Comparison of Different LC Scenarios

N. Holtkamp
1/12/00

- Introduction
- Wake Fields and Energy Spread
- Backgrounds and Collimation
- Bunch Train Differences
- At what point do differences matter to the experiment
- IP-motion + Feedback
- Statement about cost optimization
- Summary

Introduction

- What is the longest Linear Accelerator ever being build?

  - SLAC, Stanford 2 miles } Beg. of 60's
    Kharkov ≈ 500 m

- What / Where is the first Linear Collider
  Do we have one?

  - SLC, but not really!

- Does Accelerator Physics develop in big steps
  and can we do steps?

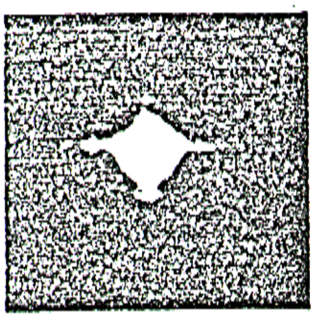
  - I don't think so, but other people
    are much more optimistic!

- Beam Break up

- Intermediate stage TF

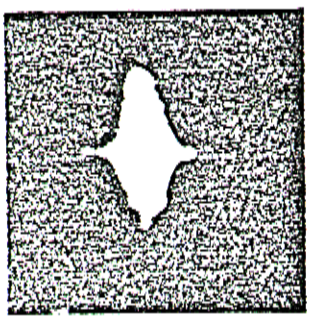
Beam Break Up in the SLAC Linac

(Blue Book PP 220)



a) CURRENT BELOW BREAK-UP (12.5 mA)

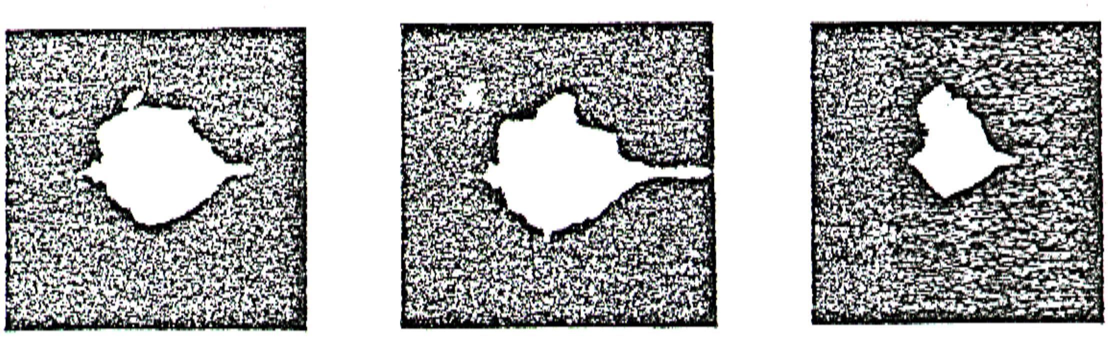
first vertical blow up!



b) CURRENT FOR PREDOMINANTLY VERTICAL BREAK-UP (25 mA)

c) CURRENT WHERE BREAK-UP BEGINS TO OCCUR IN RANDOM DIRECTION (45 mA)

horizontal blow up!



d) CURRENT FOR ENTIRELY RANDOM BREAK-UP DIRECTION (70 mA

Figure 7-28 Beam cross sections as seen on profile monitor at the end of the accelerator (1.6-μsec beam pulse). These photographs were obtained from a 16-mm movie and represent frames taken at the rate of 24 frames/sec.

