Laser-Wire Issues

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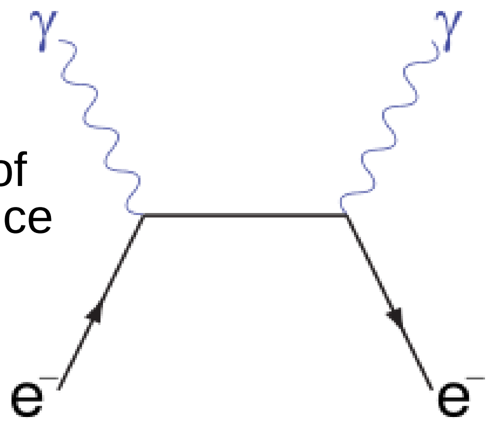
Outline

- Introduction to LW
- Review of ATF extraction line laser wire system
- Laser-wire signal extraction at CLIC

Introduction

- A means of measuring transverse **beam sizes essential** for future linear collider.
- Typical beam sizes to be measured ~few *μ*m, worst case *μ*m, to within ~few % in order to measure beam **emittance.**
- **Aim:** to develop a system which can measure **1 *μ*m beam sizes**
- **Method**: use a finely focused pulsed laser beam and measuring rate of **inverse Compton scattering** as a function of relative **displacement**.



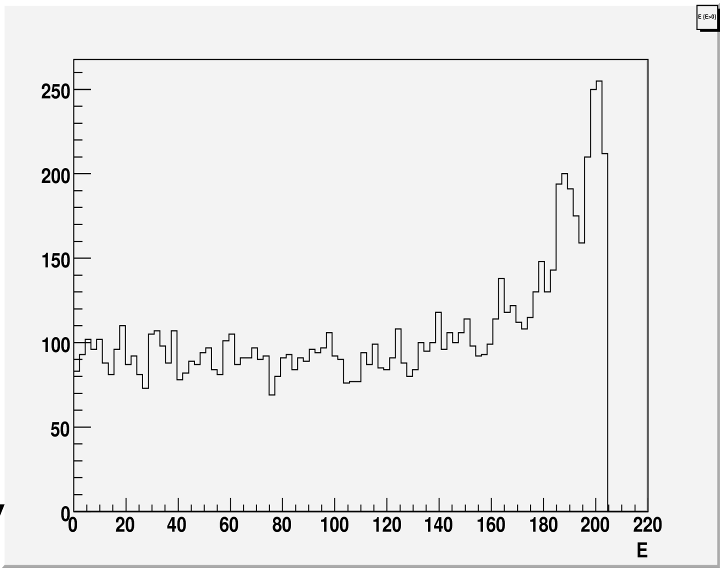
2 eV

0 - 200GeV

Angle of incidence = 90°

250 GeV

50 – 250 GeV

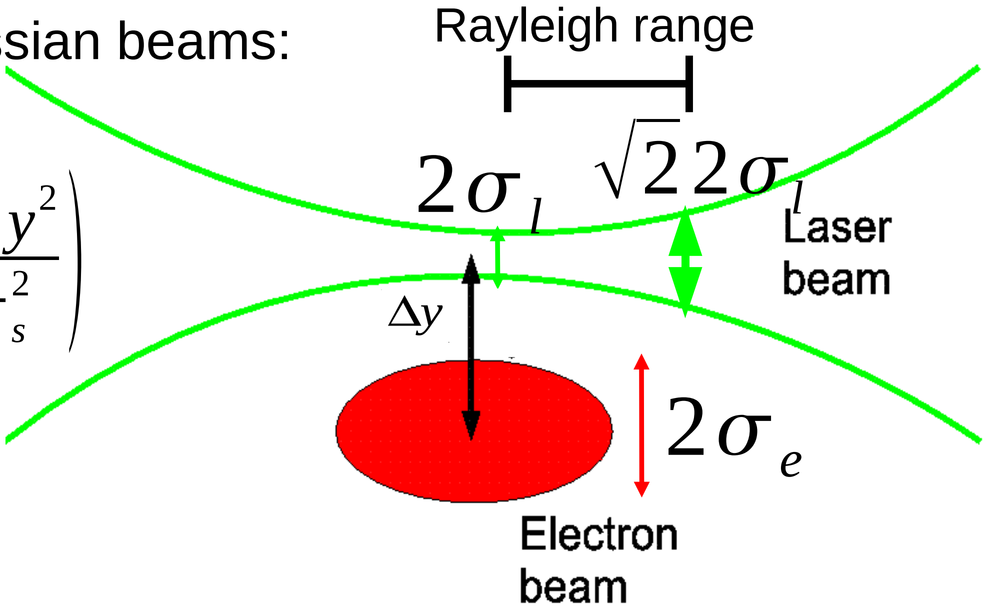


Compton Scattering Rate

- Compton scattering rate for Gaussian beams:

$$N_\gamma = N_b \frac{P_L \sigma_C \lambda}{c^2 h} \frac{1}{\sqrt{2\pi}\,\sigma_s} \exp\left(\frac{-\Delta y^2}{2\sigma_s^2} \right)$$

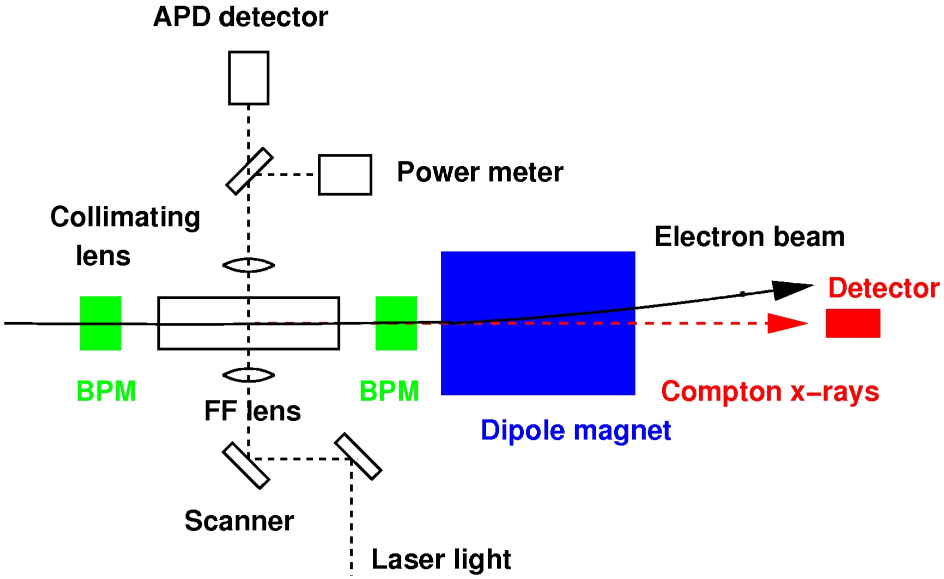
$$\sigma_s^2 = \sigma_e^2 + \sigma_l^2$$



