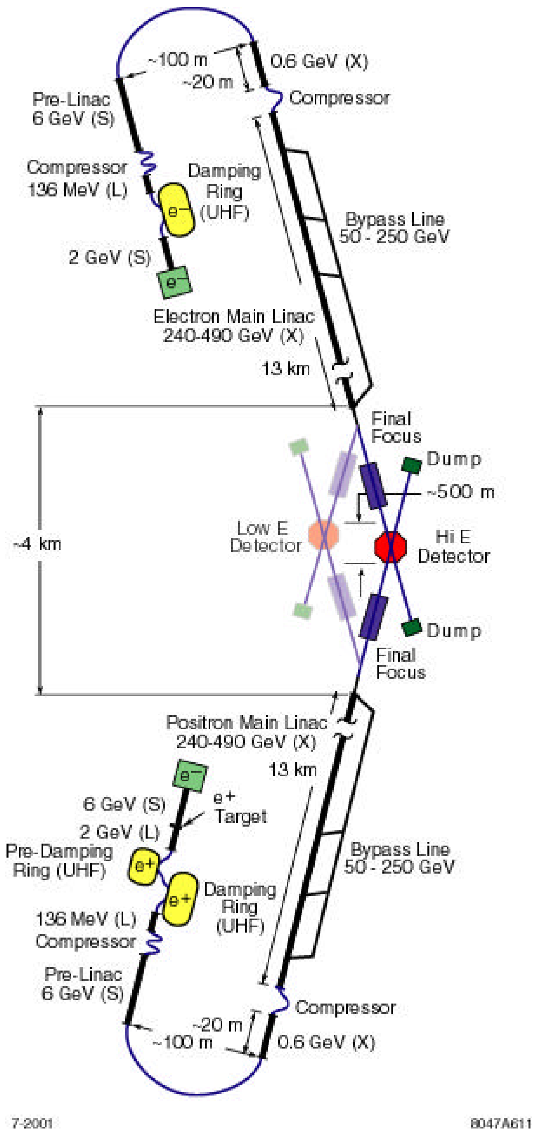
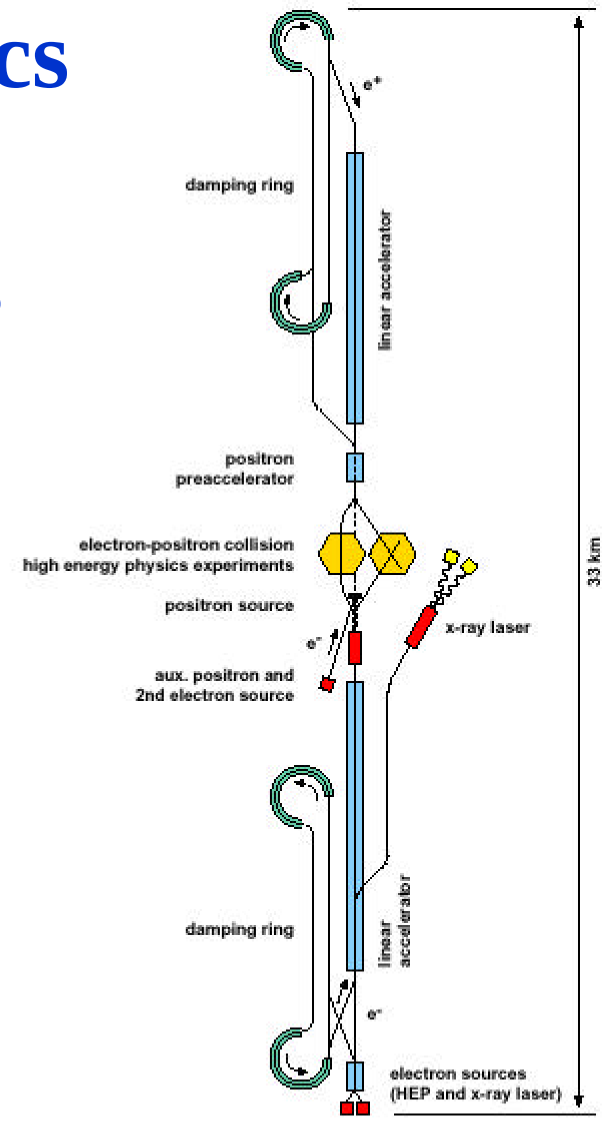


Accelerator Physics Issues in Linear Colliders

FNAL
March 27th, 2002

Tor Raubenheimer
SLAC



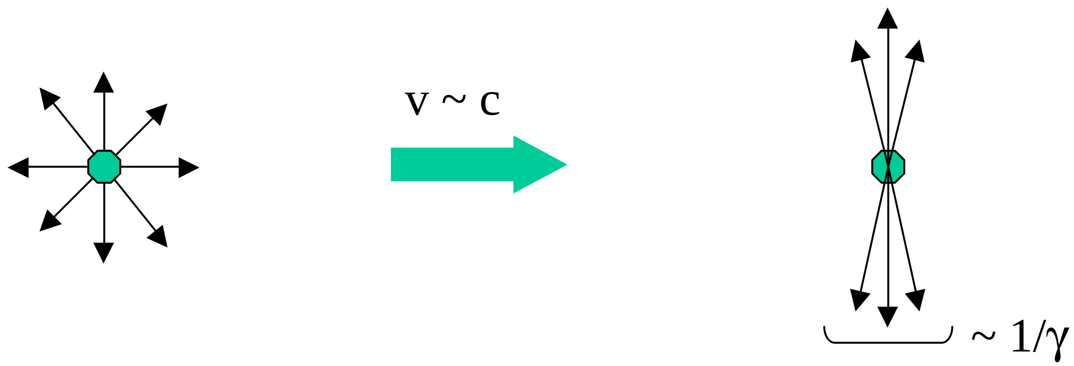
Outline

- IP Issues
  - Parameter choices for LCs
- RF systems / Beam energy
  - Modulators, klystrons, cavities and test facilities
- Luminosity issues
  - Damping rings – emittance generation
  - Main linac dynamics and alignment – emittance preservation
  - Beam delivery systems – final spot size
  - Vibration and stability

- Either TESLA or NLC could be built
  - different risks and different connections to the future

IP Issues

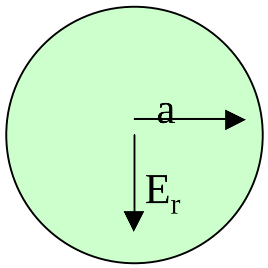
- Beam-beam force limits the parameter choices
  - Storage rings are limited by the beam-beam tune shift ~0.05
  - Tune shift can be ~1 in LC, however there are other important limitations from the beam-beam force
  - Typical field levels are 1000 Tesla or 30 V/Å



- For ultra-relativistic beam with $\sigma_z >> \sigma_r/\gamma$, the field is cylindrically symmetric – use 2-D Gauss' Law

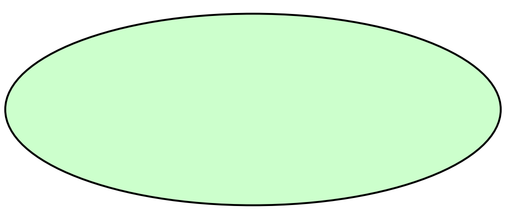
Beam Fields

- Uniform beam radius a with $\rho = \lambda / \pi a^2$



$$E_r = \frac{\lambda}{2\pi\varepsilon_0} \frac{r}{a^2}$$

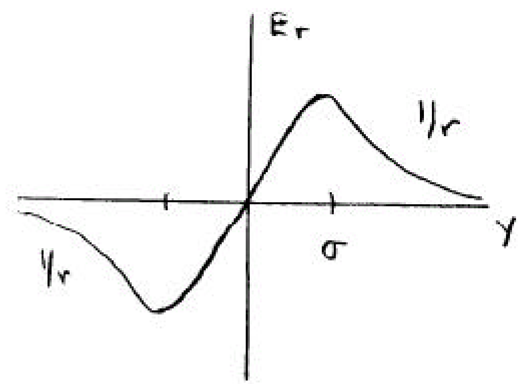
- Elliptic Gaussian beam:



$$y << \sigma_y$$

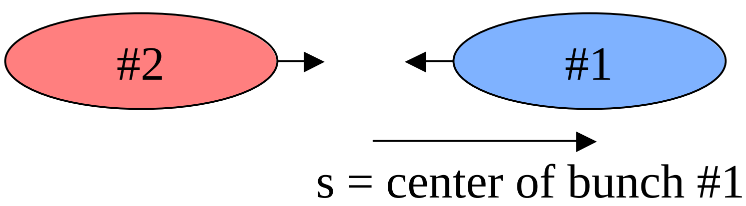
$$E_y = \frac{\lambda}{2\pi\varepsilon_0} \frac{y}{\sigma_y(\sigma_x + \sigma_y)}$$

$$\hat{E}_y \approx E_y(\sigma_y) \propto 1/(\sigma_x + \sigma_y)$$



Disruption

$$F_y = eE_y + v \times B_x = \begin{cases} 2E_y & \text{for colliding beams} \\ E_y / g^2 & \text{for self fields} \end{cases}$$



$$\frac{d^2 y}{ds^2} = \frac{4 l r_0}{g} \frac{y}{s_y (s_x + s_y)}$$

$$D_y \equiv \frac{s_z}{\text{impulse focal length}}; \quad \text{impulse} = \int dz$$

$$D_y = \frac{2Nr_0}{g} \frac{s_z}{s_y (s_x + s_y)}; \quad n_{osc} \sim 1.3 \sqrt{D_y} / 2p$$

