Linear Colliders

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- **Lecture one**
  - **Introduction and Luminosity**
- **Lecture Two**
  - **Obtaining the Energy**
- **This is a very big subject.**
- **Need to choose how much to cover and where to start.**
- **First approximation:**

$$\lim_{\substack{knowledge \to 0 \\ \mathrm{int}\,elligence \to \infty}} \{Audience\}$$

Linear Colliders: Lecture one
Introduction and Luminosity

- **Outline for Lecture One**
  - **Introduction**
  - **Emittance and Size**
  - **Final Focus**
  - **Beam-Beam effects**
  - **Some Parameters:**

	TESLA	***JLC/NLC***	***CLIC***
Energy (TeV)	0.5	1.0	3
Luminosity (10^{34})	3.4	3.4	10.0
Rf Frequency (GHz)	1.3	11.424	30
Rep. Rate (Hz)	5	120	75
# Bunch / Pulse	2820	190	154
Bunch Spacing (ns)	337	1.4	0.666
Bunch Charge (10^{10})	2.0	0.75	0.4
σ_x / σ_y at IP (nm)	553 / 5	190 / 2.1	40 / 0.6
Site Length	33	30.6	30

Motivation for Linear Colliders

- **Physics with electron-positron collisions at the Energy Frontier.**
- **Circular electron/positron Colliders have run out of gas.**
- **We would like to embark on a next generation collider which can cover a decade in energy, say from 0.5 to 5 TeV.**
- **For a Circular collider the synchrotron radiation power for an electron is**

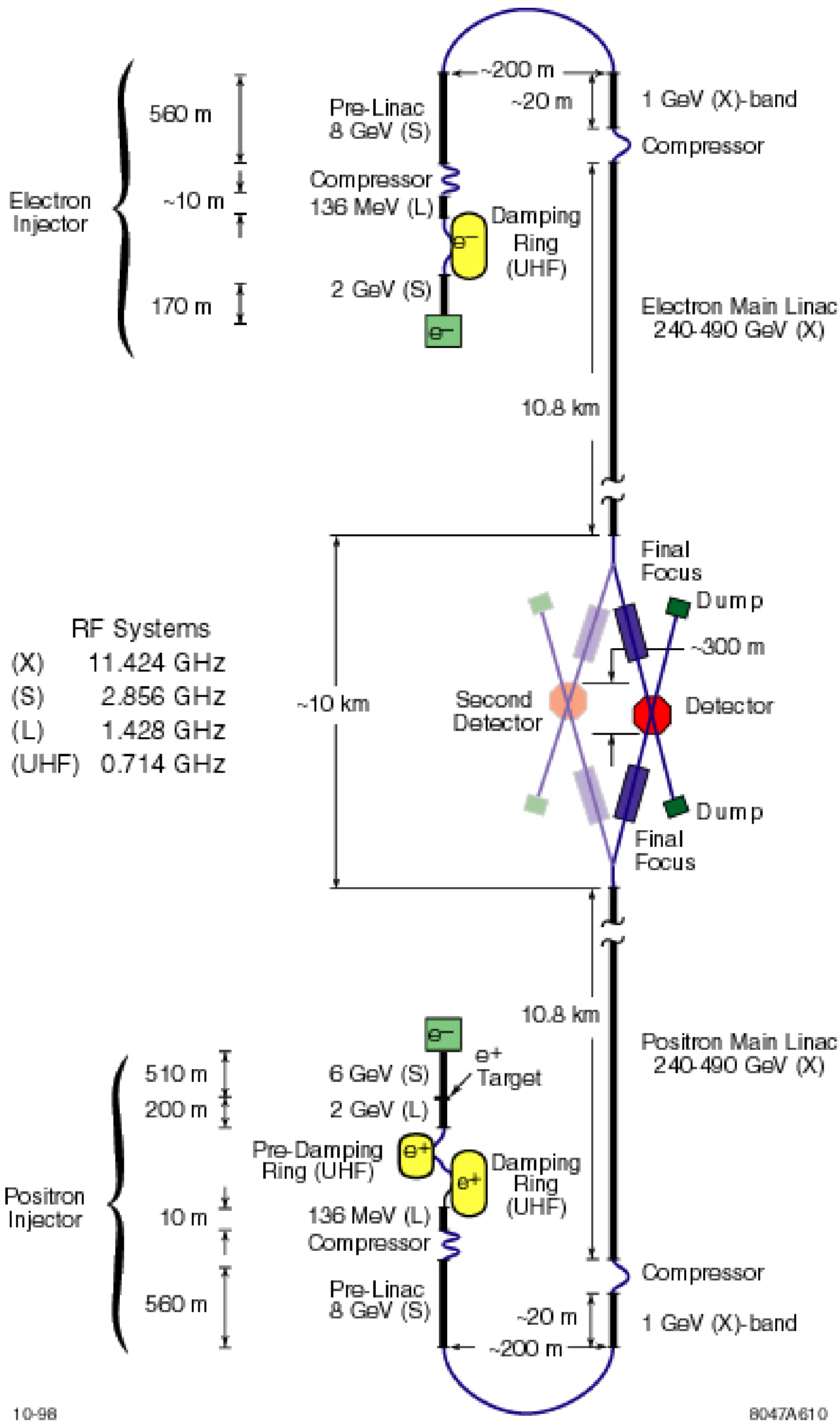
$$P_\gamma = \frac{2}{3} r_e m c^2 \frac{c\beta^4\gamma^4}{\rho^2}$$

- **Although ρ can be increased (magnetic field lowered) to compensate for the high γ, in practice LEP is the last energy frontier electron positron circular collider.**

The Basic Idea of a Linear Collider

- **Create electrons and positrons**
- **Accelerate them in a linear accelerator towards each other (no bending, no synchrotron radiation)**
- **Focus them each to a small spot at the collision point**
- **Transport the ‘disrupted bunch to dump’**
- **Start over with the next cycle.**
- **The repetition rate of the linear accelerator plays the role of the cycle time in a circular collider.**
- **The lower cycle rate is compensated by small spot size and many bunches each cycle.**

