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X. Qiu[b], P. Catravas[a], M. Babzien[b], I. Ben-Zvi[b], J.-M. Fang[d], W. Graves[b],
Y. Liu[b], R. Malone[b], I. Mastovsky[a], Z. Segalov[b], J. Sheehan[b], R. Stoner[a],
X.-J. Wang[b], and J.S. Wurtel[c]

[a]Massachusetts Institute of Technology, Cambridge, MA 02139
[b]Brookhaven National Laboratory, Upton, NY 11973
[c]Lawrence Berkeley Laboratory, Berkeley, CA 94720
[d]Columbia University, New York, NY 10027

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National Synchrotron Light Source
Brookhaven National Laboratory
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X. Qiu[b], *P. Catravas*[a*], *M. Babzien*[b], *I. Ben-Zvi*[b], *J.-M. Fang*[d], *W. Graves*[b], *Y. Liu*[b], *R. Malone*[b], *I. Mastovsky*[a], *Z. Segalov*[b], *J. Sheehan*[b], *R. Stoner*[a], *X.-J. Wang*[b], *J. S. Wurtele*[c]

[a] *Massachusetts Institute of Technology, Cambridge, MA 02139*
[b] *Brookhaven National Laboratory, Upton, NY, 11973*
[c] *Lawrence Berkeley Laboratory, Berkeley, CA 94720*
[d] *Columbia University, New York, Ny, 10027*

Abstract:

We report a new method through which the properties of an electron beam at linac energies may be studied using the spontaneous emission of a microwiggler. The setup is simple and the measurement efficient. A simple set of scaling laws is derived to describe broadening of spontaneous emission in a narrow bandwidth radiation cone. The relations suggest that one can obtain beam divergence from a cone at large angle in a single shot measurement. A systematic series of experiments was performed with the MIT Microwiggler at the Accelerator Test Facility at BNL which demonstrated the response of the cone to changes in the beam quality. Estimates of divergence can be obtained from the measurements of the radiation cone.

1. Introduction:

It has long been recognized, in theoretical studies [1,2], that wiggler spontaneous emission has the potential to serve as an important non-perturbative beam diagnostic. Experimental work has been performed [3-5] and proposed [6]. Until recently, it was difficult to infer beam parameters such as emittance and energy spread because of resolution limitations, exacerbated by numerous inherent broadening sources.

We report experiments on characterization of a linac-produced electron beam directly from the spontaneous emission of a microwiggler. We record the spatial profile of emissions into a Cerenkov cone selected by a 1 nm bandwidth interference filter. The radius of the cone can be controlled by varying the beam energy or filter central wavelength, while the cone width depends on the number of wiggler periods, and is further broadened by the beam energy spread, the beam divergence and the filter bandwidth. Systematic measurements of the emissions over a range in beam energy, energy spread, tuning parameters and wiggler field strength have been performed.

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[*] Please send proofs to : Palma Catravas
MIT
Research Laboratory of Electronics
Bldg. 36-213
77 Massachusetts Ave.
Cambridge MA 02139
Tel: 617-253-7324 or 8533; FAX 617-258-7864
email: catravas@MIT.EDU

2. *Experimental Setup.*

The experimental setup is shown in Figure 1. The electron beam passes through the microwiggler, the spontaneous emission is outcoupled and intercepted by the interference filter, and the remaining narrow bandwidth constituent is recorded by the CCD camera.

For the experiments described in this paper, a beam energy of 48 MeV and a train of 20 microbunches at 150-200 pC each was chosen. Nominal figures for energy spread and emittance were 0.5% full width and a few π mm-mrad, respectively. Further description of the Accelerator Test Facility can be found in [7].

The MIT microwiggler [8,9] is a planar, pulsed electromagnet with individually tunable half-periods which provides a 0.45 Tesla on-axis field over 70 periods of 8.8 mm each. Through its compact size, its extensive profile tunability, its adjustable field strength, its long length, and short period the microwiggler offers unique opportunities for such an application, particularly in sensitivity of emissions to beam parameters, and in the wavelength of emission (532 nm at approximately 50 MeV), where a wide variety of optical diagnostics are available.