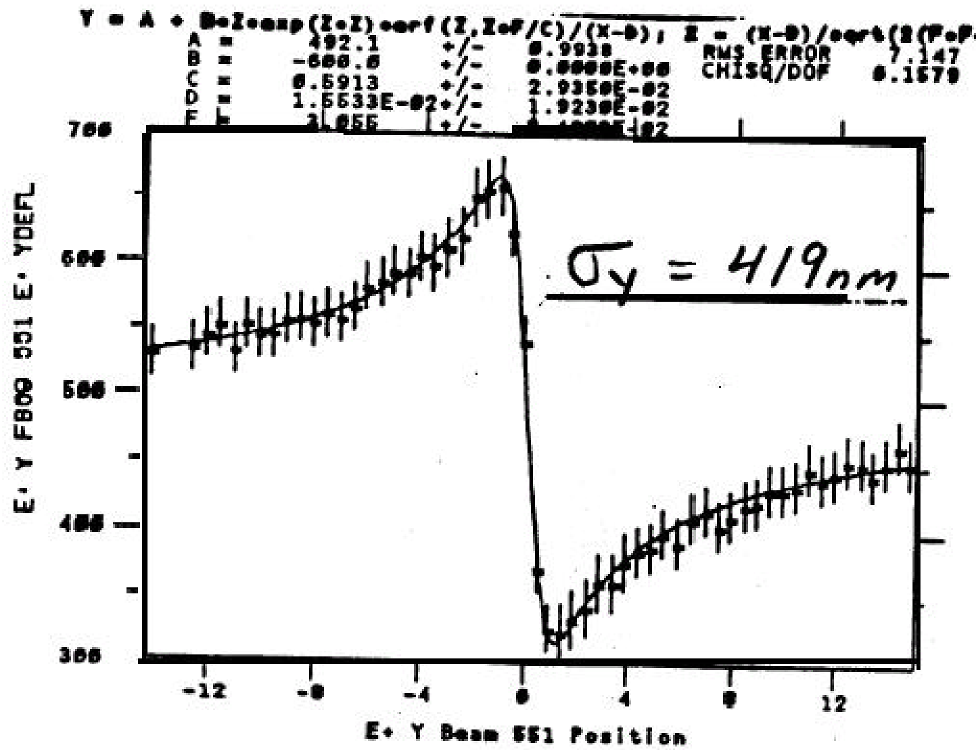
Beam-Beam Force

- Four main effects:
  1. Beam-beam deflections and increased angular distribution
     - Important diagnostic tool but makes transport to the beam dump difficult
  2. Pinch effect and luminosity enhancement
     - H_D is roughly unity for flat beams ~ 1.3 to 2
  3. Beamstrahlung and e+/e- pair creation
     - Widens luminosity spectrum and complicates transport to the beam dump
     - Incoherent and coherently produced pairs are a significant background
  4. Kink (two-stream) instabilities
     - Multibunch kink can arise from bunches too closely spaced - forces a crossing angle in normal conducting designs
     - Single bunch kink may limit luminosity and effectively reduces H_D

– Flat beams are chosen to minimize beam-beam forces for a given luminosity: $F_y \sim 1/(\sigma_x+\sigma_y)$ $\quad L \sim 1/(\sigma_x\sigma_y)$

Beam-beam Deflection

- Deflection is sensitive to beam sizes
  - Used extensively to center beams and tune SLC final focus
  - Essential to center colliding beams
  - Only tool known to ‘measure’ nanometer sized beams however *L* optimization is best performed with direct measurements



- Outgoing angular distribution:

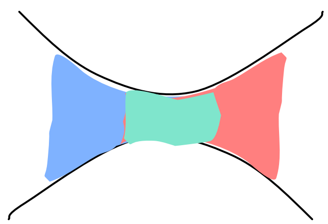
$$\Theta_{x,y} \approx \frac{D_{x,y}\sigma_{x,y}}{\sigma_z}$$

amplitude is similar in X and Y

- Requires large exit aperture

Aside: Hourglass Effect

- The beam size at the IP is given by sqrt(ε β*)
  - The beta function is a measure of the depth of focus
  - In free space about the IP, $\beta(s) = \beta^* + s^2 / \beta^*$
  - The spot size increases by sqrt(2), at $s = \beta^*$



(a poor picture of a collision with $\sigma_z \sim \beta^*$)

  - Without ‘traveling focus’ or other novel concepts, there will be significant luminosity loss if $\sigma_z >> \beta^*$
  - Final focus aberrations become worse with small β*
  - Maximum luminosity at σ_z = 1~1.5 times β*
  - Hourglass is parameterized with: $A_{x,y} \equiv \frac{\sigma_z}{\beta_{x,y}}$

Beam-beam Pinch and H_D

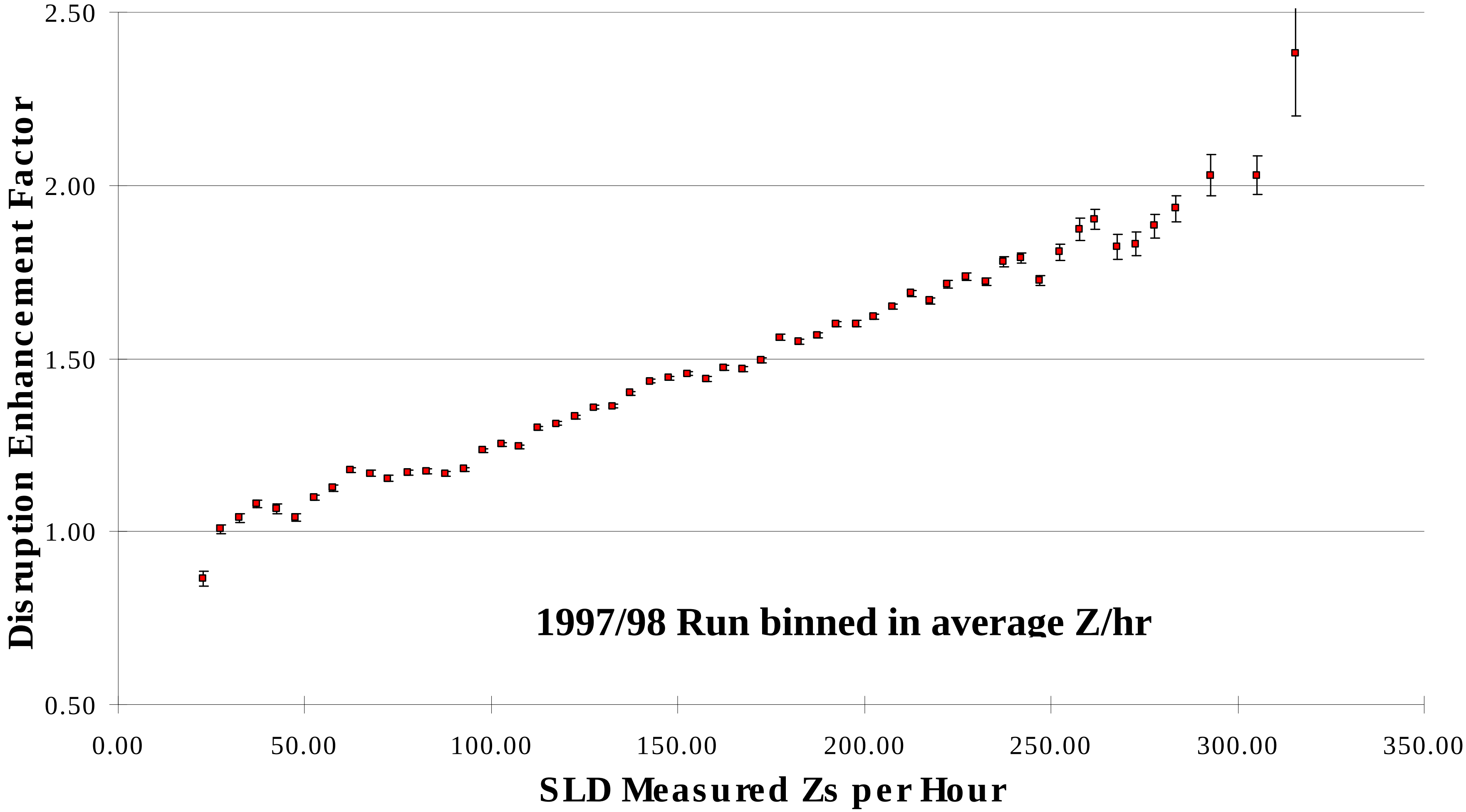
- Force between beams leads to a dynamic focusing of the opposing beams
- Force depends on D_y and hourglass $A_y = \sigma_z / \beta_y$ which compares the depth of focus to the bunch length

$$H_D(round) \approx 1 + D_y^{1/4}\left(\frac{D_y^3}{1+D_y^3}\right)\left[\ln\left(\sqrt{D_y}+1\right) + 2\ln\left(\frac{0.8}{A_y}\right)\right]$$

- In round beams, both X and Y spots sizes are reduced by sqrt(H_D)
- For flat beams, H_D is $(H_D(\text{round}))^{1/3}$ where only the vertical spot size is dynamically focused
- Typical values for H_D in flat beams are 1.3 ~ 2