- By measuring Compton rate (N_γ) as a function of relative displacement (Δy), the quadrature sum of the beam sizes (σ_s) can be determined
- If laser beam size is known then the electron beam size can be determined

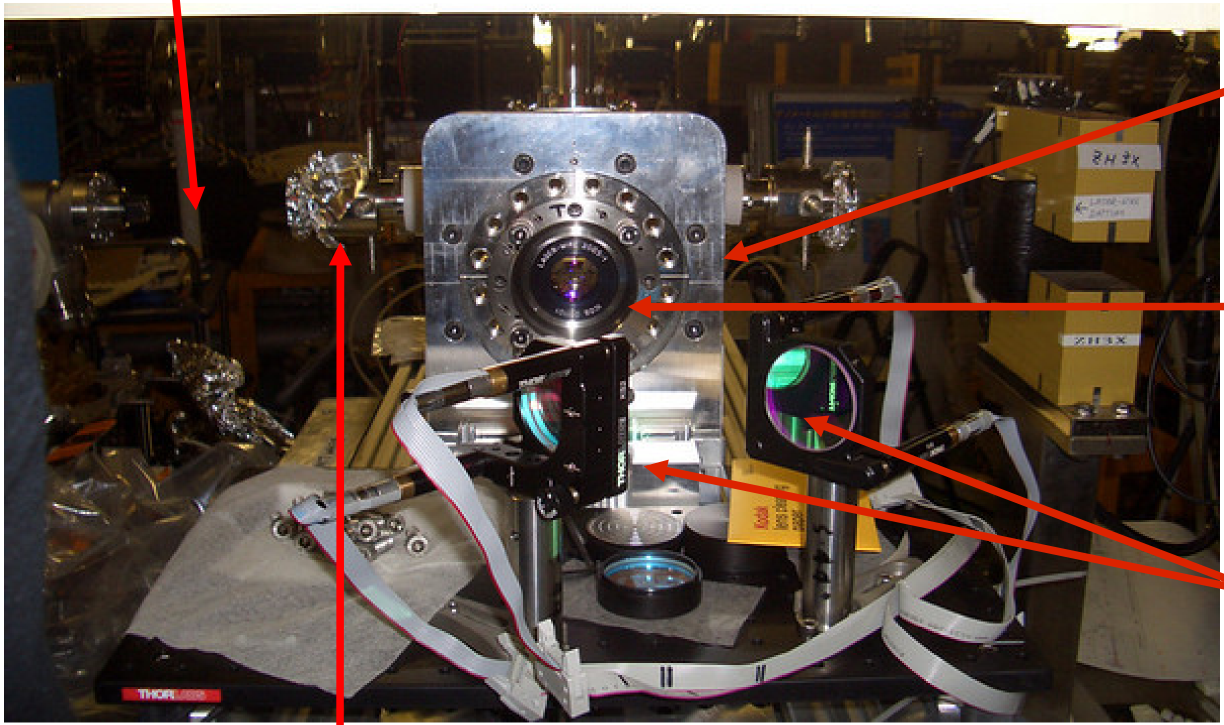
ATF Extraction Line Laser Wire System

- FF lens mounted directly on vacuum chamber. Chamber has a 3 axis translation system



- Light steered onto final focus (FF) lens using 2 mirrors

Interaction Chamber



Beam line

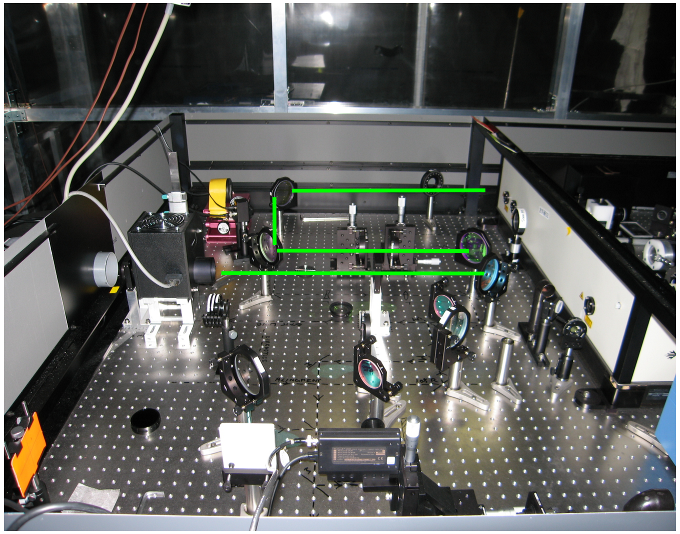
Chamber can be moved along 2 axes transverse to electron beam

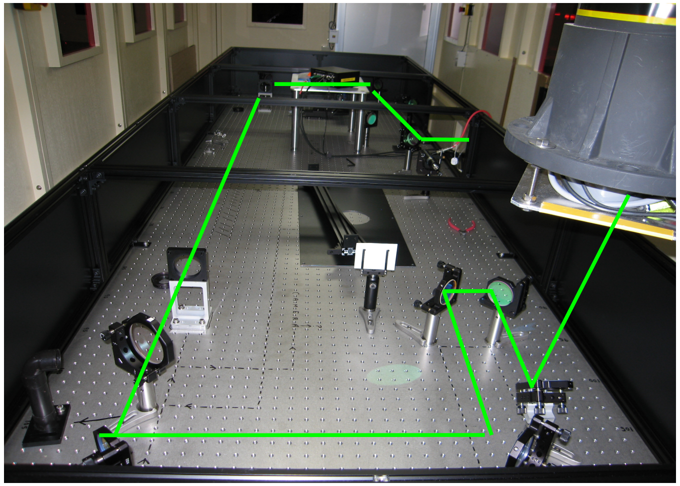
Custom f=56mm lens fixed to chamber

Two scanning mirrors

Strip line beam position monitors fixed to chamber

Laser





- High energy green (λ=532nm) laser pulses
- Amplify a single pulse from passively mode-locked seed laser
- Frequency locked to ATF RF distribution system at 357MHz
- Pulse duration ~150ps
- Pulse energy ~30mJ
- Laser light is transported collimated to extraction line by series of mirrors and aligned using irises