The narrow bandwidth interference filter is a critical element in the setup, not only for sensitivity, but for bringing out a useful scaling with beam parameters. Furthermore, one nanometer bandwidth filters are available at conveniently spaced wavelengths across the visible spectrum, essentially furnishing a coarse adjustment knob over a range of beam energies. Fine tuning of the cone angle for a desired beam energy can be achieved by reasonable adjustments of the filter tilt and/or wiggler field strength.

3. *Fixing the frequency and looking at a large angle.*

At a fixed frequency, the contribution to the cone width scales differently with cone angle for the various broadening mechanisms. Simple expressions for the contributions of natural linewidth ($\sigma_{cone,nat}$), energy spread ($\sigma_{cone,\gamma}$), and divergence ($\sigma_{cone,x'}$) to the cone width in the wiggle plane are:

$$\sigma_{cone,nat} = \frac{1}{4N_w}\frac{1+\frac{a_w^2}{2}}{\gamma^2\theta_{cone}}, \qquad \theta_{cone} >> \frac{1}{\sqrt{N_w}\gamma}, N_w >> 1 \tag{1}$$

$$\sigma_{cone,\gamma} = \frac{\sigma_\gamma}{\gamma}\frac{1+\frac{a_w^2}{2}}{\gamma^2\theta_{cone}} \tag{2}$$

$$\sigma_{cone,x'} = \sigma_{x'} \tag{3}$$

The wiggle plane corresponds to the x-z plane, where z is the direction of propagation of the beam. σ_γ and $\sigma_{x'}$ are the widths of Gaussian distributions in energy spread and x divergence, θ_{cone} is the angle at the which the resonance condition is satisfied for a fixed wavelength, N_w is the number of wiggler periods, and a_w is the wiggler parameter. For comparison with the preliminary data, analysis assumes transverse beam size small compared with the cosh variation of the magnetic field, and neglects the contribution from betatron motion. The contributions of natural linewidth and energy spread to the width decrease with cone angle, and for sufficiently large angles, the width is dominated by the distribution in x'. Note that requirements on the collection angle of the system are easy to implement for N_w=70.

For comparison with the simple analytic expressions, a code was written which convolves the spectral flux density for a single electron [1,2] with Gaussian distributions in energy spread, and x and y divergence. The code calculates the slice of the cone in the wiggle plane for an array of any two of the energy spread, x divergence and y divergence, and generates a contour plot of χ^2 for theory compared to either laboratory or synthetic data. In this way, the relative sensitivity to two fit parameters can be observed graphically. The same code, modified appropriately, was incorporated into a multi-parameter fitting routine.

4. Results

The dependence of the S.E. cones was studied as a function of beam energy, interference filter incident angle, beam energy spread, wiggler field strength, misalignment, and various beam optics.

A scan in γ (Fig. 2a) is particularly rich in information, and provided an opportunity to compare the preceeding scaling laws with experiment. Figure 3 plots cone angle θ_{cone} against beam energy along with a fit to the resonance condition. All the fit parameter values (μrad/CCD pixel, γ, filter tilt and a_w) fell within the error bar of independent measurements. In Figure 4, the measured cone width in the wiggle plane is plotted as a function of γ, or, equivalently, θ_{cone}. Two curves are shown: one starting at the forward emissions, where the unbroadened half width on axis is $\sim \frac{1}{\sqrt{N_w \gamma}}$; the other in the regime where there is no on-axis emission. An asymptote in cone width is predicted by the scaling expressions when θ_{cone} is greater than 1.3 mrad, and is observed in the data. The one-σ width at this asymptote is 0.3 mrad. As an example, at θ_{cone} = 2.6 mrad, equations 1-3 predict the natural linewidth to be 0.16 mrad and the width due to energy spread to be negligable for typical energy spreads, which yields an estimate for $\sigma_{cone,x'}$ of 0.25 mrad from the data. A least squares contour plot which compares the experimental data with the code for an array in energy spread and x divergence confirms a best fit at 0.25 mrad (Figure 5). The fit was found to be insensitive to the value of $\sigma_{y'}$. This value of divergence extracted from the spontaneous emission is reasonable for the beam tune. In principle, the Twiss parameters in the wiggle plane can now be estimated from measurements of the beam spot size on BPM 1 and 2.

