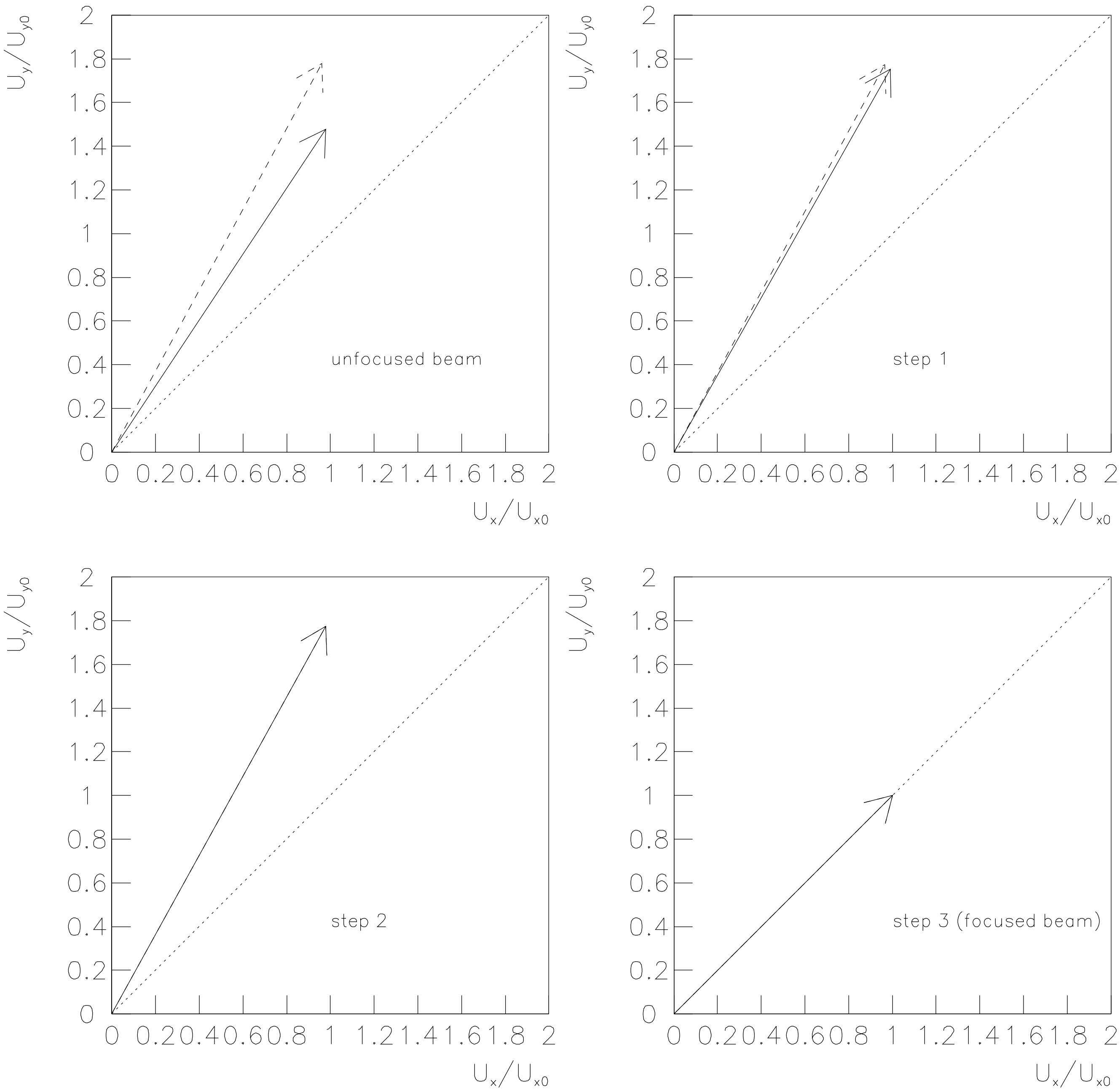

FIGURE 5. The Virtual Operator

Conclusions

This leg of the journey was a success. We created a program that worked and it worked to our expectations. Furthermore, we showed how the varying beam pathologies have obvious individual characteristics. The question now is what lies on the road ahead. The physics is valid, but is it practical? Will we be able to extract the beamstrahlung signal? Will a beamstrahlung monitor be accepted as the primary beam-beam monitoring tool. Ofcourse we believe the answers to these questions are “yes” and we shall continue on until we prove such.

Acknowledgements

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Footnotes and References

1. G. Bonvicini & J. Welch, “Large Angle Beamstrahlung as a Beam-Beam Monitoring Tool”' CLNS97-1523, 1997.
2. M. Bassetti *et al.*, IEEE Trans. Nucl. Science 30: 2182, 1983.
3. Technique created by Giovanni Bonvicini, June-July, 1998.
4. Information taken from conversations with Giovanni Bonvicini
5. Based on parameters for CESR taken from Particle Data Book 1994, Phys. Rev. D 50, 1994, page 1246