Laser M squared Measurement

- The formula for the focus spot size is

$$W_0 = \frac{M^2 \lambda f}{W_i \pi}$$

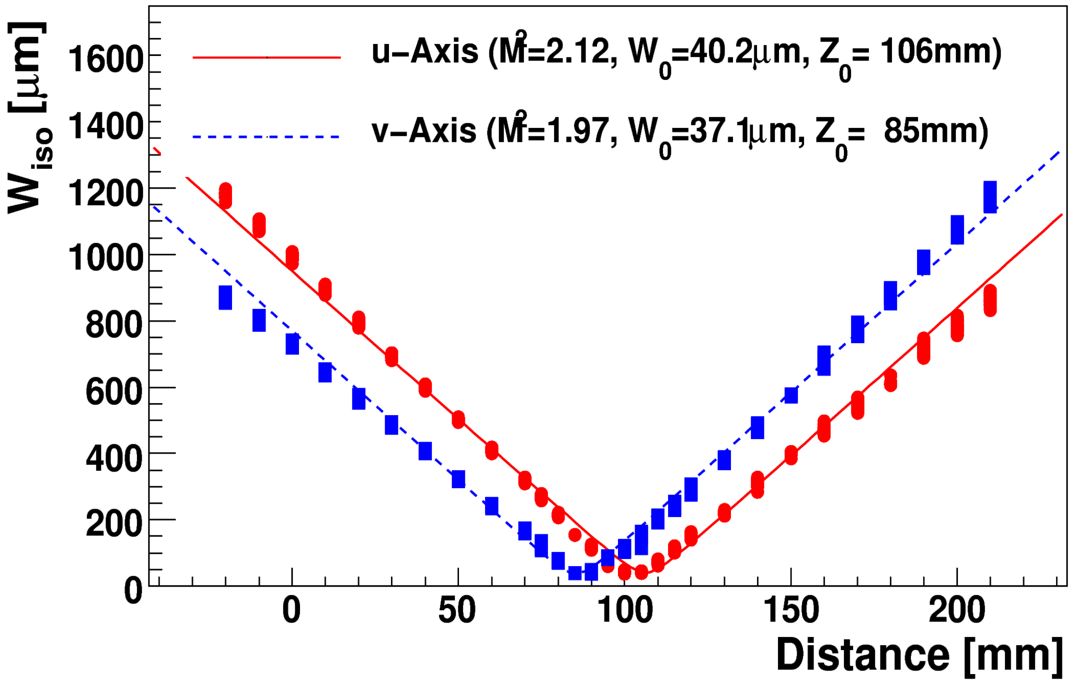
- M^2 = laser quality factor. $M^2 > 1$. For a laser with a perfect Gaussian profile $M^2=1$.
- Lambda = wavelength.
- The focal length of the lens is f.
- W_i = input beam size. ($W=2\sigma$)
- We measured the M^2 of our laser in the following way...

Laser M squared Measurement

- W was measured at different positions, z, along the propagation axis, after a 1m focal length lens

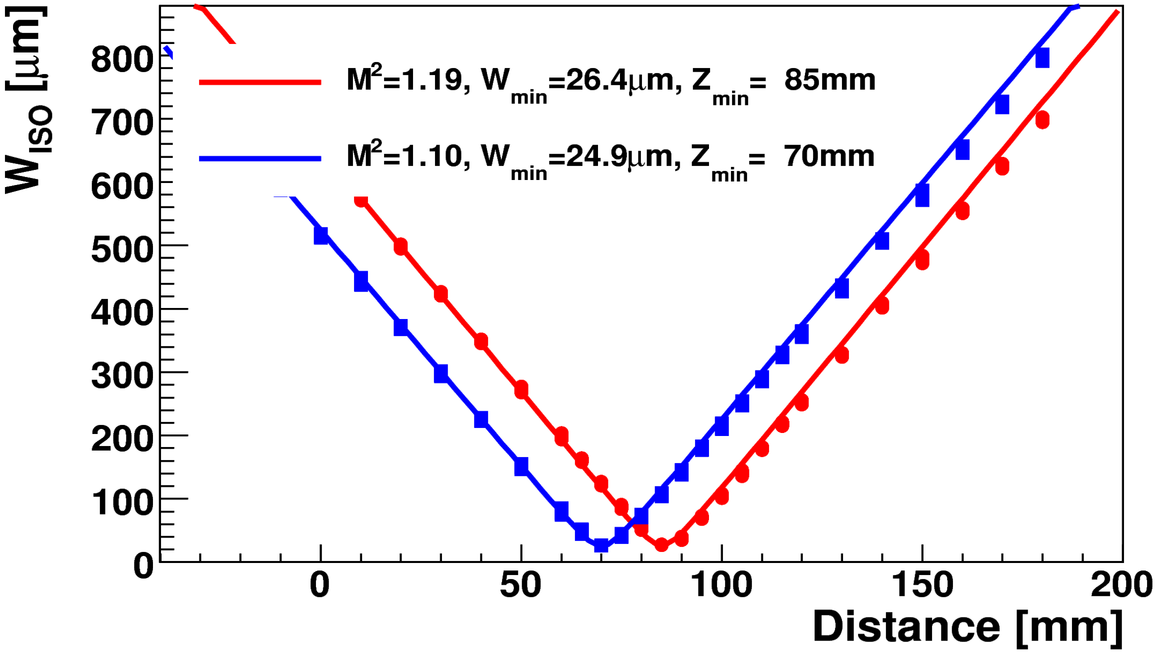
•The data were fit to the laser propagation formula; $M^2 \sim 2$

$$W(z)=W_0\left[1+\left(\frac{M^2\lambda}{\pi W_0^2}z\right)\right]^{1/2}$$



Laser M squared Measurement

- As a cross check, the same procedure was carried out with a low power CW laser
- In this case, $M^2 \sim 1.15$