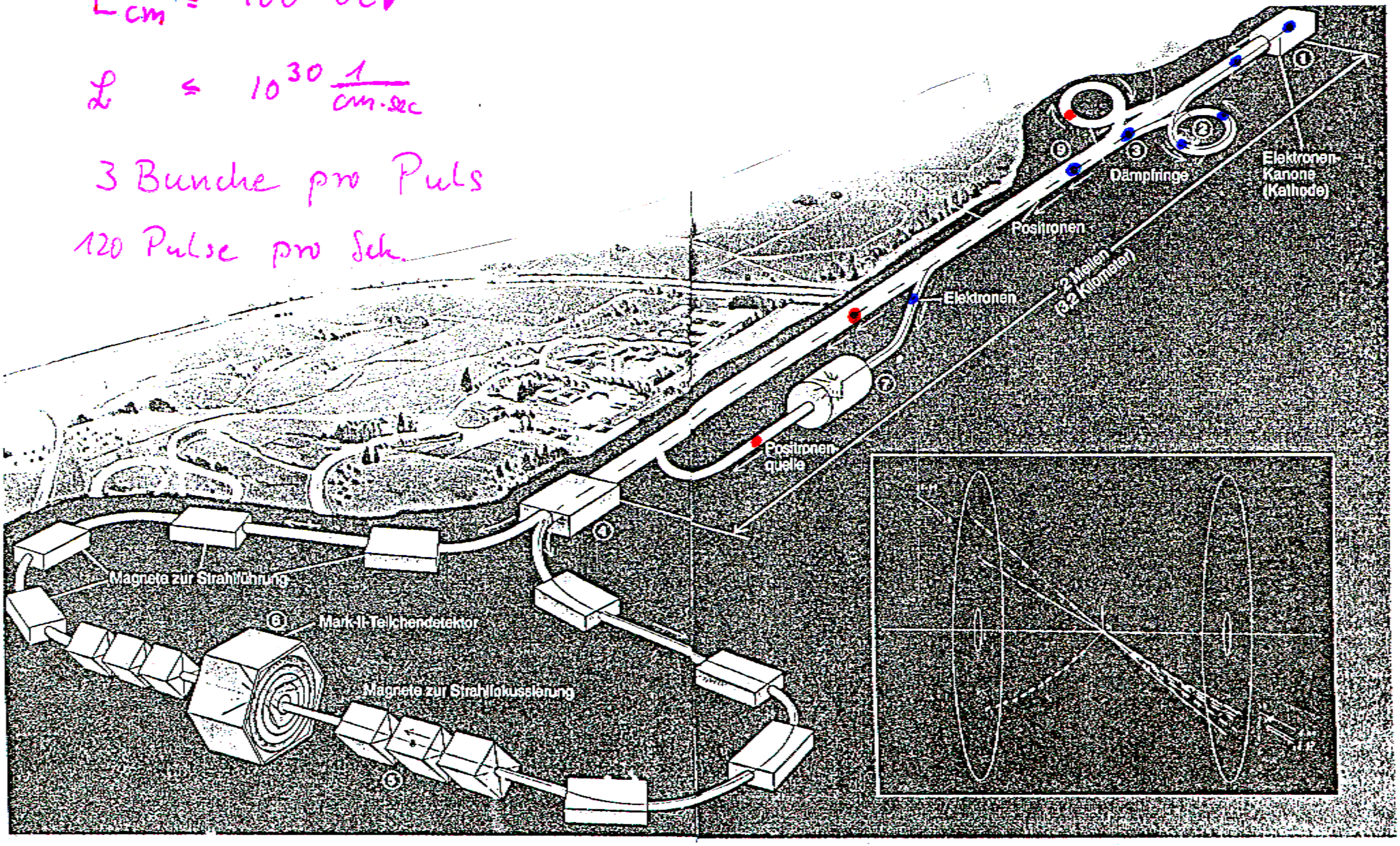
Der SLC (Stanford Linear Collider)