A Linear Collider in Detail



Linear Collider Cycle in Detail

- **A train of bunches of electrons are created and accelerated to about 2 GeV.**
- **These are injected into a damping ring which reduces the 'emittance' by synchrotron radiation cooling.**
- **The bunches are compressed in length and accelerated to an intermediate energy (~ 8 GeV).**
- **The bunches are compressed again to their final length.**
- **The bunches are accelerated in a linear accelerator with gradient Ez and length L.**
- **The bunches are delivered through a collimation system.**
- **They are demagnified in size by a telescopic final focus.**
- **Positrons have the same history except they were created and pre-cooled earlier.**
- **Each electron bunch collides with its partner positron bunch once and continues to a dump.**

Some Issues for Linear Colliders

- **Obtaining the Energy**
  - **Choice of Collision Energy**
  - **Accelerator Technology Choice**
  - **Acceleration Gradient vs. Length**
  - **Radio Frequency Energy Source**
  - **Accelerator Structures**
  - **Efficiency**
- **Obtaining the Luminosity**
  - **Damping Ring ‘emittance’**
  - **Emittance preservation**
  - **Collimation and Background**
  - **Final Focus and chromatic correction**
  - **Final spot size and ground motion**
  - **Beam-Beam disruption**
  - **‘Beamstrahlung’ and IP physics**
  - **Fundamental Limits (Oide Limit)**
  - **Other Issues for experiments**

Luminosity Basics

- **The Luminosity Formula**

$$L = \frac{N^+ N^- f_{rep} n_b}{4\pi\sigma_x\sigma_y} H_D$$

- **Where symbols have their usual meaning and H_D is the disruption enhancement factor**
- **Another useful way of writing this is:**

$$L = \frac{P_{beam}}{E_{beam}} \frac{H_D}{4\pi} \frac{1}{\sigma_y} \frac{N}{\sigma_x}$$

- **Where P_{beam} is the power in the beam.**
- **The only real control we have is to decrease σ_y or increase P_{beam}.**

Increasing Luminosity

- **The increase of the beam power and the increase of the effective repetition rate are effectively the same thing.**
- **The power in the beam is related to the wall plug power by the overall efficiency.**

$$P_{beam} = \eta_{tot} P_{wall}$$

- **How to get energy effectively into the beam will be discussed in the next lecture. The wall plug power is about 100-200 MW.**
- **The disruption H_D is limited…more later here.**
- **The vertical size σ_y is a strong handle for luminosity increase. This leads to very flat beam designs.**
- **The electromagnetic field seen by the opposing bunch is largely controlled by N/σ_x.**
- **This high field leads to beam-beam effects discussed later.**

The Vertical Spot Size

- **The vertical spot size is determined by the emittance at the IP and the optics which focus the beam.**

$$\sigma_y^* = \sqrt{\varepsilon_y \beta^*}$$

- **The betafunction is given by the optics of the final focus…more on that later.**

- **The emittance is generated in the damping rings but must be preserved throughout the acceleration.**
- **Let’s discuss emittance generation in more detail.**
- **Digression on emittance.ppt**
- **The only test facility for low emittance in the world is the ATF damping ring at KEK.**
- **ATF DR.ppt**
- **The measured vertical emittance is about 50% more than future linear collider needs.**
- **Future work includes multibunch effects.**

Emittance Preservation

- **This is a complicated subject, but here is the basic idea.**
- **First I told you that the 'normalized emittance' was an adiabatic invariant under acceleration.**
- **So that means that ideally:** $\varepsilon = \dfrac{\varepsilon_N}{\gamma}$
- **The emittance adiabatically damps with increasing energy.**
- **However the variation of the linear focusing force over the six dimensional bunch distribution can lead to correlations.**
- **These correlations can filament resulting in an emittance dilution when projected onto any two dimensional (x,p) subspace.**
- **Examples are:**
  - **chromatic and dispersive effects**
  - **Wakefield deflections**
  - **Jitter pulse to pulse**

Transverse Beam Breakup

- **Consider a two particle model of an extended bunch.**
- **The first one oscillates essentially harmonically.**

$$\frac{d^2 x_1}{ds^2} + \frac{x_1}{\beta^2} = 0$$

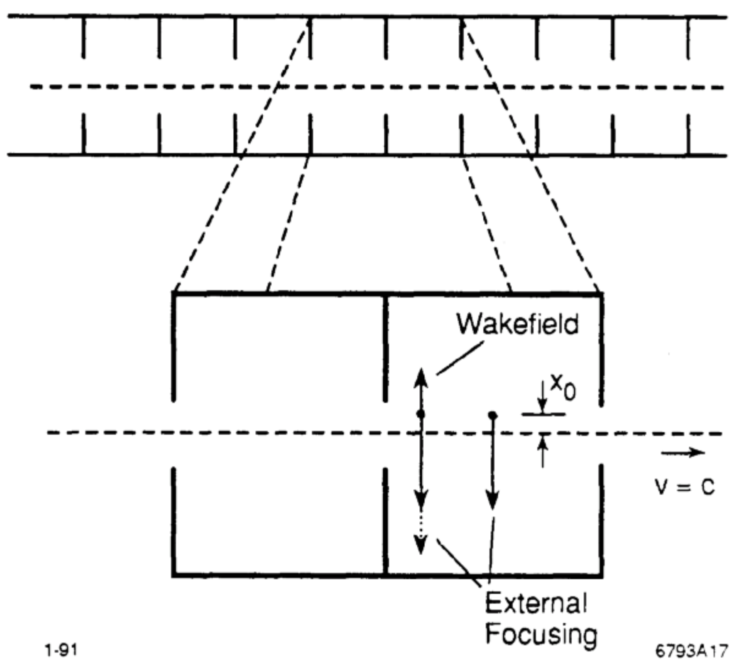
- **The second one feels a transverse deflection due to induced dipole EM fields.**

$$\frac{d^2 x_2}{ds^2} + \frac{x_2}{\beta^2} = \frac{Ne^2 W_T(\sigma_z)}{E} x_1$$