Input beam size vs focus size

- The formula indicates that spot size at the focus is inversely proportional to spot size at the lens input

$$W_0 = \frac{M^2 \lambda f}{W_i \pi}$$

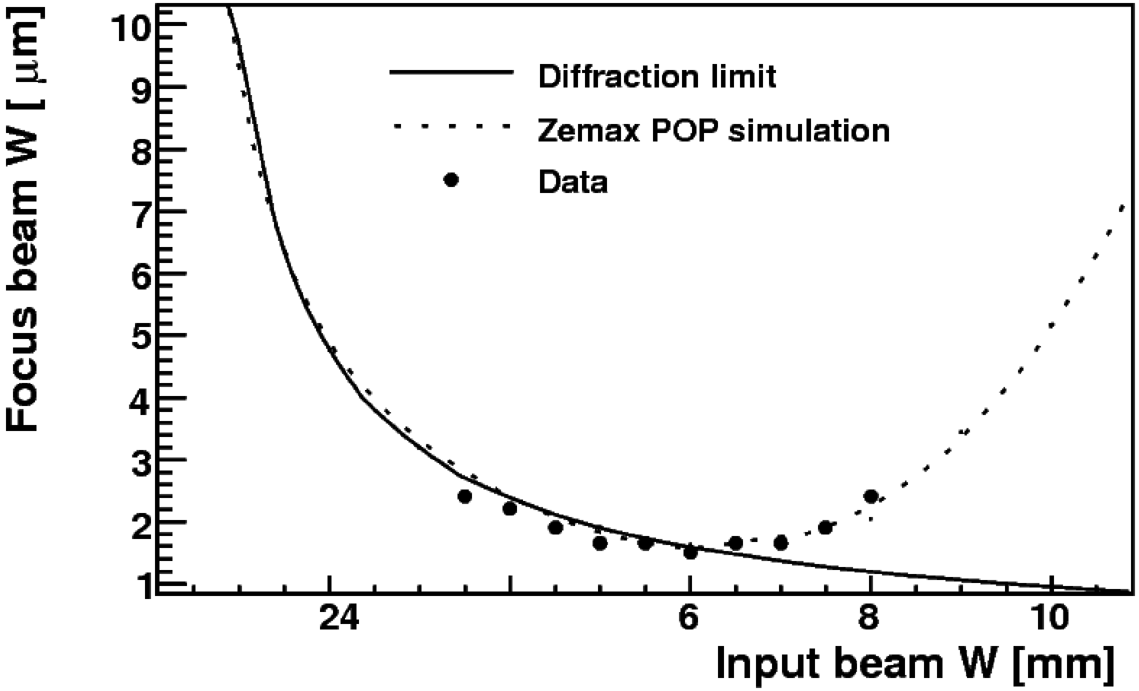
- However, this equation is modified in the presence of spherical abberations by adding a “lens M^2” term to M^2 in quadrature

$$M^2 = \left[\left(M_{r0}^2 \right)^2 + \left(M_{rq}^2 \right)^2 \right]^{1/2}$$

- Simulations and measurements were carried out and to determine M^2_{rq} as a function of input beam size...

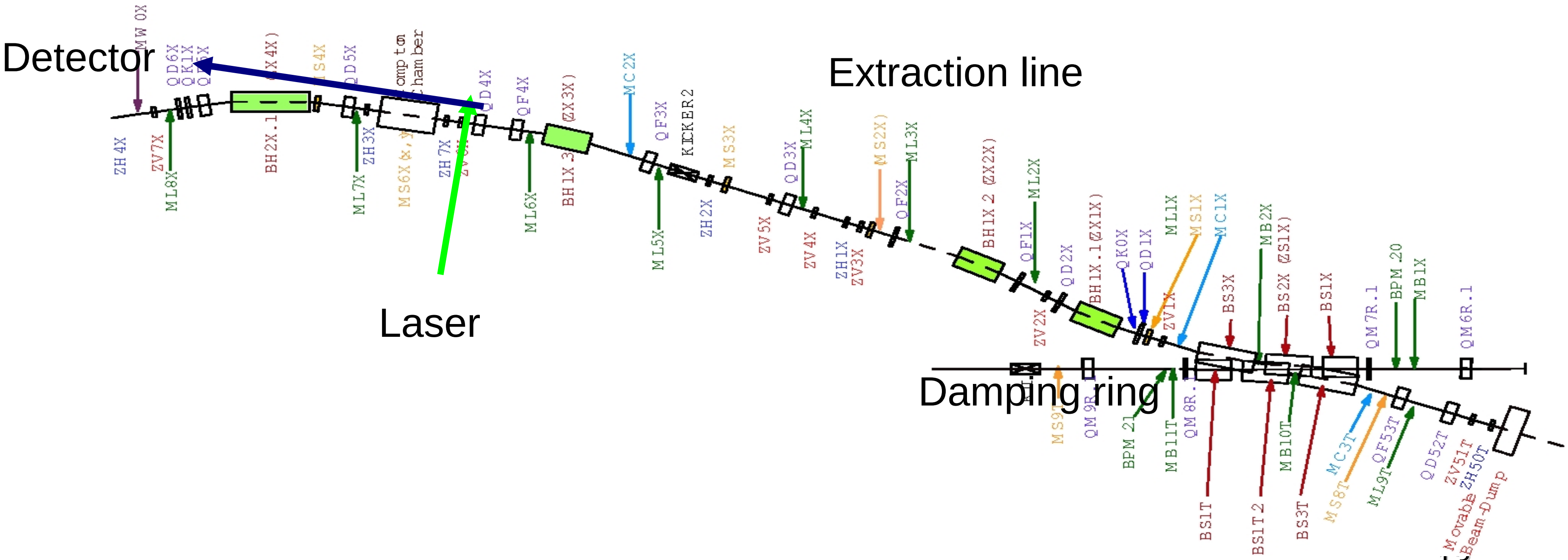
Input beam size vs focus size

- The results show that the optimum input beam size is ~6mm. With a M^2=2 laser gives a sigma ~1 mum focus size
- Our input beam size was ~8mm, which with a M2=2 laser would result in sigma~2.2 mum focus size



ATF Electron Beam Optics

- Modified so that it is possible to produce electron beam sizes from ~50 μm down to the ILC like 20 μm X 1 μm