The γ scan demonstrates why the S.E. cone makes such a practical tool: the cone provides immediate, vivid visual feedback with a change of a fraction of a percent in the mean beam energy. In practice, the qualitative attributes of the cone earned it a natural role in the tuning process.

A set of measurements bearing strong resemblance to the γ scan was obtained by tuning the filter central wavelength. Substantial tilts of the filter were required, however, to obtain the same range of variation as the γ scan.

Studies of cone response to energy spread were performed by varying the phase of the second section of linac, where RF curvature places a chirp on the beam, changing the energy spread. Figures 2b and 6 show the variation of the cones during these changes. The effect of energy spread was also visible in the single shot spectra.

S. E. cones may be used to complement studies of slice emittance. The head, middle, and tail slice of the beam can be obtained by placing an energy chirp on the beam and using the high energy slit as a selector, a method developed at ATF in order to demonstrate emittance compensation[10]. Marked changes in cone width (θ_{cone}~1.5 mrad) were observed when different portions of the beam passed through the high energy slit.

The response of cones to changes in a_w was studied in two ways. A family of cones was recorded for ten values of a_w. This type of scan provides a way to study the contribution of betatron motion in a planar wiggler. The beam was then misaligned deliberately in the plane of field variation by the maximum amount allowed by the 3.5 mm wiggler bore. The latter is included in Figure 2c.

5. Conclusion

A systematic series of experiments was performed to demonstrate that a 50 MeV beam may be characterized with the spontaneous emission from a microwiggler. Simple analytic expressions have been derived to quantify broadening of spontaneous emission into a 1 nm bandwidth cone of chosen radius. With fixed frequency and a large angle radiation cone, simple theory predicts that divergence broadening will dominate over natural linewidth and energy spread broadening, so that at sufficiently large angles, a direct, single-shot measurement of beam divergence can be obtained. A reasonable estimate of divergence in the wiggle plane was extracted from the data. We are currently refining our diagnostic techniques and our data analysis as well as improving our theoretical modelling.