- **Thus the transverse position of the second 'particle' grows linearly.**

‘BNS’ Damping

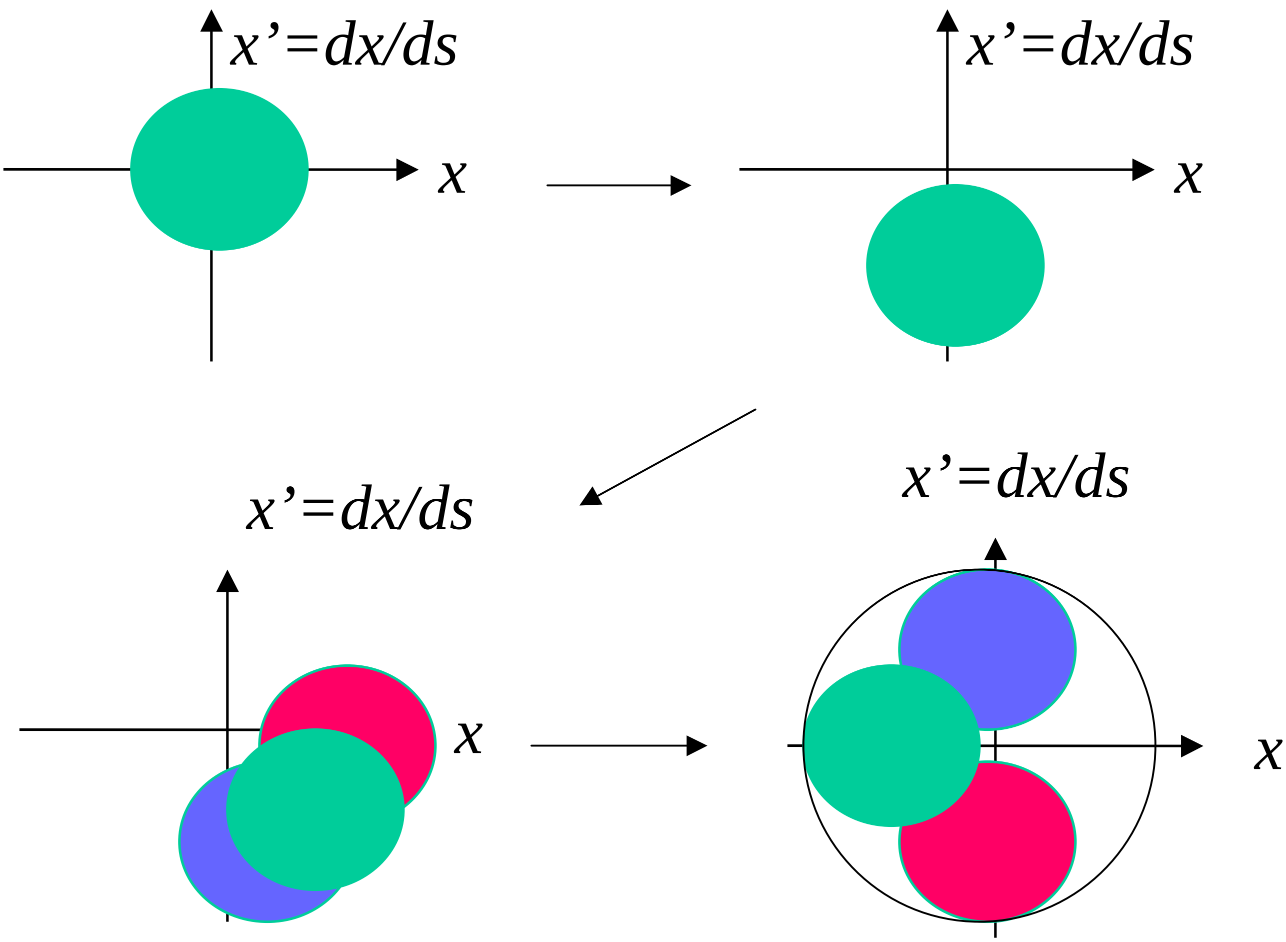
- **This problem looks bad but can be solved by BNS damping (Balakin, Novochatski, Smirnov)**
- **If both particles start in phase, this wake gives and extra deflection away from the axis.**
- **But if we arrange for the trailing particle to have lower energy, it will get an extra deflection from the focusing magnets.**



- **There is no resonant growth and the two particles move in phase when offset together.**

Chromatic/Dispersive Dilution

- **Consider three different energy slices each with equal emittance.**
- **Kick the beam in the magnetic lattice.**
- **Allow it to propagate down the linac.**