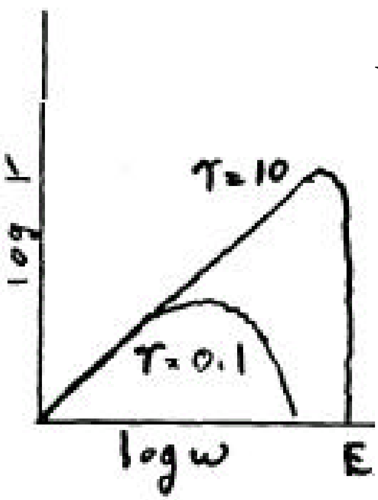
Lum. Enhancement in the SLC

SLD Measured Luminosity from Zs & Bhabhas / Luminosity Calculated without Disruption



Beamstrahlung

- Beamstrahlung is synchrotron radiation from particles deflected by the collective field of the opposing bunch
  - Leads to degradation of the luminosity spectrum as well as a potential background source
  - Beamstrahlung is described with 3 parameters:



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

$$n_\gamma \approx \frac{2 N r_e \alpha}{\sigma_x + \sigma_y}\frac{1}{\sqrt{1+\Upsilon^{2/3}}}$$

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

  - Minimize beamstrahlung with flat beams
  - Energy dependence makes it hard to keep Υ and δ_B small at E ~ TeV

Luminosity

- IP effects force us to flat beams to minimize beam fields
- The luminosity can be written:

$$L = \frac{f_{rep} n_b}{4\pi} \frac{N^2}{\sigma_x \sigma_y} \quad \Rightarrow \quad L = \frac{P_{beam}}{4\pi E_{cms}} \frac{N}{\sigma_x} \frac{H_D}{\sigma_y}$$

- This can be expressed in terms of the δ_B:

$$L \propto \frac{P_{beam}}{E_{cms}} \sqrt{\frac{\delta_B \sigma_z}{\gamma \varepsilon_y \beta_y}} H_D \left(1 + (1.5\Upsilon)^{2/3}\right)$$

(Usually $\sigma_z \sim \beta_y$)

- Better options may be:

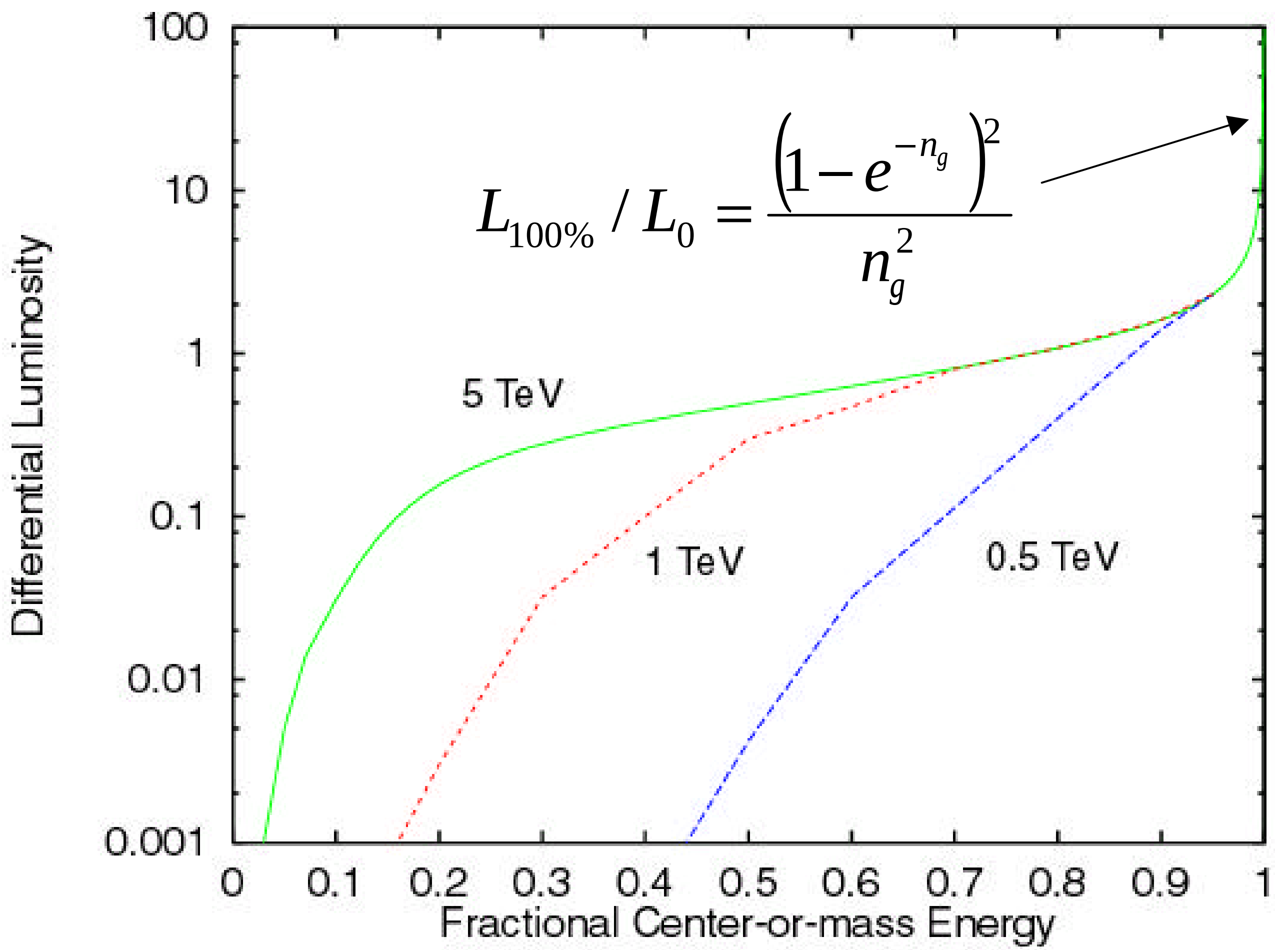
$$L \propto \frac{P_{beam}}{E_{cms}} \sqrt{\frac{1}{\gamma \varepsilon_y \beta_y}} n_\gamma H_D$$

or

$$L \propto P_{beam} \frac{D_y}{\sigma_z} H_D$$

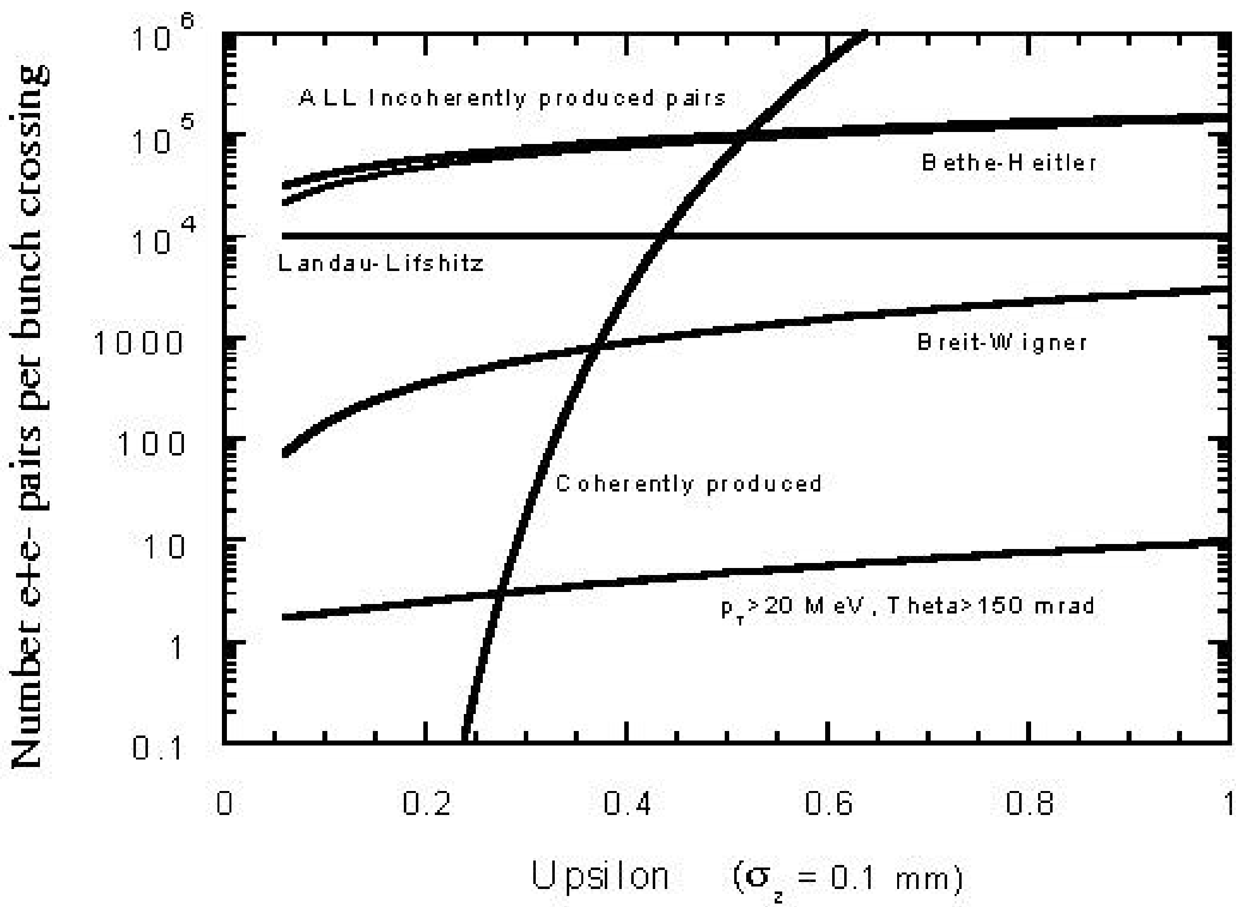
Luminosity Spectrum

- Comparison of different spectra as a function of energy
  - Spectrum also depends on beam offsets and emittance correlations
  - To fold spectrum into physics it is probably necessary to measure the spectrum after the IP