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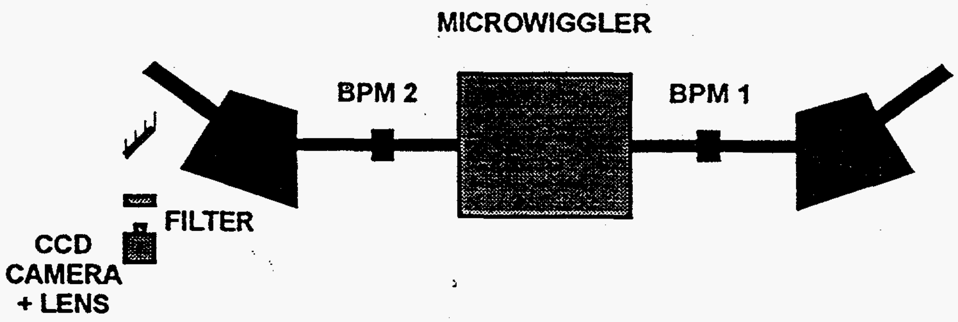
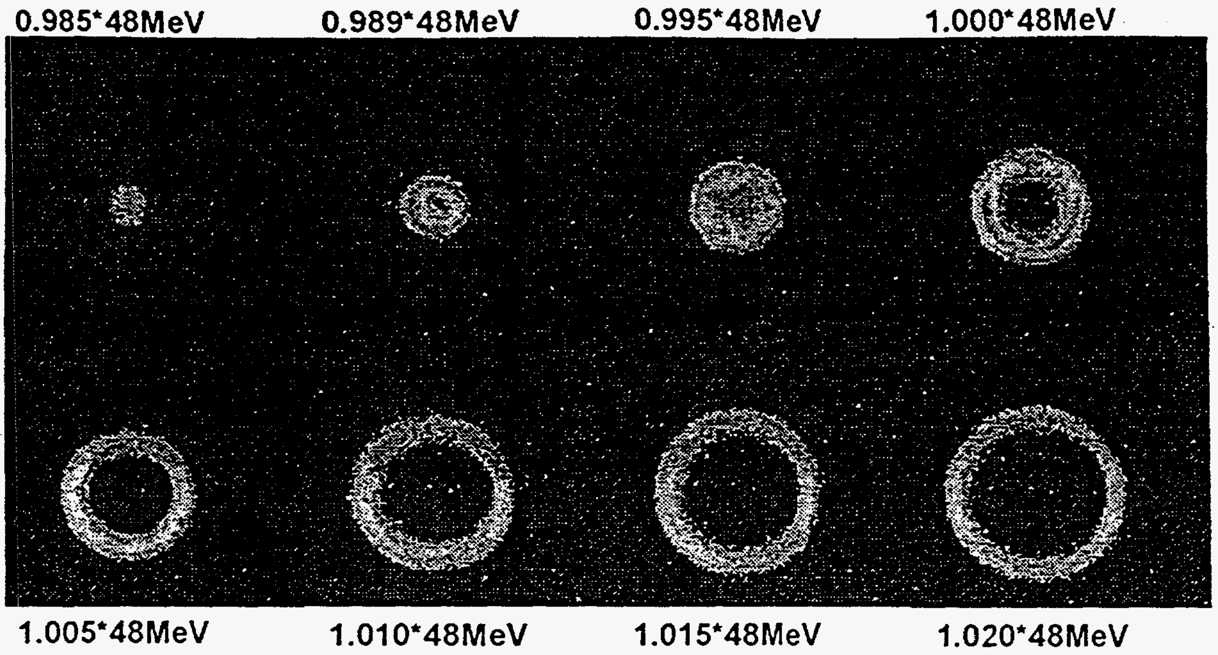
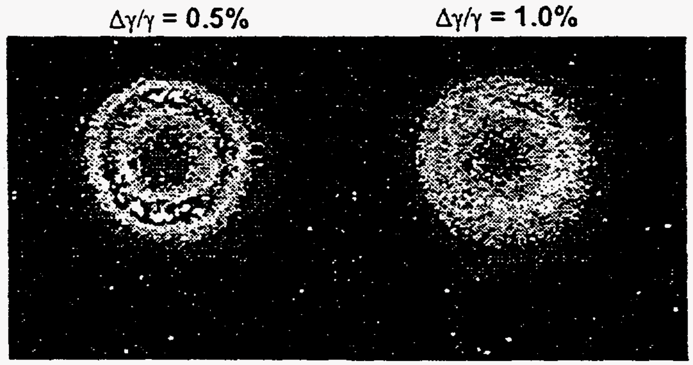


Figure 1. Experimental setup.