Alignment

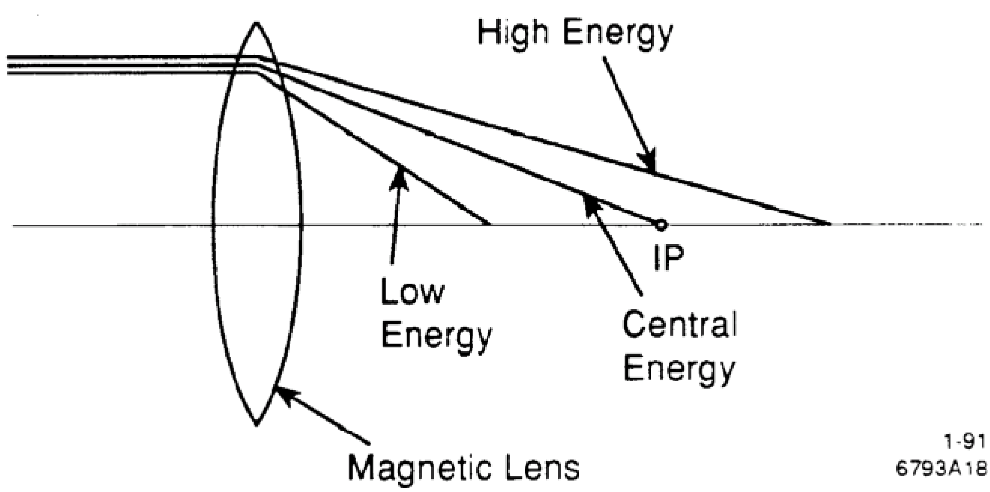
- To avoid emittance dilution we need to send the beam rather precisely down the linac.
- This is accomplished with ‘beam-based’ alignment.
- The key issues are:
  - Precise position monitors in the quadrupoles and structures.
  - Methods for measuring the beam size precisely to see how well you are doing.
- During the past 10 years there have been
  - Extensive simulations worldwide.
  - Experience with SLC
  - Experience with the Final Focus Test Beam
- All indications are that we have the technology and the strategy to use it correctly.
- This should get the beam to the end of the linac with only modest emittance dilution.

Collimation and Background

- **This is a boring subject….well maybe not for a HEP experimental physicist.**
- **The beam distribution in the damping ring is a six dimensional gaussian in phase space.**
- **The particles in the tail of the distribution feel variation of the linear focusing fields.**
- **Thus, they can get to even larger amplitude.**
- **So….collimate early and often.**
- **The often part of this is expensive.**
- **Collimators, especially at the end of the linac can be easily destroyed by a missteered beam.**
- **Large aperture magnets in the final focus help….just let the tails go through.**
- **Enough on collimation**
- **We return to the issue of backgrounds induced by fundamental processes later.**

Final Focus

- **The purpose of the final focus is to demagnify the beam.**
- **This is done with an arrangement of magnetic focusing which acts like an optical telescope.**
- **The primary problem is that the final magnet focuses different energy particles to different positions.**

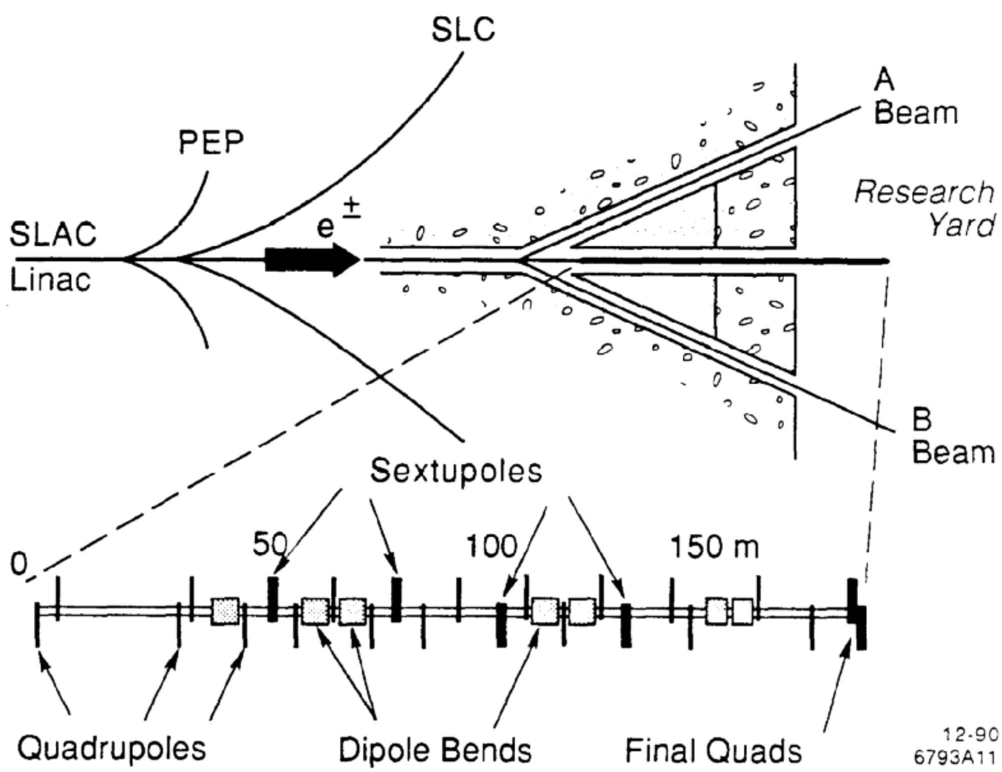


- **This causes the spot to be enlarged at the interaction point.**

Chromatic Correction

- **We have to provide a correlation of angles with energy at the final lens to exactly cancel the effect. Need to use nonlinear magnets, sextupoles, together with dispersion (position, momentum correlation).**

- **This has been tested at the SLC and Final Focus Test Beam below.**

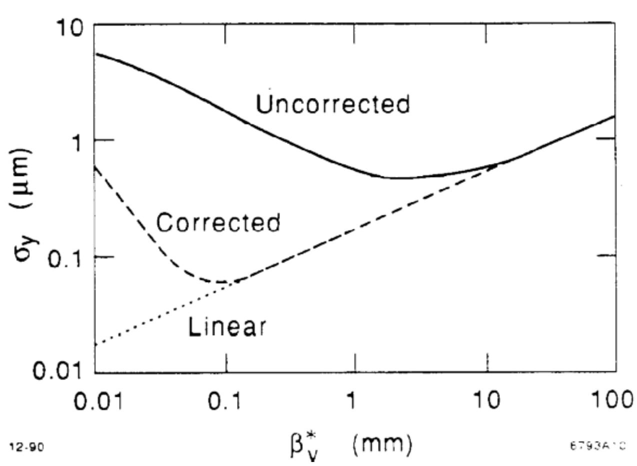


Final Spot Size

- **In a field free region a focused particle beam converges to a waist and then diverges.**