$E_{cm} = 100$ GeV

$\mathcal{L} \leq 10^{30} \frac{1}{cm \cdot sec}$

3 Bunche pro Puls

120 Pulse pro Sek.



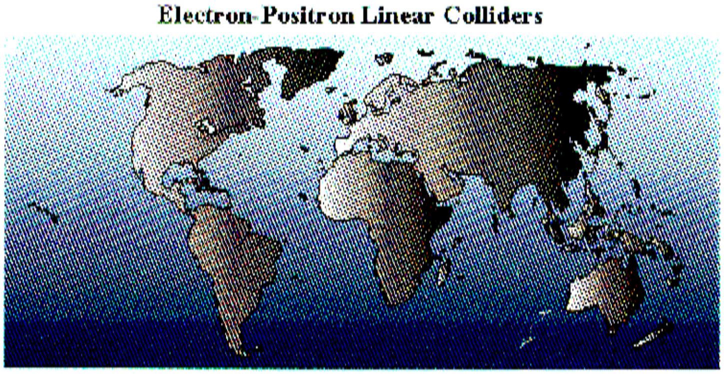
Linear Collider Concepts

Overview Of Linear Collider Concepts							
Name	TESLA 1.3 GHz	SBLC 3 GHz	JLC-C 5.7 GHz	JLC-X NLC-X 11.4 GHz	Vlepp 14 GHz		CLIC 30 GHz
Techno-logy	sc-Niob Cavities	Cu structures & klystrons					Two Beam
Challenge	gradient Q0, cost	high rf peak power and power conversion efficiency					Wakefield drive beam
grad. MeV/m	25	17	32	58	32	91	78
L km	32	36	22	22	14	10	12
σ_y nm	19 /15	15	3.0	3.1	3.2	4	7.4
P_{beam} MW	16 /22	7	3.1	3.6	4.4	2.4	4.9

All Designs have $L \approx 5 \times 10^{33}$ and $P_{ac} \approx 100$ MW at 500 GeV cms

more details: http://www.slac.stanford.edu/xorg/ilc-trc/ilc-trchome.html

Interlaboratory Collaboration for R&D Towards TeV-scale Electron-Positron Linear Colliders



International Linear Collider Technical Review Committee

ILC-TRC

Parameter Limitations

A Few Basic Equations

$$L = \frac{N^2 \cdot f_{rep}}{4\pi \cdot \sigma_x \cdot \sigma_y} \times H_D$$

a few 10^{33}

$$P_b = E_{cm} \cdot N \cdot f_{rep}$$

max. aver. current. long pulses

$$\delta_E \approx 0.86 \frac{r_e^3 N_e^2 \gamma}{\sigma_z \left(\sigma^*_x + \sigma^*_y\right)^2}$$

ave. fract energy loss due to beam strahlung

$$L \approx 5.74 \cdot 10^{20} m^{-3/2} \times \frac{P_b}{E_{cm}} \times \left(\frac{\delta_E}{\varepsilon_{y,N}}\right)^{0.5} \times H_D$$

Pb=7,5 MW cw per beam
$s_x * s_y = 400 \times 20\ nm^2$

$\Delta E/E_0$ per bunch < one percent

_-> $\Delta W/W$ < zwei Prozent

$W_{stored} \sim Grad^2/F^2_{rf}$

Problems:

-which depend on $\Delta E/E_0 \sim F^2_{rf}$

-which depend on $\Delta\varepsilon/\varepsilon \sim F^3_{rf}$

if warm -> 3 GHz

from R. Brinkmann

General LC luminosity scaling:

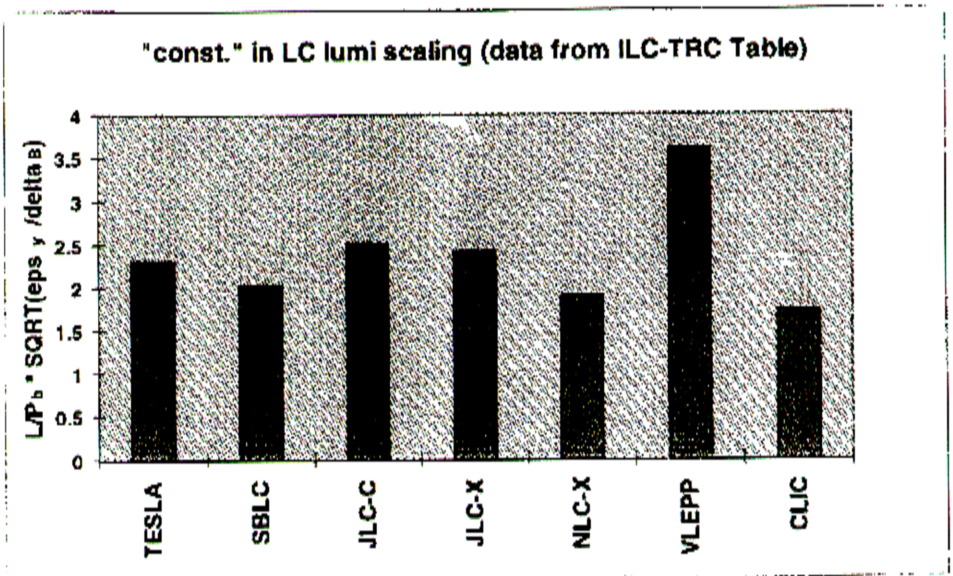
$$L \approx const. \times \frac{\eta \cdot P_{AC}}{E_{cm}} \cdot \sqrt{\frac{\delta_B}{\varepsilon_y}}$$

FIGURE OF MERIT

$$\frac{\eta}{\sqrt{\varepsilon_y}}$$

⇒ optimised design should have

- maximum AC-to-beam efficiency η
- minimum dilution of emittance ε_y
- minimum ε_y



How do Wake Fields Scale with Frequency?

- purely geometric:

$W'_\perp \sim f^3$ → transverse WF

↳ drive Emittance growth

$W'_\parallel \sim f^2$ → longitudinal WF

↳ drive Energy spread

Bunch length:

$W'_\perp \sim \sqrt{\sigma_z}$ → σ_z in "long structures"

$W_\parallel \sim \frac{1}{\sqrt{\sigma_z}}$ → $\frac{1}{\sigma_z}$ "

Single Bunch Wake Fields

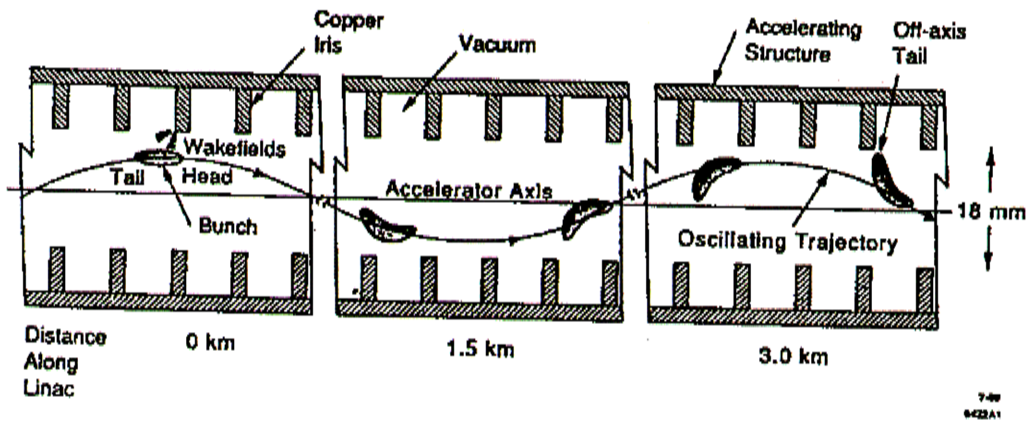


Figure 18 A beam oscillation in an accelerating structure produces head-tail transverse wakefields which distort the transverse bunch profile. Trajectory correction downstream will have difficulty converging as some part of the bunch is always off axis.