a) dependence on beam energy



b) dependence on energy spread



c) dependence on steering

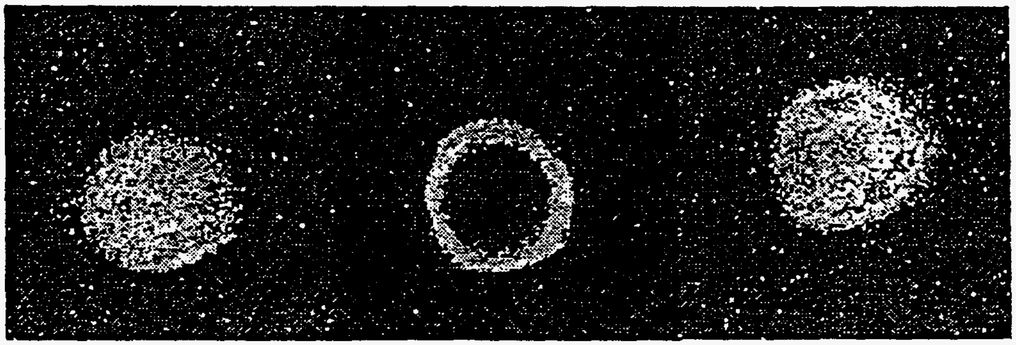


Figure 2. CCD images showing dependence of S. E. cones on beam energy, energy spread and steering. The wiggle plane corresponds to the vertical axis. The color map represents emission intensity.

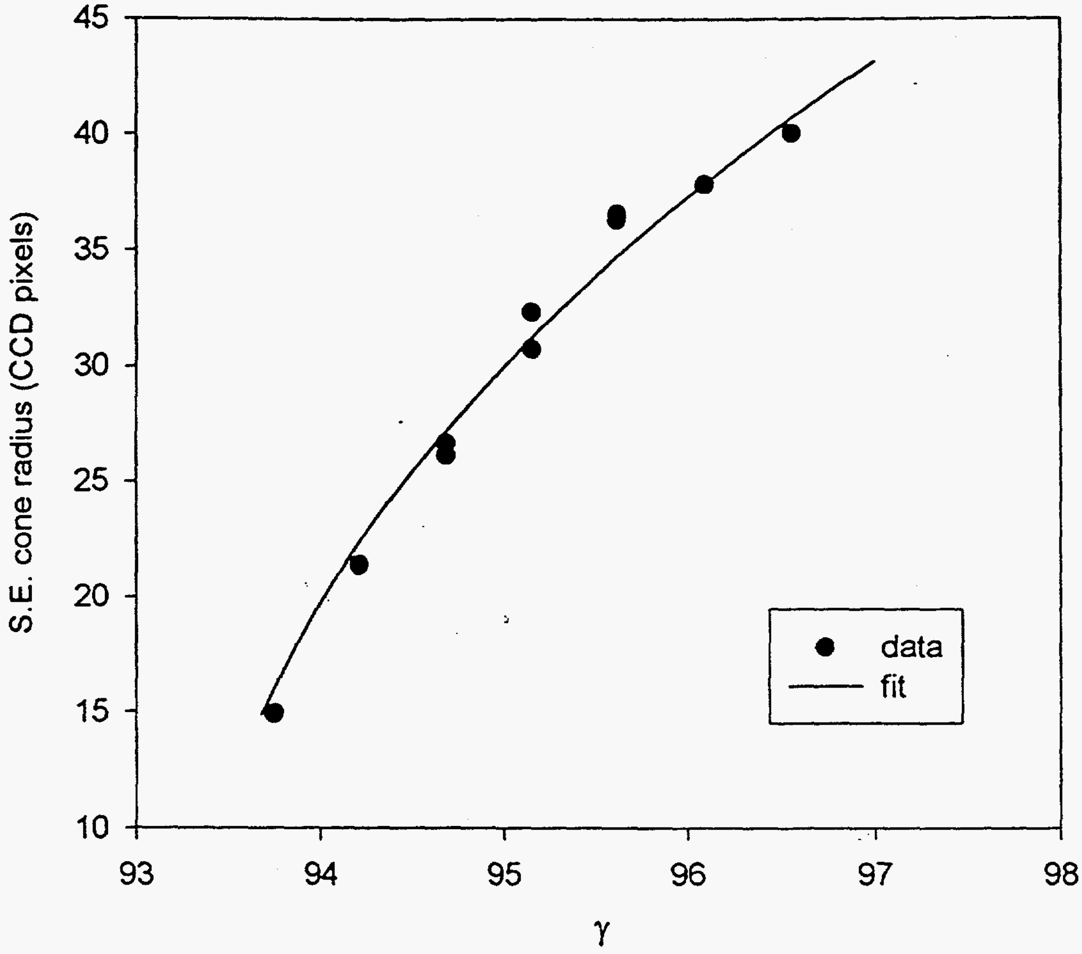


Figure 3. S.E. cone radius as a function of beam energy. The fit to the data was obtained with values of the parameters μrad/CCD pixel, γ, filter tilt and a_W which all lie within their respective error bars.