Detector

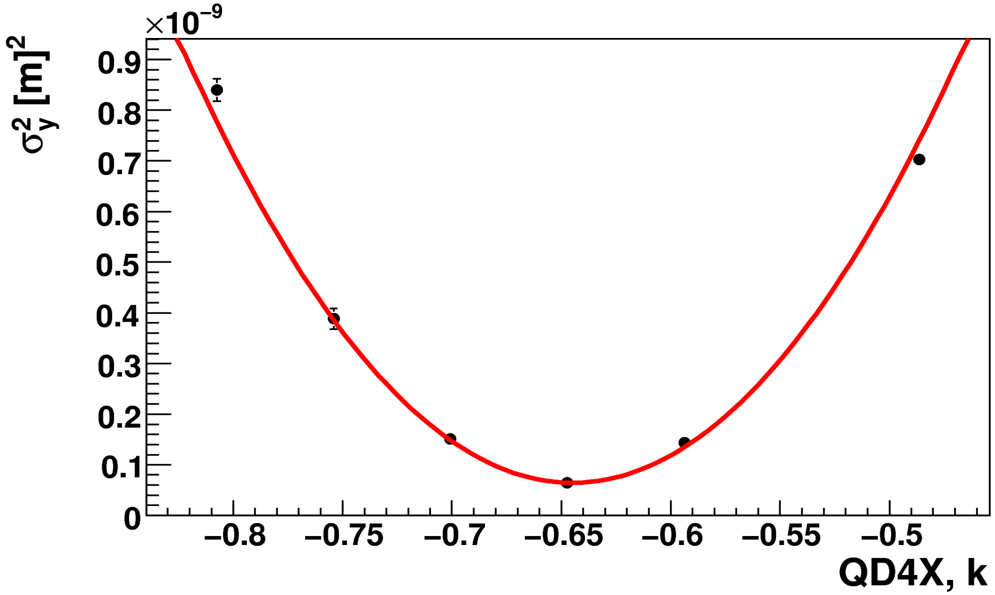
Extraction line

Laser

Damping ring

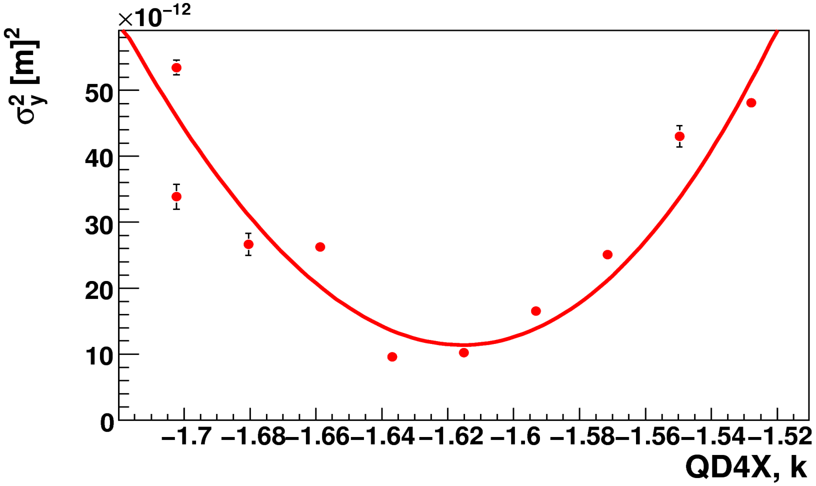
Emittance Measurement

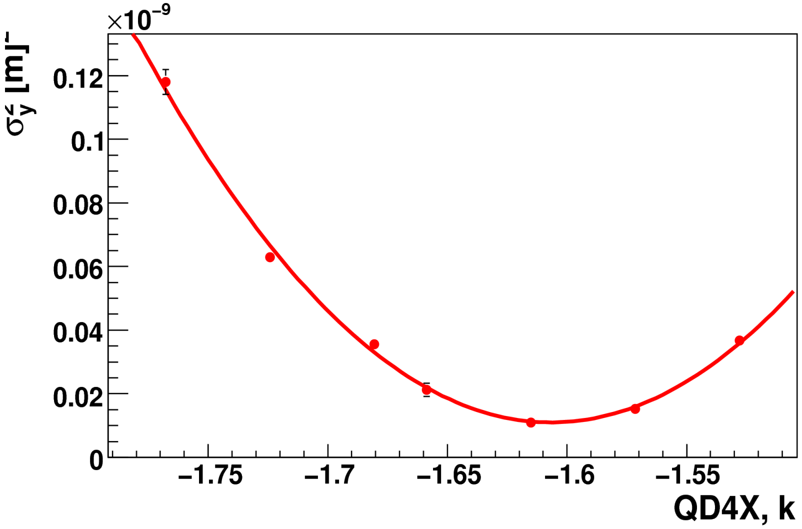
- To probe a 1 micron laser spot an equivalent size electron beam is required
- This depends on the emittance and the dispersion
- The emittance was measured by performing a quad scan using a wire scanner
- Result: emittance = 207± 2 pm, so e beam size at LWIP expected to be ~3 micron, without dispersion



LW Emittance Measurement

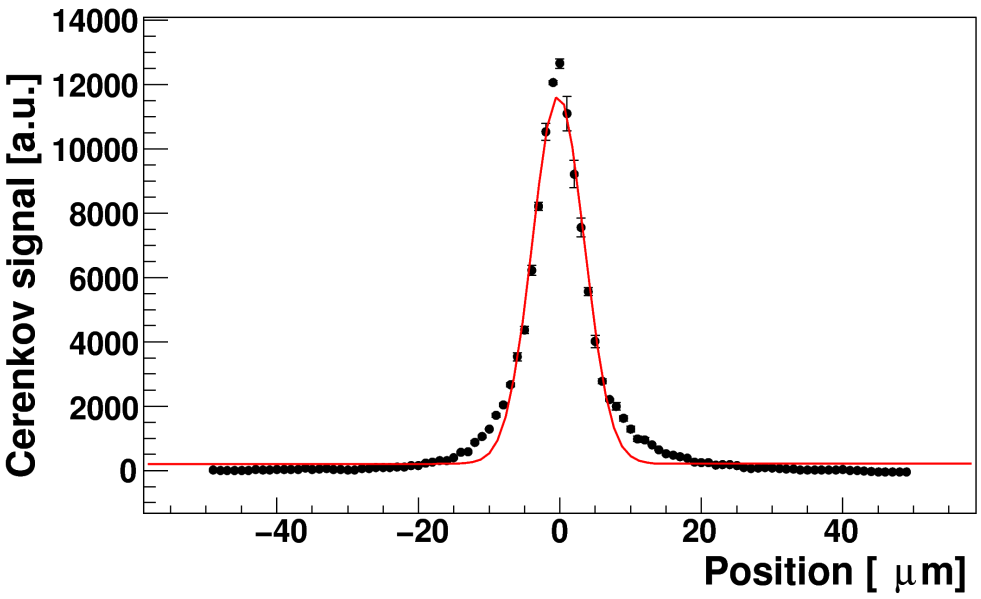
- The emittance was measured using the LW by performing a quad scan (below left).
- The dispersion was measured at the LWIP using the upstream/downstream BPMs
- The beam size due to the dispersion and laser beam size as calculated from the M^2, lens M^2 and input beam size measurements were subtracted in quadrature from each convoluted beam profile
- Result: vertical emittance = 232^{+92}_{-174} pm – error dominated by error in dispersion measurement
- Wire scanner result: 207 +/- 2 pm
- Below right: another laser-wire quad scan. The points follow the curve better, but on this occasion no dispersion measurement was performed.