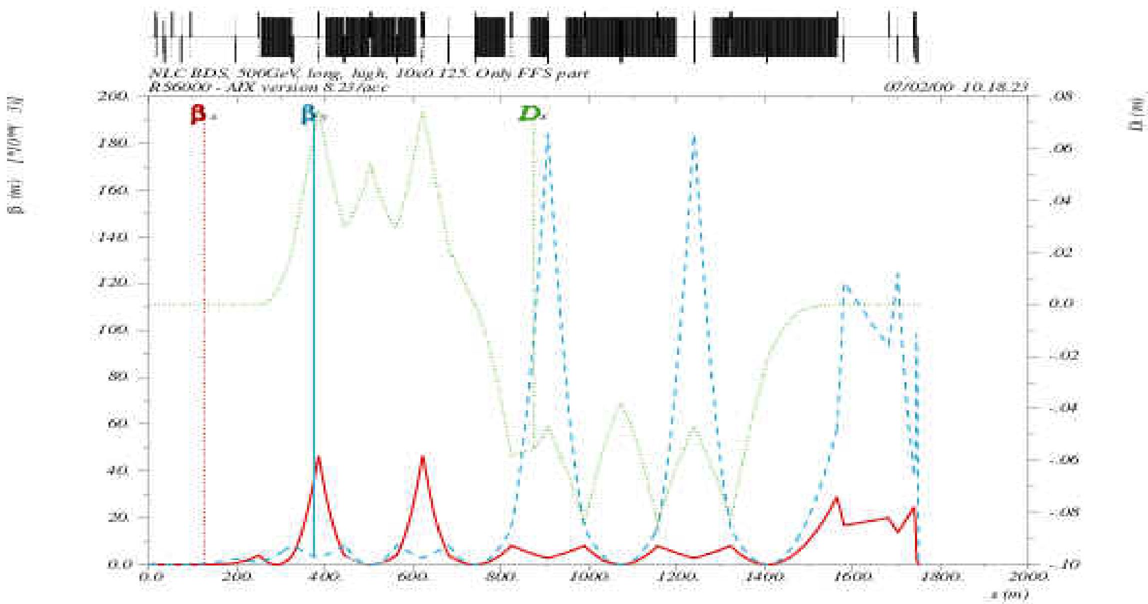
$$\sigma^2(s) = \varepsilon\beta^* + \varepsilon\frac{(s-s_0)^2}{\beta^*} = \varepsilon\beta(s)$$

- **The spot size is given by the usual formula and the Courant Snyder beta function plays the role of the depth of focus.**
- **Both the spot size and divergence are governed by the beta function with the product yielding the emittance.**
- **With chromatic correction (FFTB):**