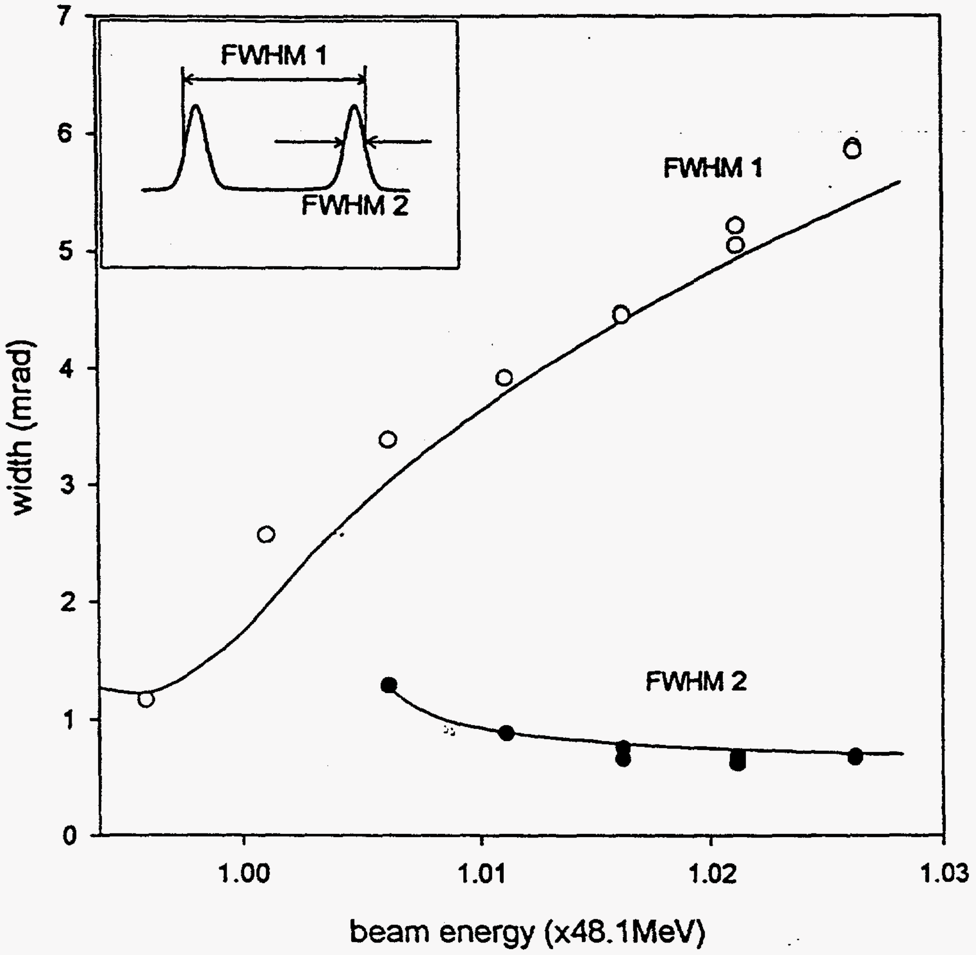


Figure 4. Study of S.E. cone widths as a function of beam energy. The solid line was computed with parameters: $\Delta\gamma/\gamma$=1% full width, σ_x'=0.24mrad, σ_y'=0.35mrad, and a_w, N_w, λ_w and calibrations the same as in Figure 3. Note the asymptote in the lower curve as γ increases.