E+/E- Pairs

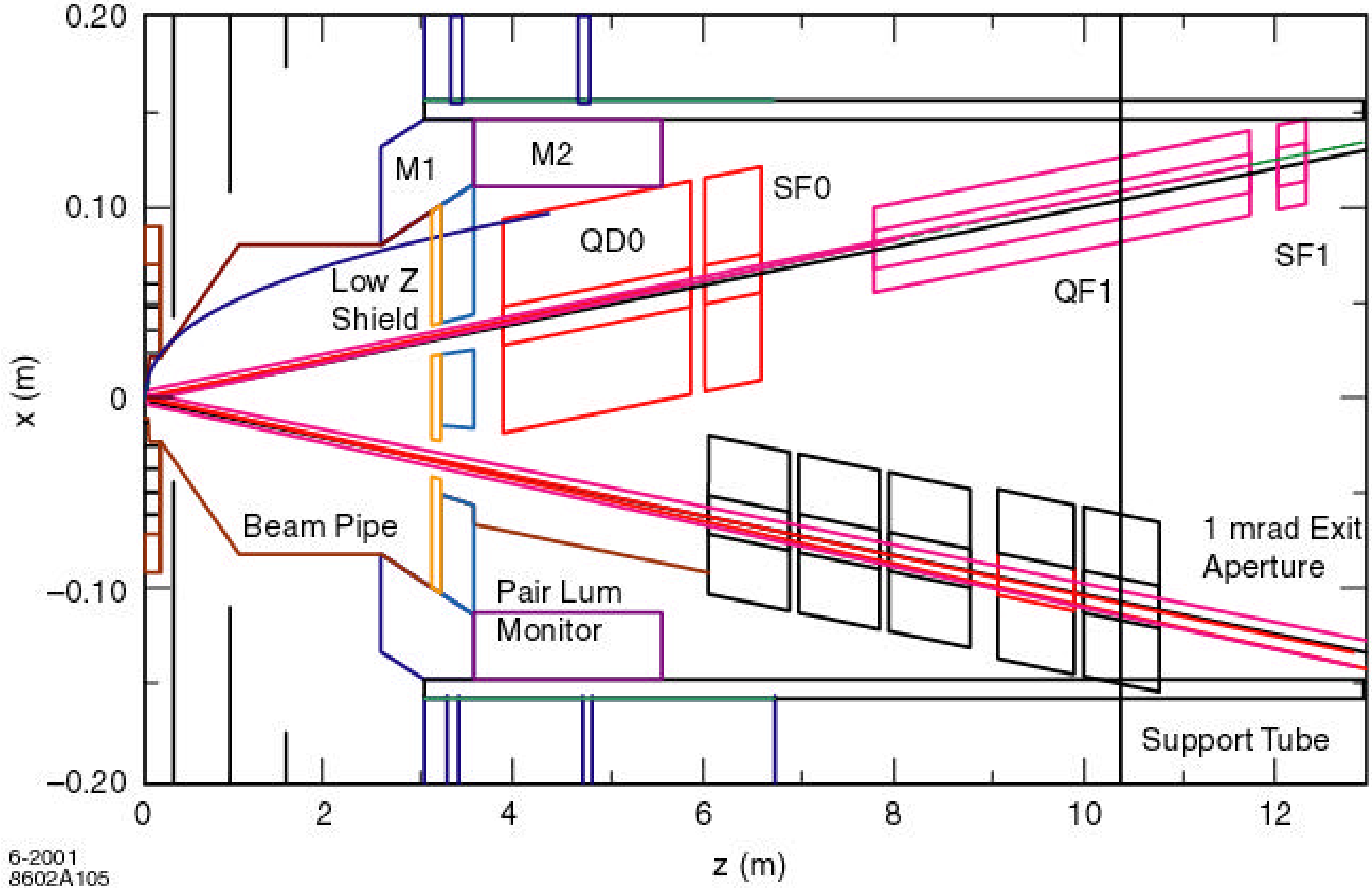
- Real and virtual photons can interact with individual particles to produce incoherent e+/e- pairs
  - Proportional to luminosity
- Also interact with collective beam field to produce coherent pairs
  - Strong function of Y
  - In multi-TeV collider, the # coherent pairs ~ beam particles



Multi-Bunch Kink

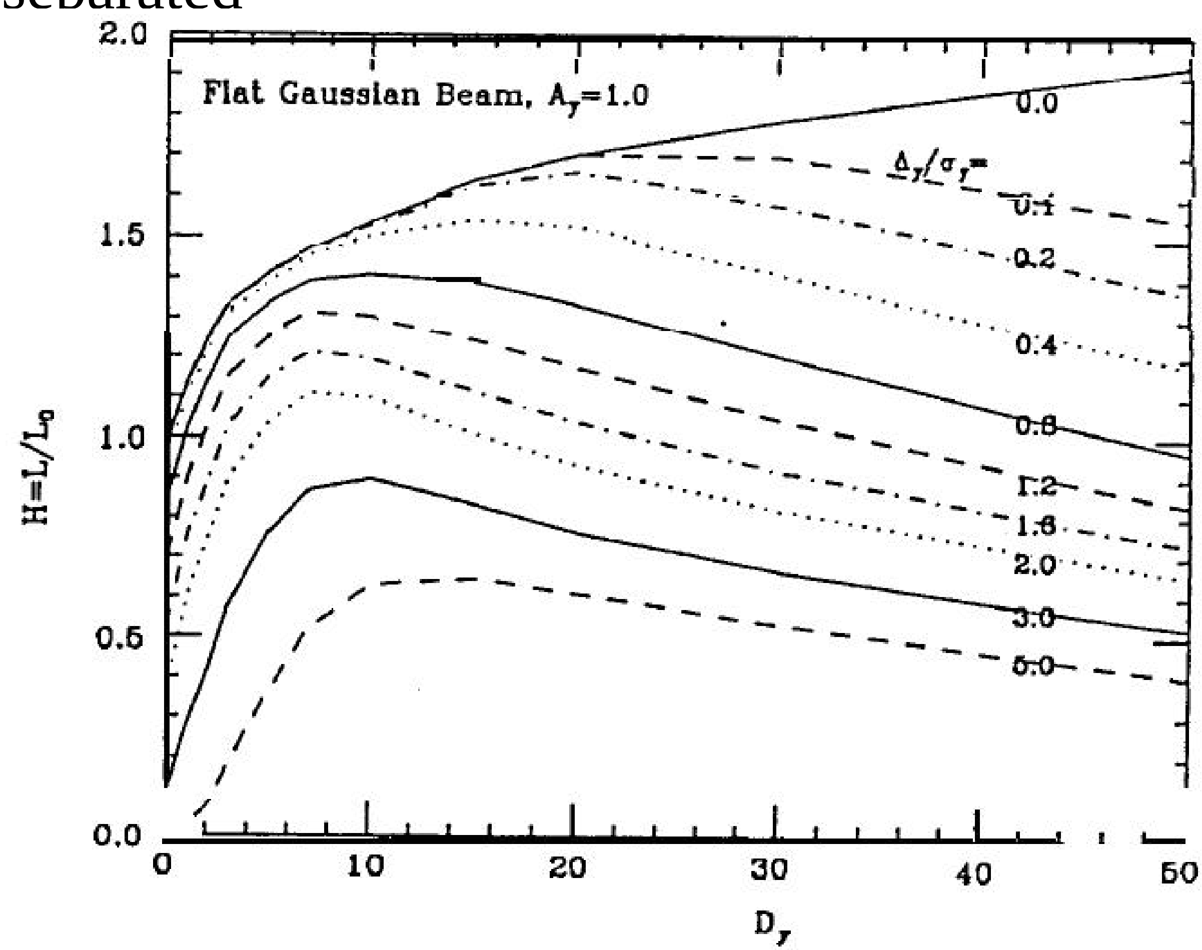
- All LC designs have long trains of bunches
- Parasitic collisions can lead to a kink (two-stream) instability unless the bunches are sufficiently separated
  - In JLC/NLC, this requires a crossing angle of at least 2 mrad
  - In multi-TeV colliders with Y >> 1, the coherent pairs become important and require a much larger crossing angle
    - ~ 20 mrad in the 3 TeV CLIC design
- With angles less than σ_x / σ_z , there is minimal luminosity loss – larger angles require some form of 'crab' crossing
  - Crab crossing can be generated with either an rf 'crab' cavity with a time dependent transverse deflection or using dispersion at the IP with a correlated energy spread

NLC IR Layout



Single Bunch Kink

- Beam-beam force will help *restore* collisions if (oppositely charged) beams are separated
- Clear gains for $D_y < 10$
- Still important for $D_y \sim 20$ or more
- At large D_y, the luminosity becomes increasingly sensitive to small offsets



Single Bunch Kink

- High disruption → single bunch kink instability
  - Sensitive to IP position and angle offsets (IP feedback)
  - Sensitive to position correlations along the bunch, i.e. $\Delta\varepsilon$
  - Fractional luminosity decrease is much larger for correlated errors such as those from the linac or bunch compressor