Smallest Scan

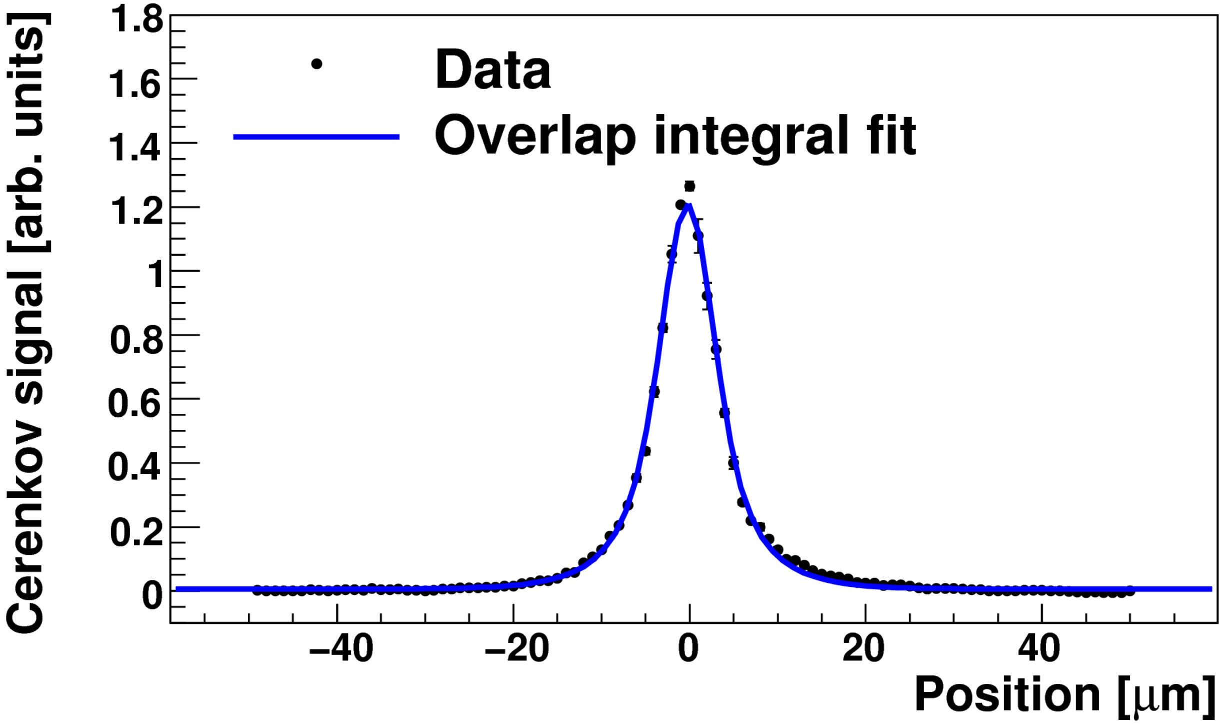
- Size of electron/laser beam overlap with Gaussian fit: sigma = 3.65 +/- 0.09 mum
- Subtracting laser beam in quadrature gives sigmae=2.9+/- 0.2 mum – this is consistent with the measured emittance and dispersion
- The tails could be due to Rayleigh range or spherical abberation effects



Full e gamma overlap fit

- The fit gives results for the vertical beam size of the right order of magnitude. The fit is good, implying that the tails in the distribution are due to Rayleigh range effects.
- However, the horizontal electron beam size was not directly measurable. Fit results (electron beam size):

$$\sigma_x = 58 \pm 20\,\mu m \quad \sigma_y = 1.8 \pm 0.2\,\mu m$$



Summary of ATF Extraction Line Laser Wire

- Measurements were made to account for the contributions to the size of the convolution between the laser and electron beam profiles, σ_c, as measured in a laser wire scan
- Factors contributing to laser beam focus size are laser M^2 and input beam size, which determines lens M^2
- Impact of astigmatism is small
- Using an input beam size of W_i=6mm will allow us to achieve a laser spot size of ~ 1 micron
- Data taking at ATF2 is planned to start early next year.
- Emittance tuning and dispersion correction at ATF2 will allow us to achieve an e beam spot size of ~ 1 micron. The emittance at ATF2 is expected to be smaller and more stable.
- More details can be found in my thesis, “A Micron-Scale Laser-Based Beam Profile Monitor for the International Linear Collider”, www.pp.rhul.ac.uk/~deacon/thesis/ldThesisCorrected_v5.pdf

Laser-Wire Signal Extraction at CLIC

- To use the laser-wire the Compton scattering rate must be measured. This requires separating the Compton scattered electrons and/or photons from the main beam.
- The CLIC beam delivery system was simulated using BDSIM from the emittance diagnostics section to the IP. The beam sizes at the laser-wire stations agree with the MAD simulation.
- A Monte Carlo method was used to simulate the laser-wire Compton scattering process and track the Compton scattered particles through the beam delivery system.