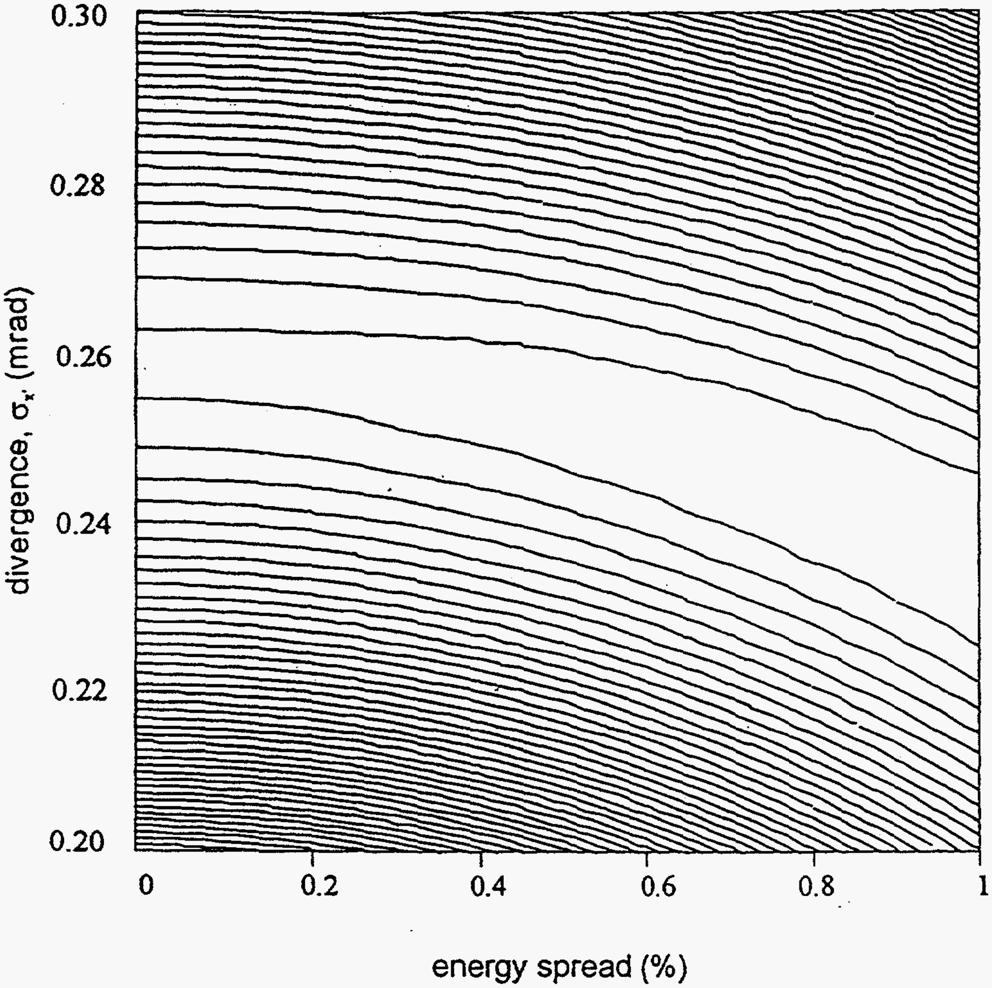


Figure 5. χ^2 plot indicating region of best fit between data and simulation for a S.E. cone at θ_{cone} = 2.6mrad. The intensity as a function of angle in the wiggle plane was computed for the array of energy spreads and divergences shown, with σ_y at 0.35 mrad. The best fit to the data is seen to lie within the range $\sigma_{x'}$ = 0.25+/-0.01 mrad and is relatively insensitive to energy spreads below 1% full width.