Simulation by R. Brinkmann for TESLA

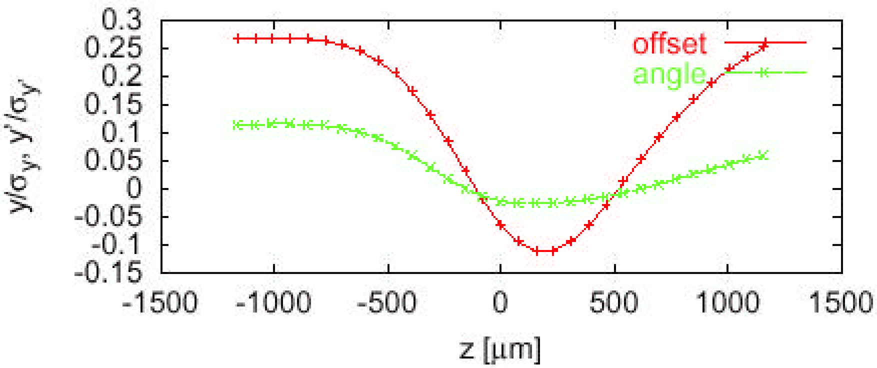
	Uncorr. $\Delta\varepsilon$	Corr. $\Delta\varepsilon$
L_{design} ($\Delta\varepsilon = 50\%$)	3.4×10^{34}	
L_0 ($\Delta\varepsilon = 0\%$ i.e. from DR)	4.1×10^{34}	4.1×10^{34}
L_{sim} ($\Delta\varepsilon = 10\%$)	3.9×10^{34}	3.2×10^{34}
L_{sim} ($\Delta\varepsilon = 20\%$)	3.7×10^{34}	2.7×10^{34}

  - Effect can be reduced by decreasing bunch length but this increases beamstrahlung energy spread
  - Smaller fractional effect for large emittance dilutions and smaller disruption – calculations suggest smaller problem in NLC design

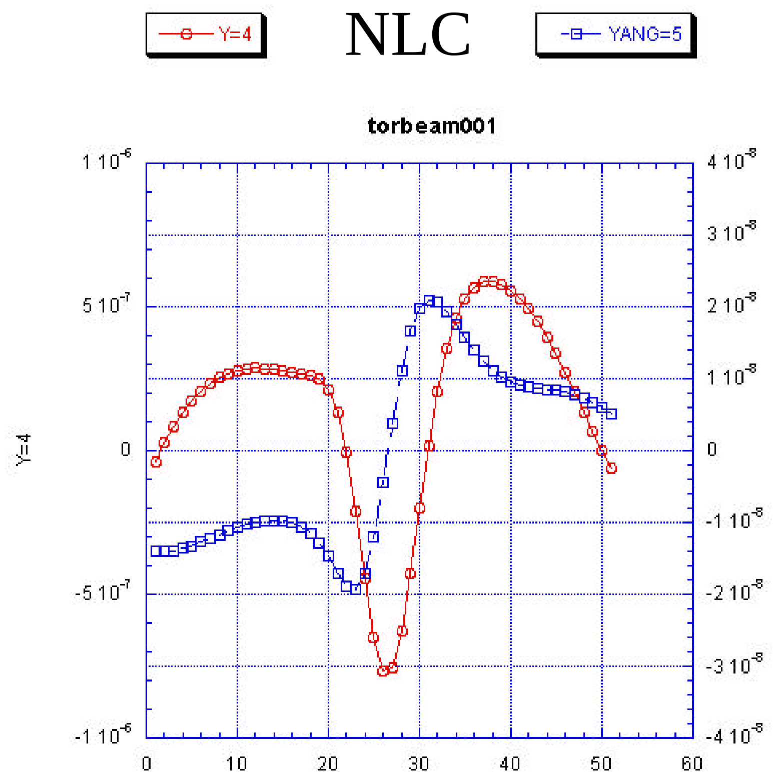
Correlated Emittance Dilutions

- Usually estimate luminosity based on increase in projected spot sizes
- Correlated emittance growth arises from bunch compressors and linacs

TESLA



NLC



Disruption Values

	TESLA		NLC		CLIC
Energy	500		500		3000
N	2.00E+10		7.50E+09		4.00E+09
DR emitx		8.00E-06		3.00E-06	
DR emity		2.00E-08		2.00E-08	
IP emitx	1.00E-05		3.60E-06		6.80E-07
IP emity	3.00E-08		4.00E-08		2.00E-08
betax (mm)	15		8		8
betay (mm)	0.4		0.1		0.15
sigmax	5.54E-07	4.95E-07	2.43E-07	2.21E-07	4.30E-08
sigmay	4.95E-09	4.04E-09	2.86E-09	2.02E-09	1.01E-09
sigmaz	3.00E-04		1.10E-04		3.00E-05
Dy	**24.82**	**34.02**	**13.45**	**20.90**	**5.14**
L0	1.64E+34	2.24E+34	1.47E+34	2.28E+34	6.67E+34
Approx Hd	2.09E+00	2.17E+00	1.40E+00	1.49E+00	1.91E+00
Approx Lum	3.42E+34	4.87E+34	2.06E+34	3.40E+34	1.27E+35

Gaussian Beam Simulations

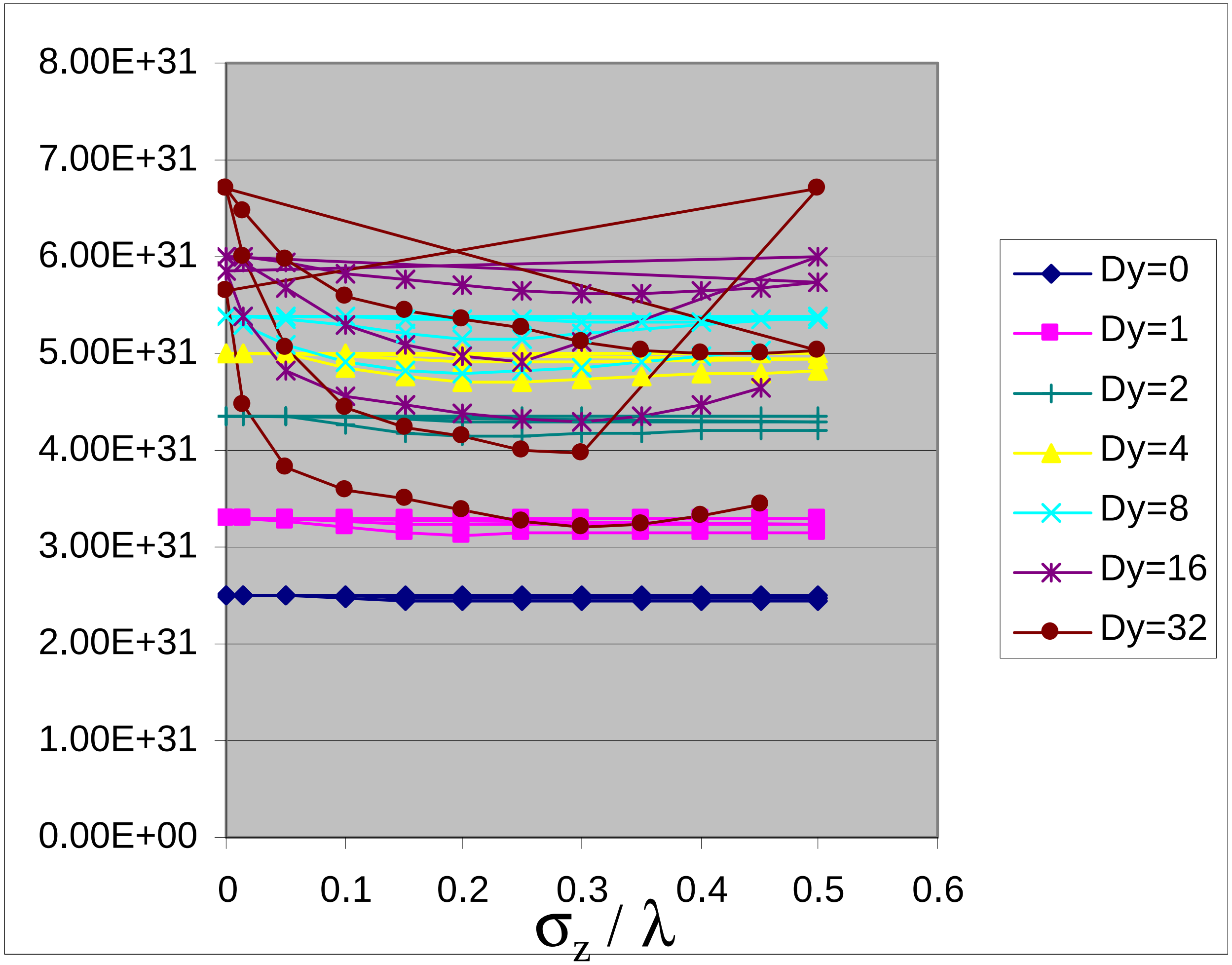
From Daniel Schulte

Sinusoidal offset versus σ_z / λ

Each D_y has 3 curves for $y = 0.1, 0.3, 0.5\ \sigma_y$

Note increase in luminosity with D_y due to pinch

Effect reduces pinch enhancement



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IP Issues

- Disrupts the outgoing beams
- Forces to flat beams
- Limits ratio N / σ_x to constrain beamstrahlung
- Degrades the luminosity spectrum
- Generates large number of high energy photons which is a background source and problem for the dump
- Generates a large number of e+/e- pairs – another background
- Forces a crossing angle in closely spaced bunch trains
  - Crossing angle simplifies extraction line diagnostics
- May limit maximum disruption acceptable