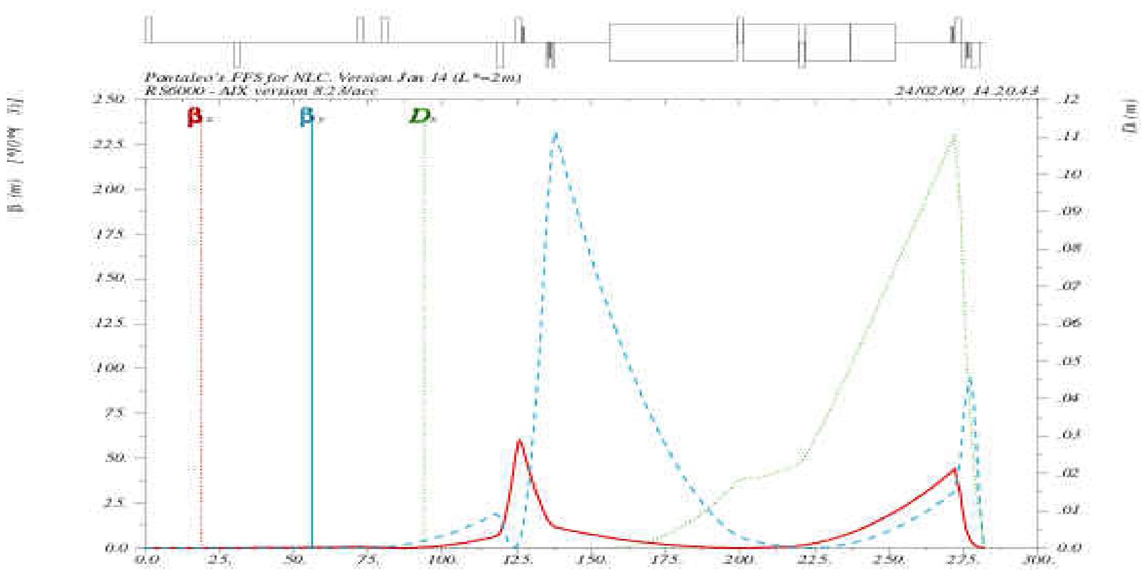


Optics for Final Focus Systems

- **Old NLC Design**

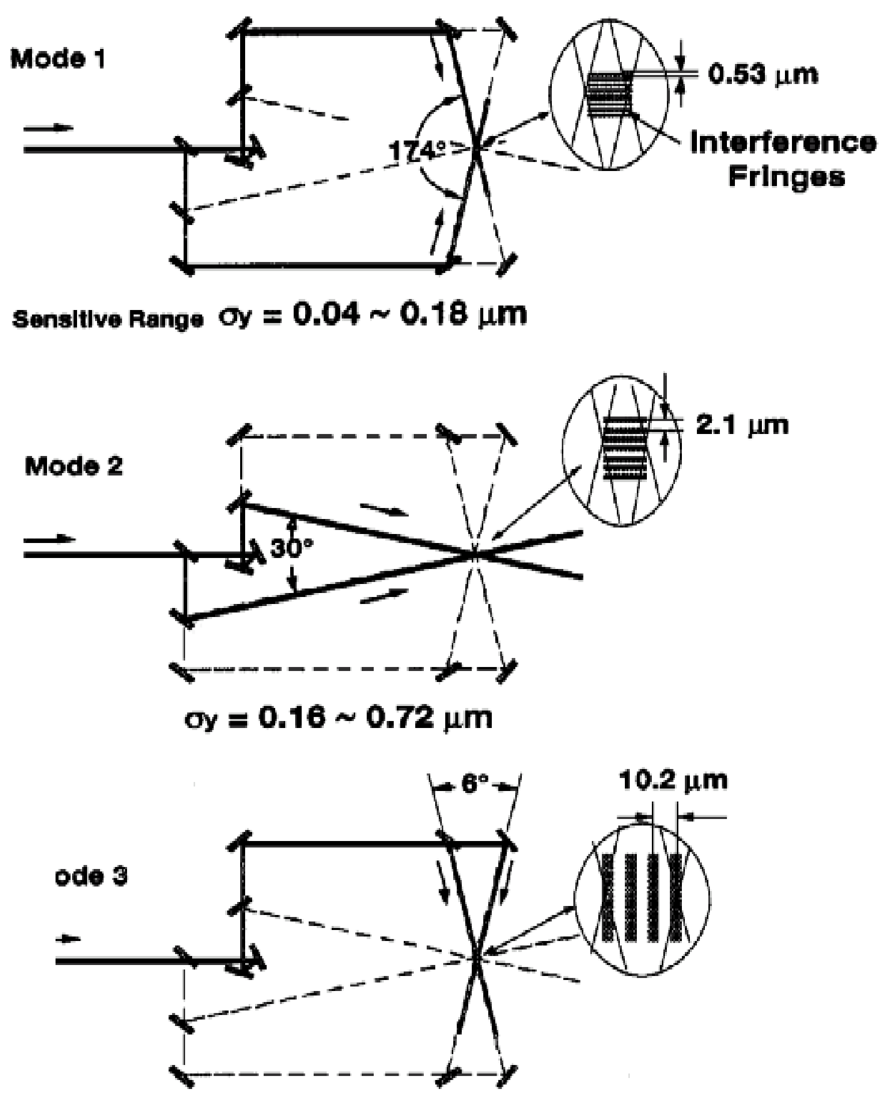


- **New NLC Design**



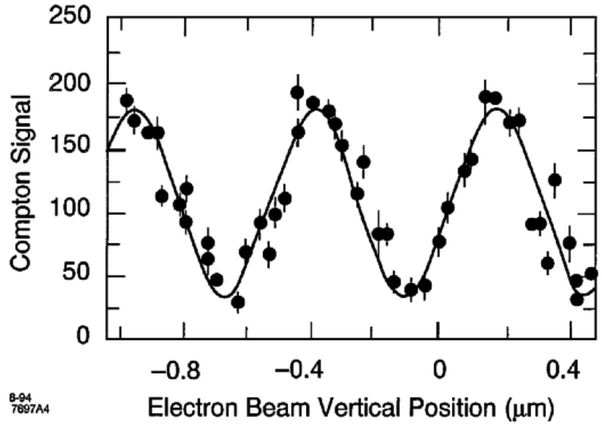
Measuring Small Spot Size

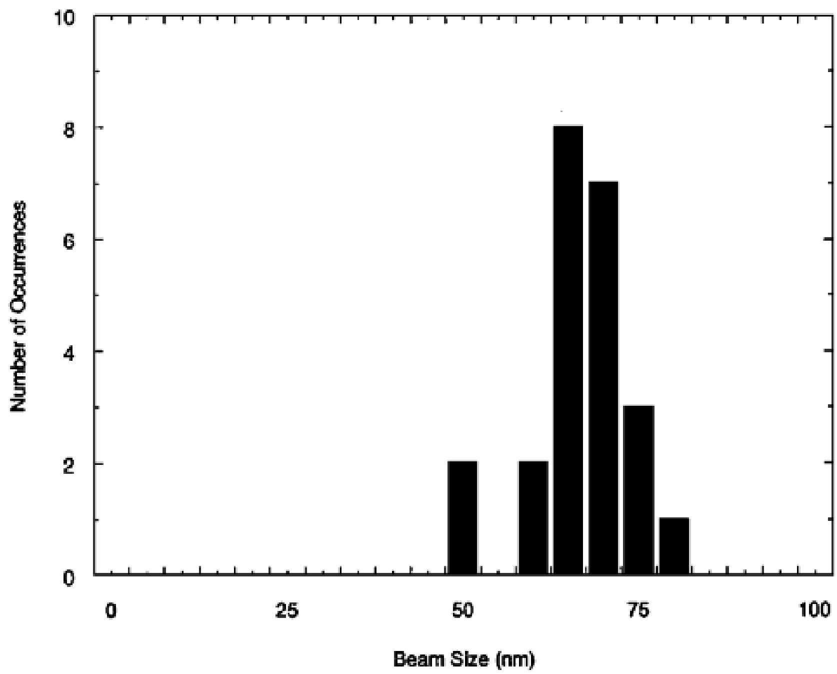
- **The final spot in the FFTB was measured with interfering laser beams (Shintake)**



FFTB Measurements

- **The beam was scanned across the fringes. No modulation yields large size, deep modulation yields small size. (Tenenbaum, Shintake,..)**





Digression on Ground Motion

- **In order for the beams to collide they must not move more than about one sigma at the IP from pulse to pulse.**
- **Offsets in the linac are demagnified with the beam size.**
- **If the correlation length is long enough, there is no relative motion of the colliding beams.**
- **Offsets of the final magnet are mapped directly to the final focus.**
- **Zero mode movement of pair of final magnets is OK, but pi mode is not.**
- **Techniques for solving this problem will be discussed later.**
- **Ground motion digression.ppt**