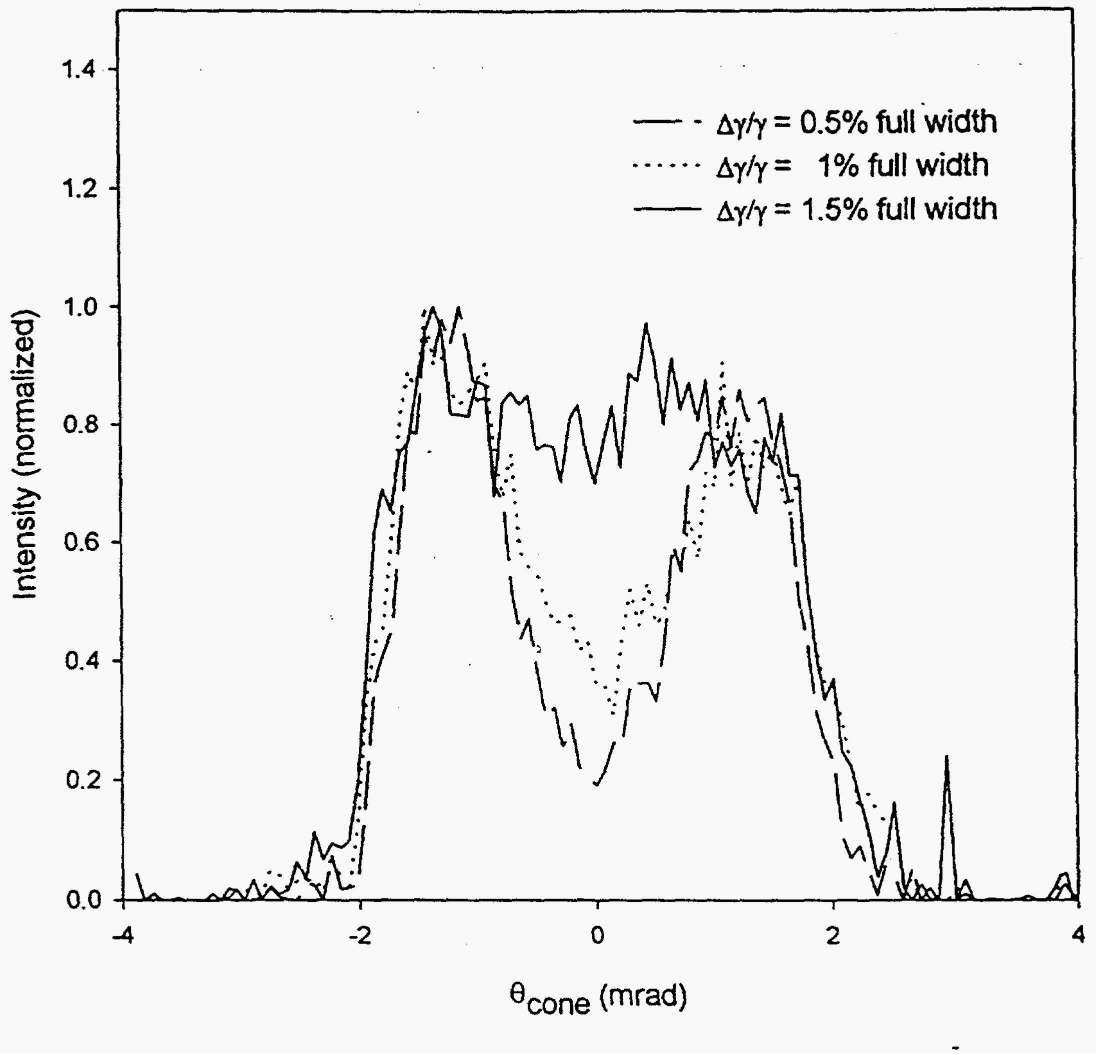


Figure 6. A cone angle was selected having a small ratio of on-axis to peak intensity at $\Delta\gamma/\gamma$ = 0.5% FW. A series of cones was then recorded for $\Delta\gamma/\gamma$ = 0.5%, 1%, 1.5% FW. Slice in the non-wiggle plane is shown.