Luminosity

- IP effects force us to flat beams to minimize beam fields
- The luminosity can be written:

$$L = \frac{f_{rep} n_b}{4p} \frac{N^2}{s_x s_y}$$

$$L = \frac{P_{beam}}{4pE_{cms}} \frac{N}{s_x} \frac{H_D}{s_y}$$

- This can be expressed in terms of the δ_B:

$$L \propto \frac{P_{beam}}{E_{cms}} \sqrt{\frac{d_B s_z}{ge_y b_y}} H_D \left(1 + (1.5Y)^{2/3}\right)$$

(Usually $\sigma_z \sim \beta_y$)

- Better options may be:

$$L \propto \frac{P_{beam}}{E_{cms}} \sqrt{\frac{1}{ge_y b_y}} n_g H_D$$

or

$$L \propto P_{beam} \frac{D_y}{s_z} H_D$$

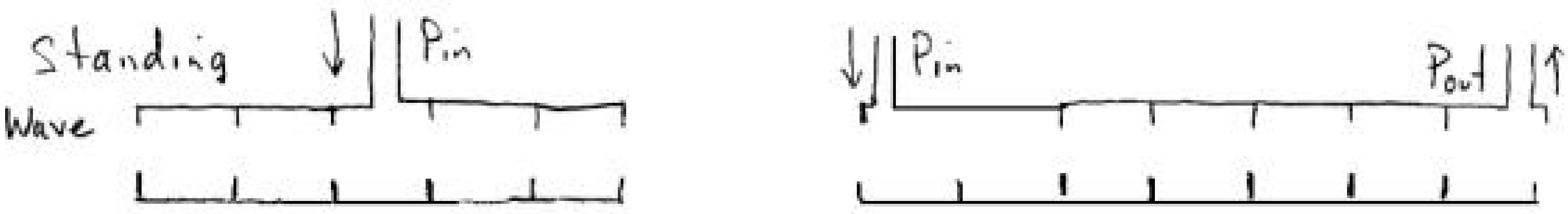
Beam Power

- Need efficient transfer from wall plug to the beam
  - $P_{beam} = P_{ac}\eta_{ac}\eta_{beam}$

Rf technology

Beam and cavity parameters

- There are two type of rf cavities: standing wave and traveling wave:



  - Standing wave cavities are matched so that input power flows to beam and cavity walls – no reflected power with beam
  - Traveling wave are matched as a transmission line
  - Both types of cavities are most efficient when $V_{beam} = \frac{1}{2} V_{cav}$

RF Cavities

- Rf cavities are describe by a Q and $R_s = V_{cav}^2 / P_c$ where P_c is the power lost to the cavity walls
- The ratio R/Q ~ 100 for most cavities – just geometry

$$\eta_{beam} = \frac{P_{beam}}{P_{beam} + P_{cav} + P_{out}} \frac{T_{beam}}{T_{fill} + T_{beam}}$$

First factor: = 1 TESLA; = 0.5 NLC

Second factor: = 0.67 TESLA; = 0.8 NLC

	SC Cavities	NC Cavities
Q	10^{10}	5000
Shunt imp. R_s	10^{13} Ω/m	80 MΩ/m
R / Q	100 / cav.	100 / cav.
P_{cav}	60 W/m	30 MW/m
P_{beam}	~250 kW / coupler	$P_{beam} > P_{cav}$
I_{beam}	10 mA	1 A

Linear Collider RF Systems

- The RF systems consist of 4 primary components:

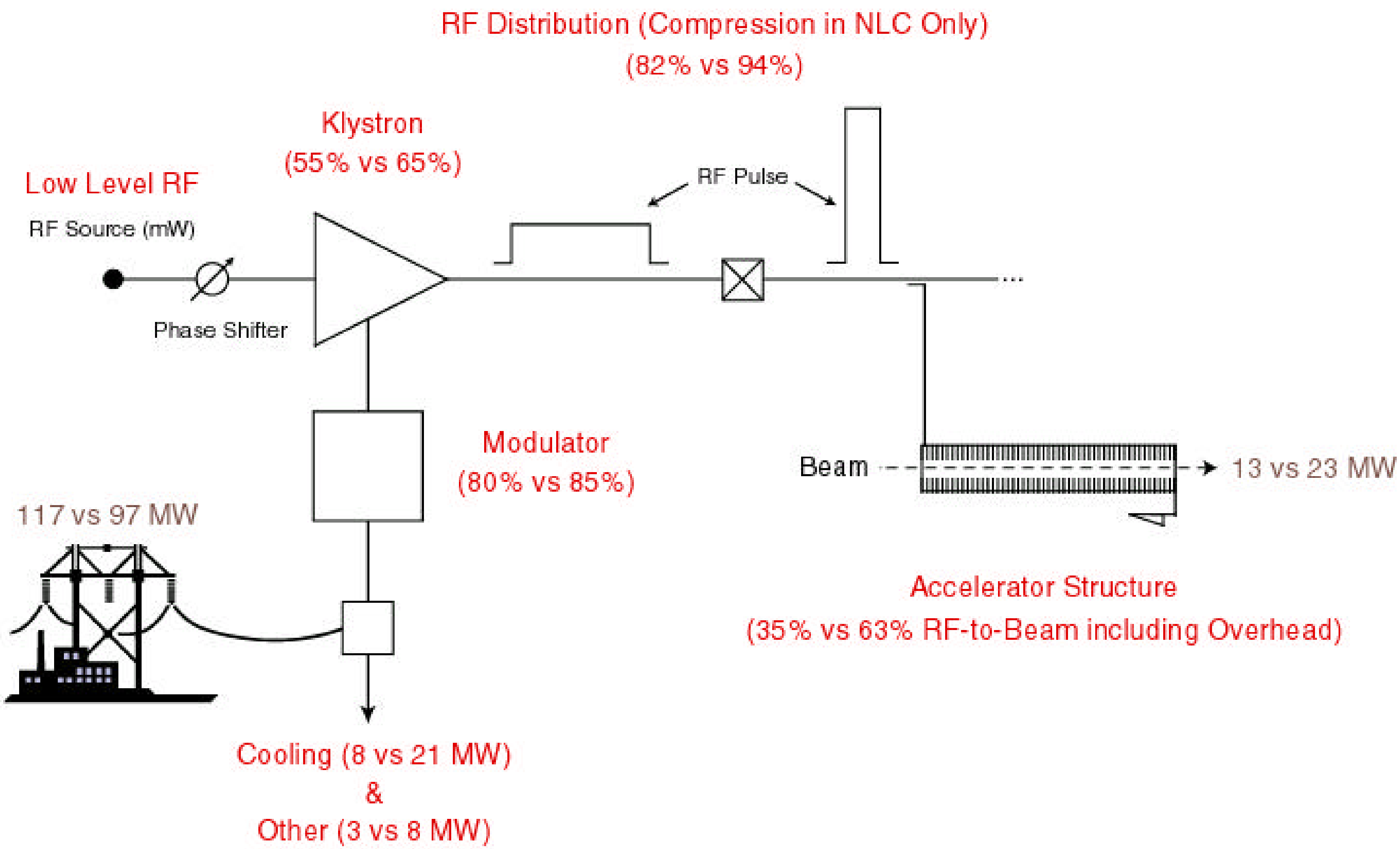
Modulators:
line ac → pulsed dc for klystrons
TESLA distributes pulse dc (12 kV) in long 2.8km cables
NLC needs 500 kV / 250 A per klystron

Klystrons:
dc pulse → rf at 1.3 or 11.424 GHz
TESLA multi-beam klystron delivers 10 MW / 1.5 ms
NLC klystron delivers 75 MW / 3.1 μs

RF distribution:
transport rf power to accelerator structures
TESLA needs couplers and circulators on each structure
NLC compress klystron power to increase peak power

Accelerator Structures:
→ power to beam, prevent dipole mode instabilities

RF Schematic



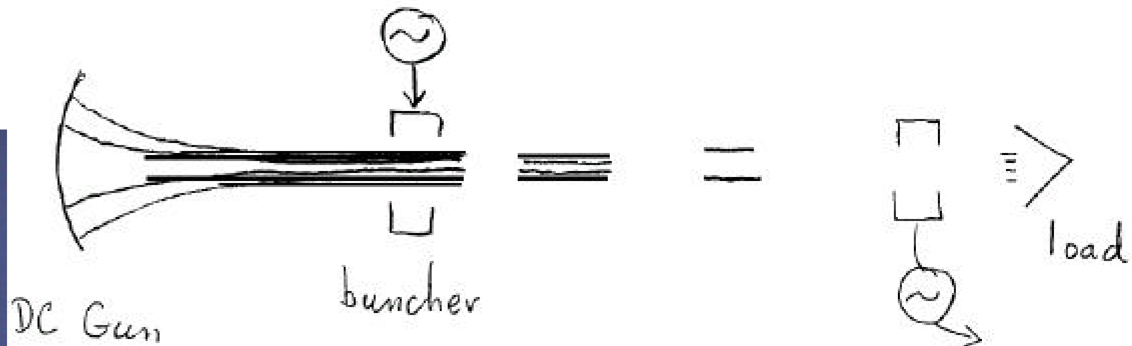
Modulators

- Energy storage devices with fast switches
  - Current generation use IGBT's which switch MW's in ~200 ns