Beam-Beam Disruption

- **For particles in the same beam the electric and magnetic forces cancel, so the net space charge force drops like $1/\gamma^2$.**
- **For a test particle offset by x_0 in the opposing beam, the forces add and the particle is deflected.**

$$\Delta x' = -\frac{2Nr_e}{\gamma}\frac{x_0}{\sigma_x(\sigma_x+\sigma_y)}$$

- **It is useful to define the disruption parameter, $D=\sigma_z$/(focal length).**

$$D = \frac{2Nr_e}{\gamma}\frac{\sigma_z}{\sigma_x(\sigma_x+\sigma_y)}$$

- **If D is greater than one, the luminosity is enhanced because the beams pinch each other during collision.**
- **Flat beams should have $H_D \sim 2$**

Beamstrahlung and IP Physics

- **The bending field on a test particle in the opposing beam is of order kilo-Tesla.**
- **Therefore the synchrotron radiation called Beamstrahlung plays an important role.**
- **The radiation is characterized by the critical energy ω_c. A useful Lorentz invariant parameter Υ (upsilon) is given by**

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E} \cong \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha\sigma_z\left(\sigma_x + \sigma_y\right)}$$

- **For typical parameters upsilon is of order one so the radiation reaction must be taken care of.**
- **The energy of the particle effectively cuts off the synchrotron radiation spectrum.**

Energy Loss and Number of Photons

- **The radiation can be calculated following Sokolov and Ternov.**
- **The Beamstrahlung energy loss is given approximately by**

$$\delta_B \cong \frac{5}{4}\frac{\alpha\sigma_z \Upsilon^2}{\lambda_c \gamma}\frac{1}{\left(1+(1.5\Upsilon)^{2/3}\right)^2}$$

- **The number of photons emitted per electron is**

$$n_\gamma \cong \frac{2r_e\alpha N}{\sigma_x+\sigma_y}\frac{1}{\left(1+\Upsilon^{2/3}\right)^{1/2}}$$

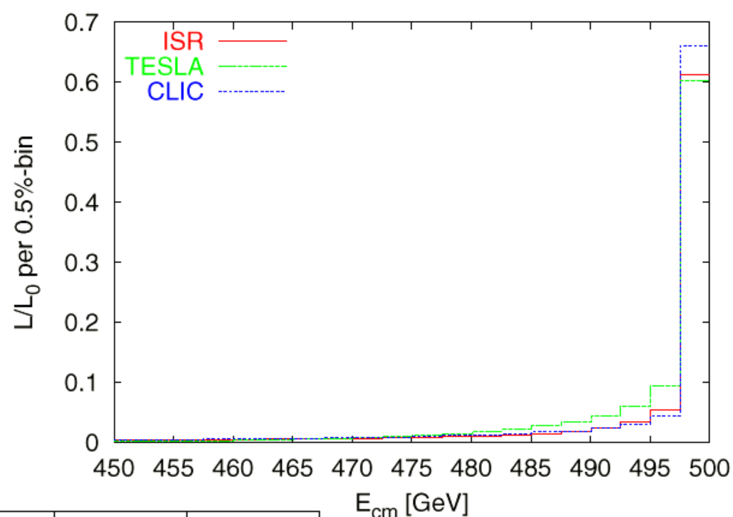
- **Both parameters are important because of the non gaussian nature of the process.**

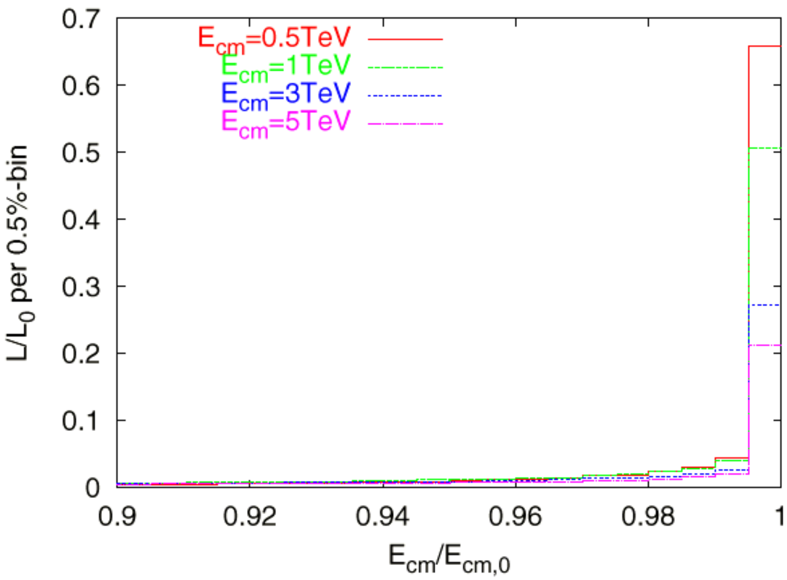
Luminosity Spectrum

- **The luminosity at full energy is given by**

$$L_{100\%} \cong L_0 \frac{\left(1-e^{-n_\gamma}\right)^2}{{n_\gamma}^2}$$

- **Simulations of the differential luminosity (Schulte, 99)**





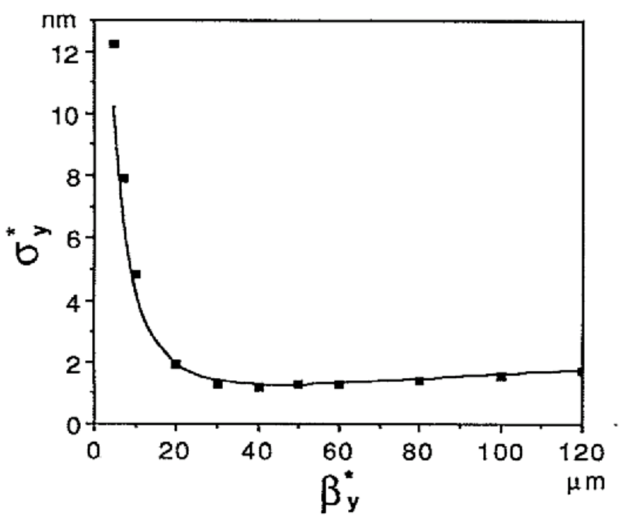
Fundamental Limits to the IP spot size (Oide, 1988)