High-Energy Compton Scattering Monte Carlo

- Monte Carlo for Compton scattering used in BDSIM is based on an approximation.
- The full Compton scattering differential cross section in the electron rest frame is

$$\frac{d\sigma}{d\Omega}=\frac{r_0^2}{2}\left(\frac{1+x^2}{1+\gamma(1-x)^2}\right).\left(1+\frac{\gamma^2(1-x)^2}{(1+x^2)[1+\gamma(1-x)]}\right)$$

- Where x is the cosine of the scattering angle, r0 is the classical electron radius and

$$\gamma=\frac{E_\gamma}{m_e c^2}$$

- The Monte Carlo used in BDSIM assumes that the photon energy is much smaller than the electron mass so gamma is approximately zero (differential Thomson cross section):

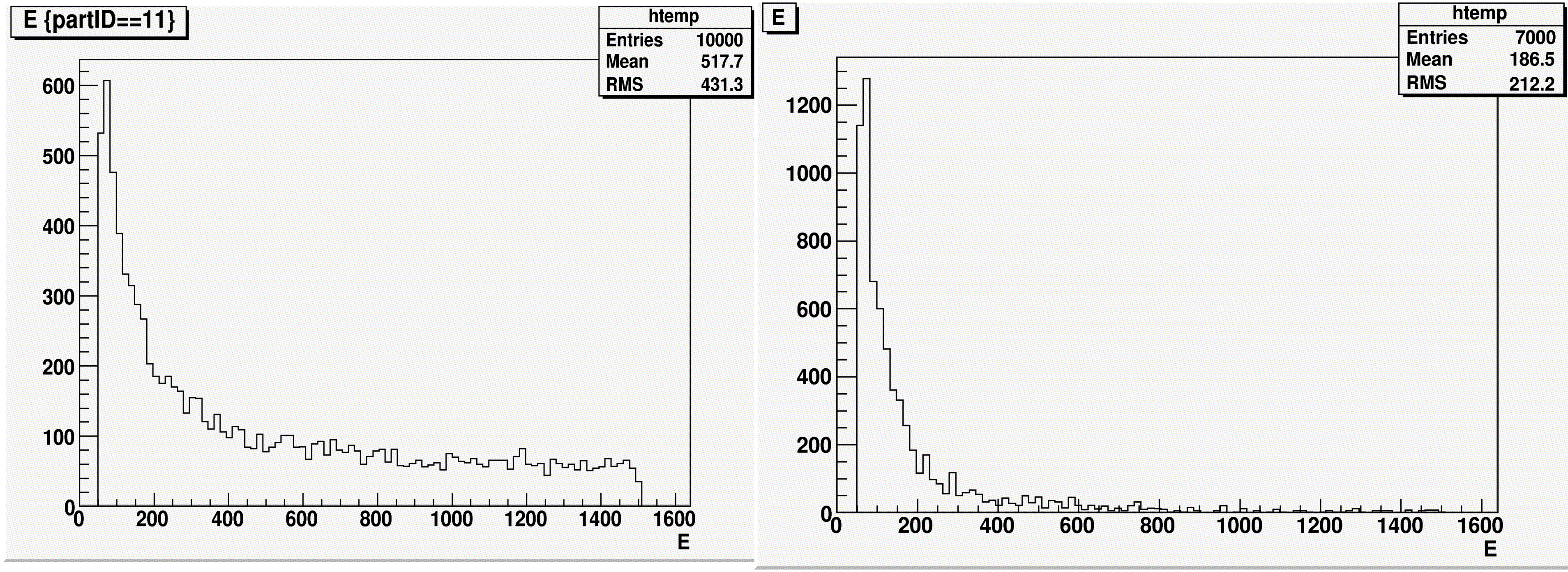
$$\frac{d\sigma}{d\Omega}=\frac{r_0^2}{2}(1+x^2)$$

High-Energy Compton Scattering Monte Carlo

- This approximation does not hold for 1.5 TeV electrons colliding with 532 nm photons.
- I modified the Monte Carlo to use the full scattering cross section.
- The approximate and exact Monte Carlos agree on the energy spectra of the Compton scattered particles for low energy collisions (tested with 1GeV electrons and 532 nm photons)
- At CLIC energies there are significant differences. The photons are at higher energies (and the electrons at lower energies) – see next slide.
- The exact Monte Carlo currently uses a basic rejection method instead of direct generation and takes more CPU time.

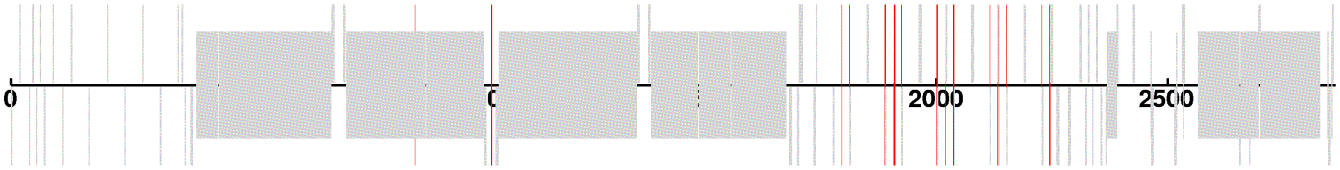
High-Energy Compton Scattering Monte Carlo

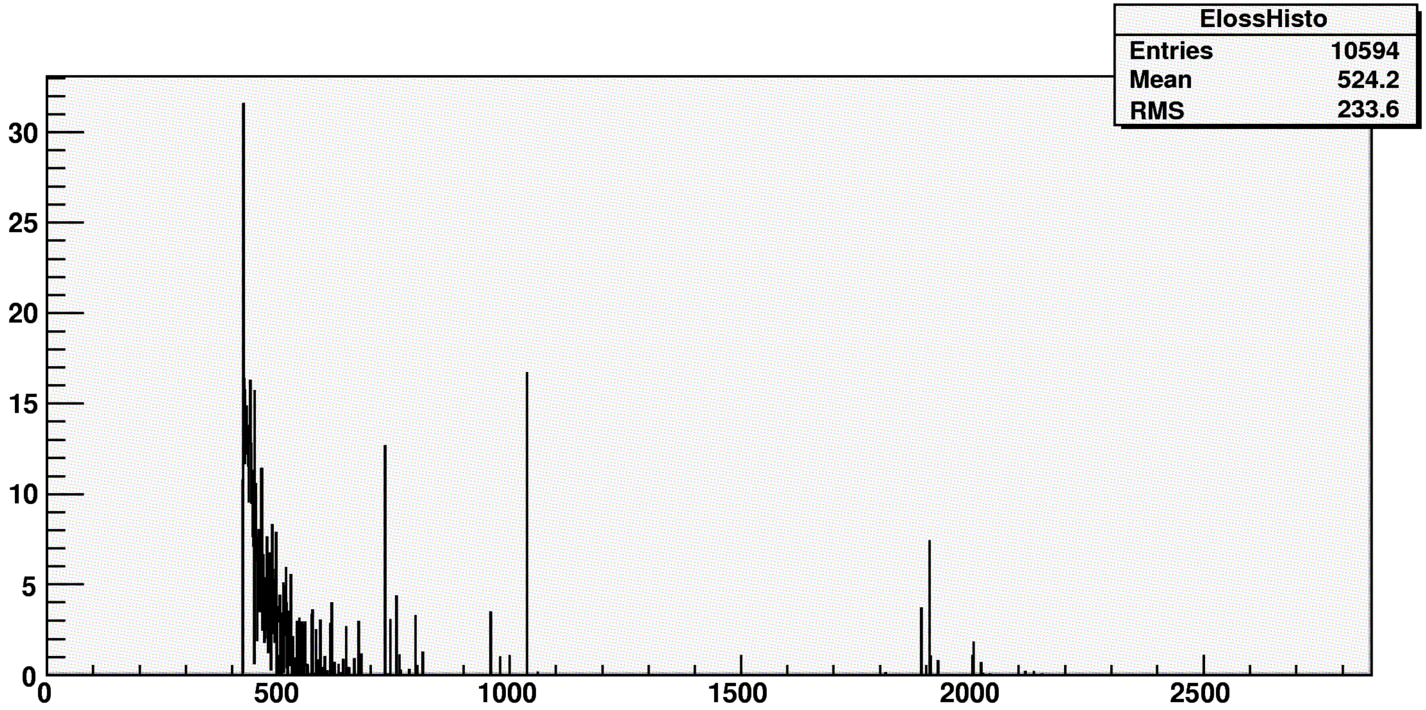
- Left: Compton scattered electron spectrum using approximate Monte Carlo for 1.5 TeV electrons colliding with 532 nm photons at 90 degrees. Right: spectrum generated by new Monte Carlo.