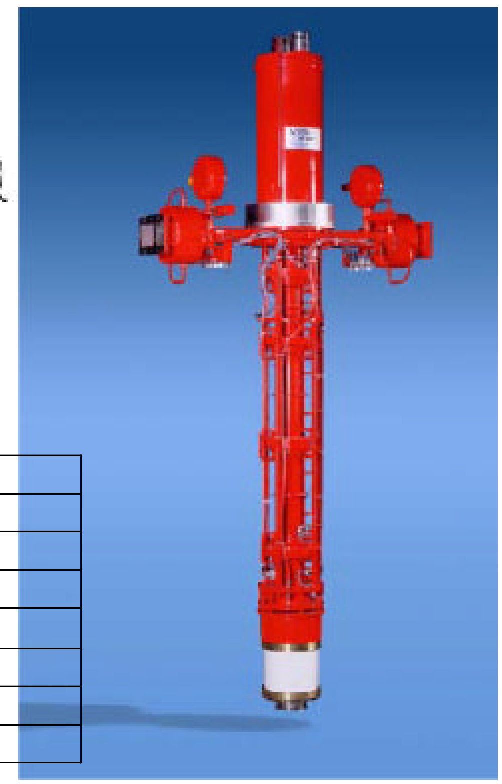
	NLC	TESLA
Output voltage	500 kV	115 kV
Output current	2120 A	130 A
Repetition rate	120 Hz	5 Hz
Pulse length	3.2 μs	1.4 ms
Rise/fall time	200 ns	200 μs
Energy per pulse	3.4 kJ	21 kJ
Transformer ratio	3:1 step up	12:1 step up
Output load	Eight 75 MW klystrons	One 10 MW klystron
Efficiency	>80%	>85%

Klystrons

- Rf amplifiers
  - Take a dc beam; velocity modulate it; let it bunch while drifting; extract the rf power; dump the beam into a load.



Typical efficiencies are 50 ~ 70%



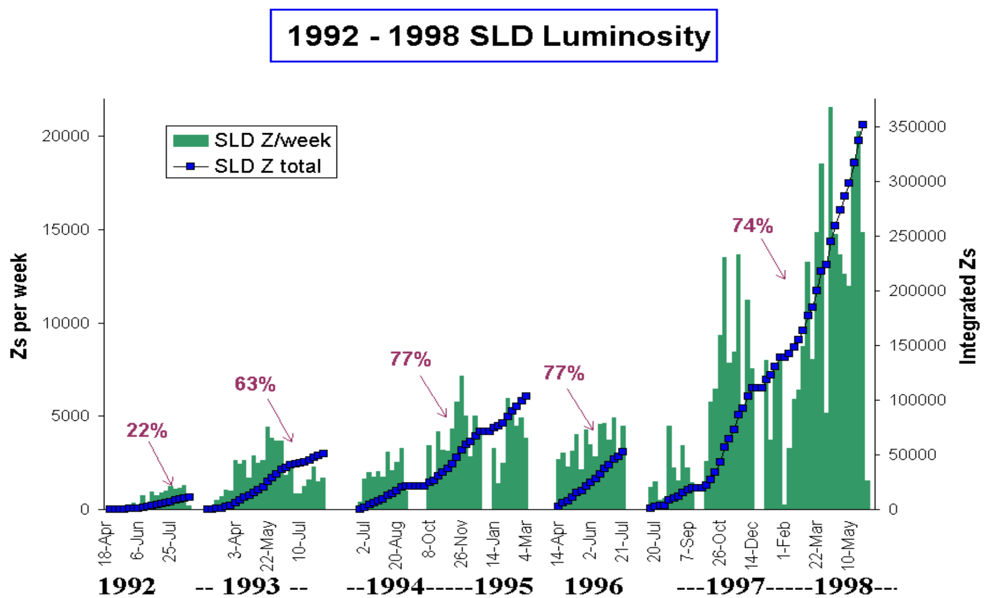
	NLC	TESLA
Rf frequency	11.424 GHz	1.3 GHz
Beam Voltage	490 kV	115 kV
Beam Current	260 A	130 A
Rf pulse length	3.2 μs	1.5 ms
Output power	75 MW	10 MW
Input power	1 kW	160 W
Efficiency	60%	65%

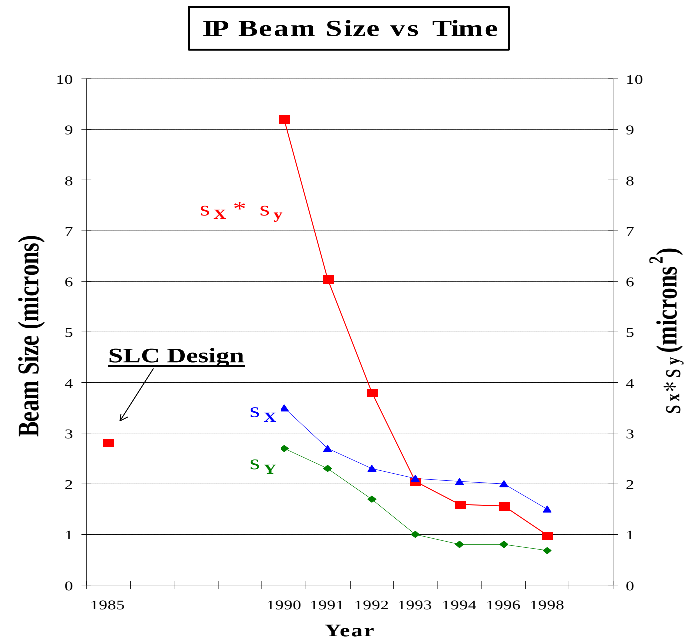
‘Nominal’ Parameters

NLC and TESLA Parameters				
	Stage 1		Stage 2	
	NLC	TESLA	NLC	TESLA
CMS Energy (GeV)	500	500	1000	800
Luminosity (10^{33})	**20**	**34**	**34**	**58**
Repetition Rate (Hz)	120	5	120	4
Bunch Charge (10^{10})	**0.75**	**2**	**0.75**	**1.4**
Bunches/RF Pulse	192	2820	192	4886
Bunch Separation (ns)	1.4	337	1.4	176
Eff. Gradient (MV/m)	**50.2**	**23.4**	**50.2**	**35**
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 2	1000 / 2	300 / 2	800 / 1
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	360	1000	360	800
ge_y at IP (10^{-8} m-rad)	**4**	**3**	**4**	**1.5**
β_x / β_y at IP (mm)	8 / 0.10	15 / 0.4	10 / 0.12	10 / 0.12
s_x / s_y at IP (nm)	**245 / 3**	**553 / 5**	**190 / 2.3**	**391 / 2.8**
σ_z at IP (um)	110	300	110	300
Υ_{ave}	0.11		0.29	
Pinch Enhancement	1.43	2.1	1.49	2.1
Beamstrahlung δB (%)	4.7	3.2	10.2	4.3
Photons per e+/e-	1.2	2	1.3	2??
Linac Length (km)	6.3	30	12.8	30

- Most NLC studies performed with 1 TeV parameters
- Most TESLA studies performed with 500 GeV parameters
- TESLA 800 GeV parameters require improved damping ring performance and smaller IP emittances

Luminosity: Building on the SLC





New Territory in Accelerator Design and Operation

- Extensive feedback & online modeling
- Correction techniques expanded from first-order (trajectory) to include second-order (emittance), and from hands-on by operators to fully automated control

“It’s the diagnostics, stupid”

“The damping rings are the source of all evil”

Electron and Positron Sources

- Polarized electron source is based on polarized lasers and ‘strained’ GaAs photocathodes
  - Limitation on polarization is the scattering within cathode
  - Also limitations on the extracted currents
  - Looks like no problem for either NLC or TESLA
- Positrons are captured from electromagnetic shower generated by either an electron beam on a target or a photo beam
  - NLC baseline design is an extrapolation of the SLC system with a 6 GeV electron beam on a 4 r.l. Wre target
    - Problem is target damage due to shock of beam impact
  - TESLA uses a photon beam on a thin target
    - Photons are created in a wiggler
    - Need high energy gammas (20 MeV) → 150+ GeV e- beam

Damping Rings

- Damping rings are needed to generate the very small beam phase spaces required at the IP
- Louiville made this process a bit difficult!
  - Electron cooling
  - Stochastic cooling
  - Incoherent radiation
- Damping rings are based on the later

$$ge_{ext} = ge_{inj}e^{-2t/t} + ge_{0}(1 - e^{-2t/t})$$

- The damping time is the time that it takes a particle to radiate all of it energy (energy is replaced with rf cavities)!
  - Typically store the beams for 5+ damping times