- **From the beam size formula it appears that the size can be reduced arbitrarily by simply reducing** β.
- **Due to the depth of focus problem we must restrict**

$$\beta \geq \sigma_z$$

- **However, the particles radiate photons as they are focused in the final lens. The lower energy results in differing focal lengths. Oide finds**

$$\sigma_y^2 = \beta_y^* \varepsilon_y + \frac{110}{3\sqrt{6\pi}} r_e \lambda\!\!\!^{-}_e \gamma^5 F(quad) \left[\frac{\varepsilon_y}{\beta_y^*} \right]^{5/2}$$



Back to Backgrounds (D. Schulte,99)

- **When an electron and positron bunch collide at high energy a lot happens (besides the desired collision for HEP).**
- **Very strong fields pinch the particle beam.**
- **High energy photons are emitted.**
- **These photons can convert to electron-positron pairs.**
- **The pairs feel the strong fields and are deflected.**
- **Incoherent pairs are also produced via**
  - **ee ->ee(e+e-), eγ ->e(e+e-), γγ ->(e+e-),**

name		TESLA		NLC/JLC		CLIC	
E_{cm}	[TeV]	0.5	0.8	0.5	1.0	0.5	3.0
N_{pairs}	10^3	160	242	39.5	92	21	455
E_{pairs}	10^3 GeV	310	1070	124	965	113	38500

- **The particles are of both signs, have a large spectrum of energy and are deflected by the strong fields.**

Detector and Background issues

- **The particles are curled up in the detector solenoid, but even so masking must be used.**

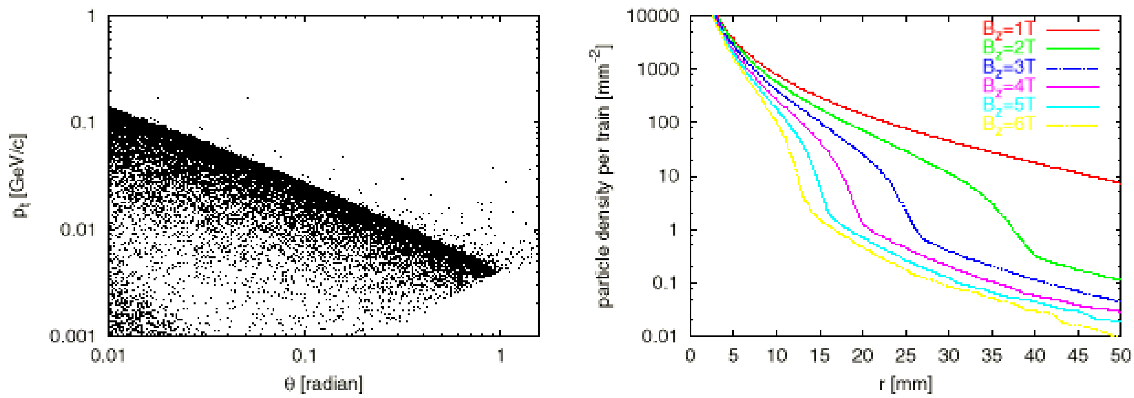


Figure 7: Particles from incoherent pair creation after the collision (CLIC at E_{cm} = 3 TeV). Each dot presents one particle. On the right hand side the number of particles is shown that hit the inner layer of the vertex detector as a function of the radius. Different magnetic fields are assumed for the detector solenoid. The detector half-length is always $z = 5r$, given a coverage of $|\cos\theta| \leq 0.98$.

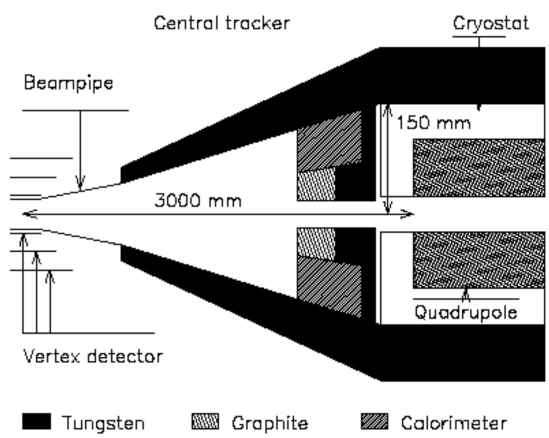


Figure 9: The masking system as foreseen for TESLA, the one for CLIC is expected to have similar properties.

Digression on Detector Issues

- **There is a lot of work that has been done and a lot more to do on the integration of the detector and the linear collider.**
- **There are the background issues discussed.**
- **There is the stability of the final focus quadrupoles.**
- **The list goes on.**
- **Here are a few samples taken from Markiewicz.**
- **IR Issues Digression.ppt**

Luminosity Summary

- **First we need high quality (low emittance) bunches to start with.**
  - **The KEK ATF is a prototype damping ring very similar to those proposed for NLC/JLC/CLIC.**
  - **The TESLA damping ring is a novel design (dog bone) which is much longer (17km/ring).**
- **Next we need to preserve the emittance.**
  - **This requires beam based alignment techniques using experience from SLC.**
  - **We also need to control transverse deflecting fields from accelerators (more on that next time).**
- **We deliver collimated beams to the IP.**
  - **Focus them to a small spot.**
  - **Control the jitter due to ground motion.**
  - **FEEDBACK (Important)**
- **Collide with High Luminosity.**
- **Next lecture….How we get to High Energy.**