Laser-Wire Signal Extraction at CLIC

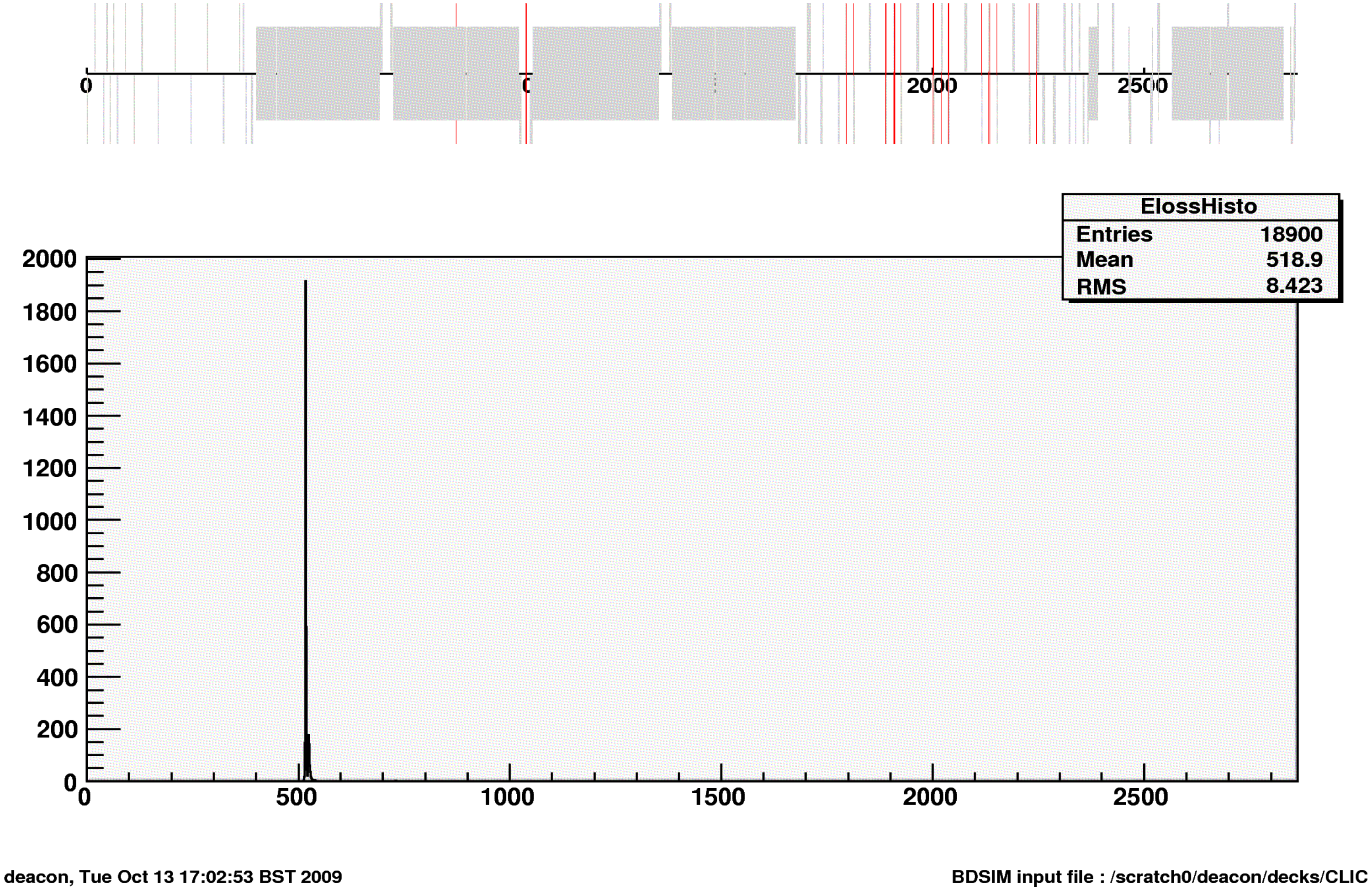
- Compton scattered electrons were tracked from the first vertical laser wire. Below is the corresponding energy loss map, GeV/m vs. distance





Laser-Wire Signal Extraction at CLIC

- Compton scattered photons were also tracked from the first vertical laser wire. Below is the corresponding energy loss map, GeV/m vs. distance



Laser-Wire Signal Extraction at CLIC – points to consider

- Photon energy loss occurs at a single location.
- However, there background may be a problem due to line of sight with linac and synchrotron radiation from dipoles.
- Synchrotron radiation peaks at low energy, Compton photons peak at high energy, therefore backgrounds in Compton photon detection could be removed by filtering out low energy particles.
- The fluctuations in the detected Compton electron signal effect the length of time needed to carry out an emittance measurement.
- Could reduce fluctuations in Compton electron signal by putting detectors at more locations in beam line.
- Future work – quantify these effects and how they affect emittance measurement.