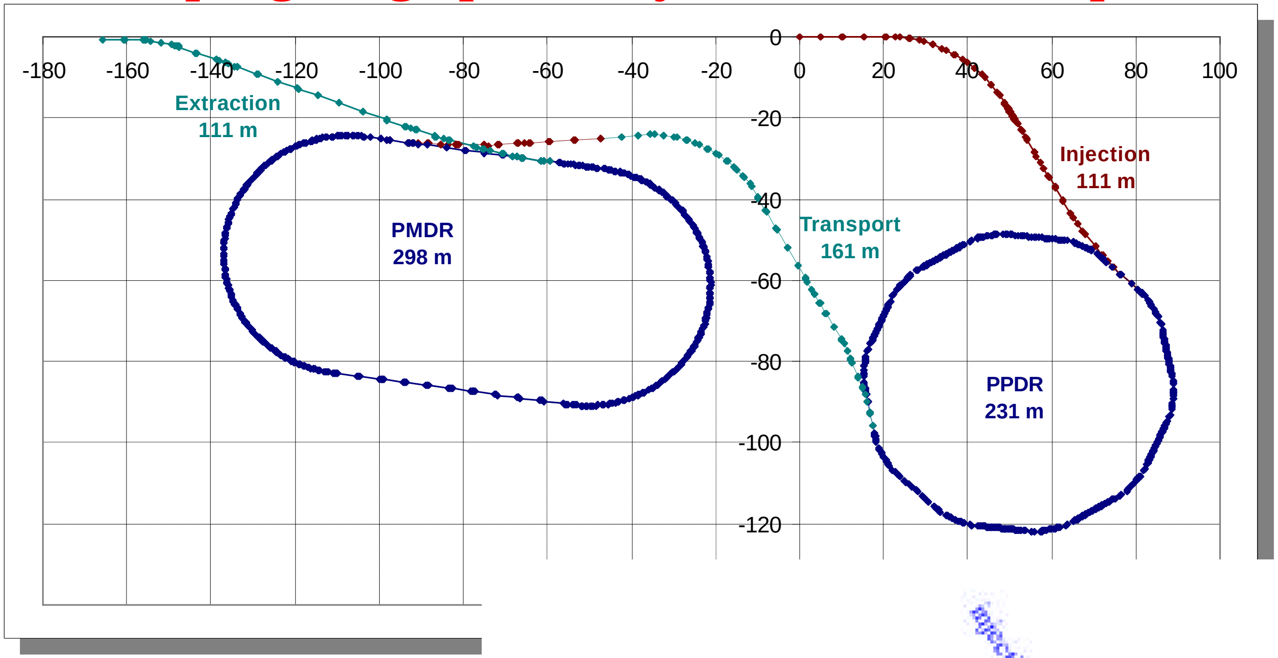
Damping Rings

- Beam is stored for a relatively long time in the rings (ms)
  - More questionable physics in the rings than elsewhere in LC
- Rings have beam currents and bunch trains similar to the high operating luminosity factories
  - However they have much smaller beam sizes (higher densities) and are much more sensitive to weak instabilities
  - They also require much better alignment to get flat beams ~ 50 um
- High beam density pushes frontier in electron machines
  - Space charge tune depression
  - Ion trapping effects
  - Electron cloud effects

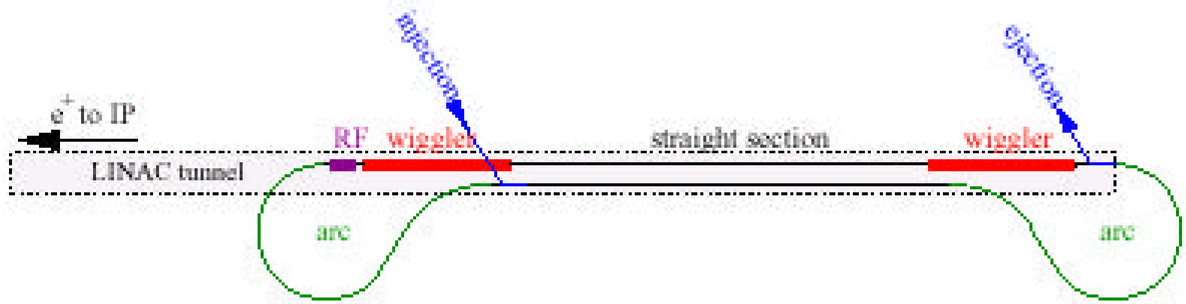
Damping Rings

NLC rings are similar to present generation of light sources (similar energies, emittances, sizes, and currents)

Damping rings probably have most complex acc. physics issues

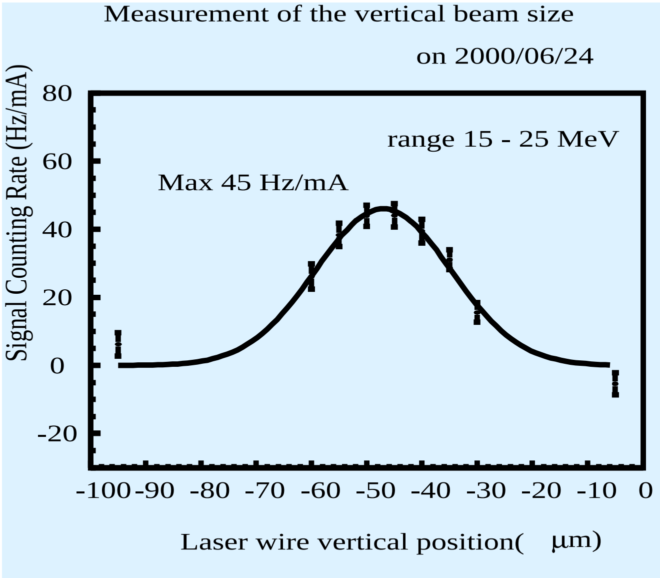


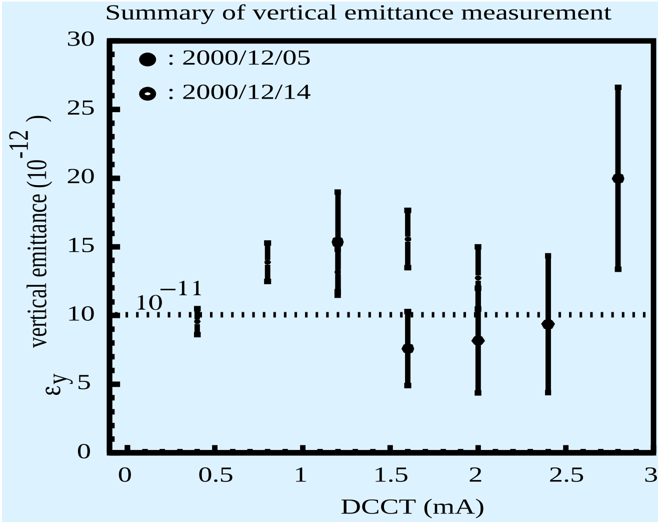
Rings use lots of wiggler to increase the synchrotron radiation!



ATF Damping Ring at KEK

Vertical emittance 3.5×10^{-8} measured with laser wire (~2 x NLC spec)

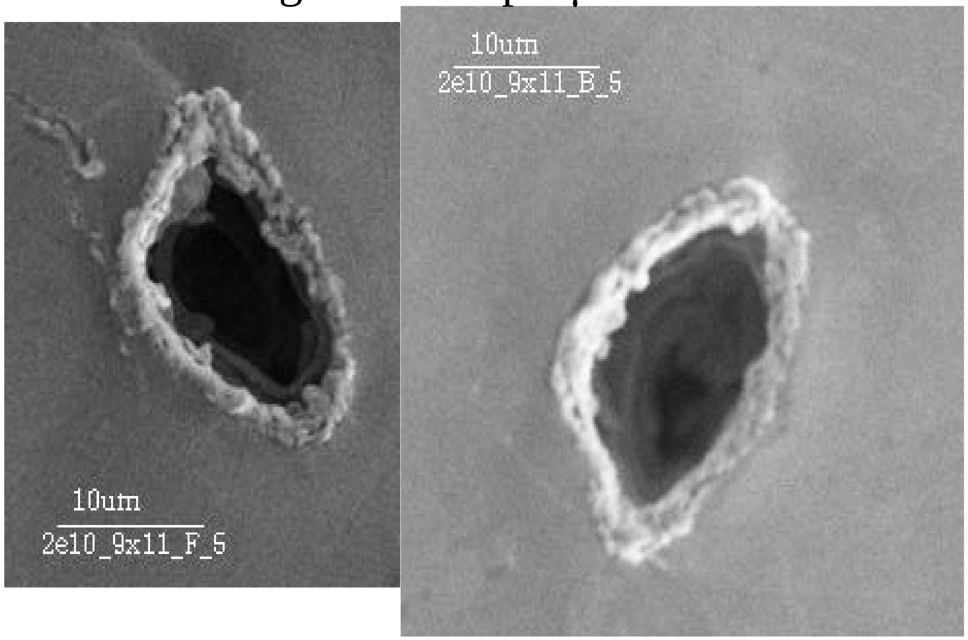




Machine Protection Issues

- Single bunches will likely damage any material at the end of the linac or in the beam delivery
  - Complicated turn-on process to prevent damage
  - Complicated MPS system with diagnostics on many components
    - Anything that can change from pulse-to-pulse

Damage from 13 pC/μm^2



  - Some impact on operation not yet fully quantified

  - Problems are similar for TESLA and NLC!

Summary

- IP issues constrains possible parameter space
- LC rf systems are making great progress
  - Rf systems for 500 GeV cms is close to being ready
    - Need to test final prototypes for modules, HOM damping, couplers or pulse compression, and klystrons
    - Need to gain operational time at nominal gradients
  - Rf cavities for 1000 (800) GeV cms will probably be ready in 2003
- Luminosity issues are a larger concern!
  - Damping rings are essential for stable operation
    - Lots of potential problems – still largely not understood
  - Both linear collider designs require complicated BBA procedures
    - FFTB and SLC developed instrumentation and techniques necessary for beam-based alignment
  - Beam-beam effects are significant and may force reduction in luminosity in both designs