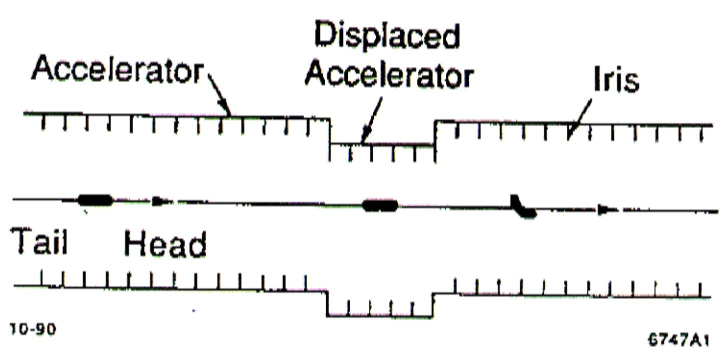
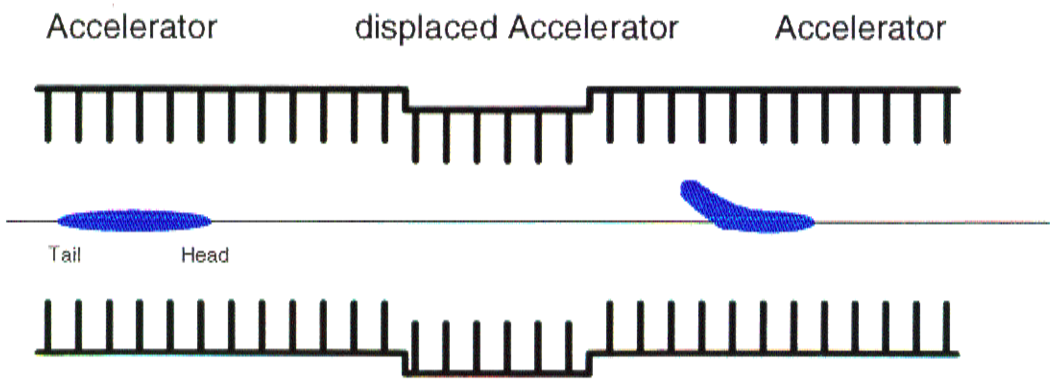


Figure 19 A displaced accelerating structure will induce wakefield distortions in a bunch. Again, trajectory correction will have difficulty correcting the result. There are many of these small distortions (random) in an accelerator and they collectively contribute to the beam shape.

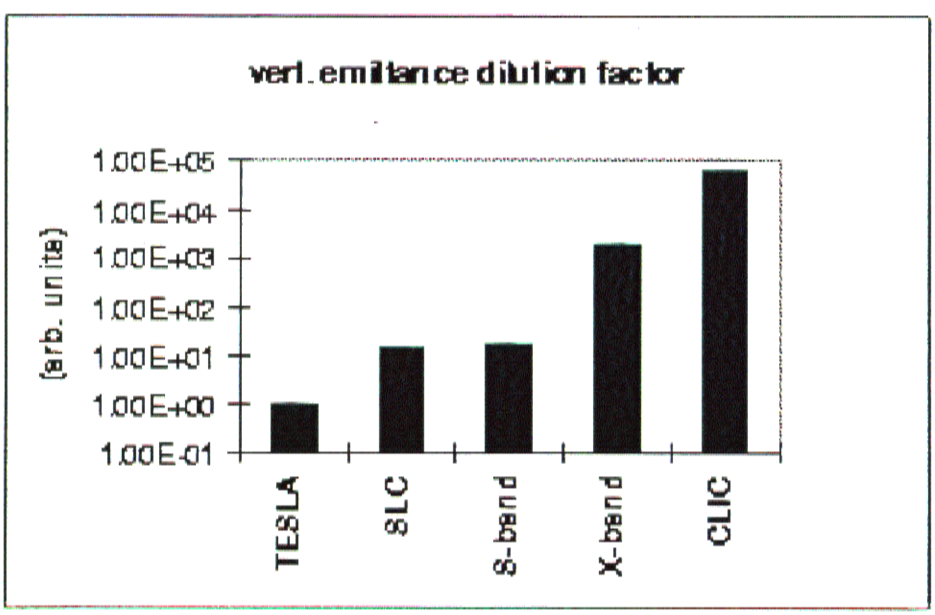
Cure: $\frac{\Delta E}{E}$ from Head to Tail cures Instability

but leads to Emittance growth from Dispersion 9

Comparison of Single Bunch Emittance growth



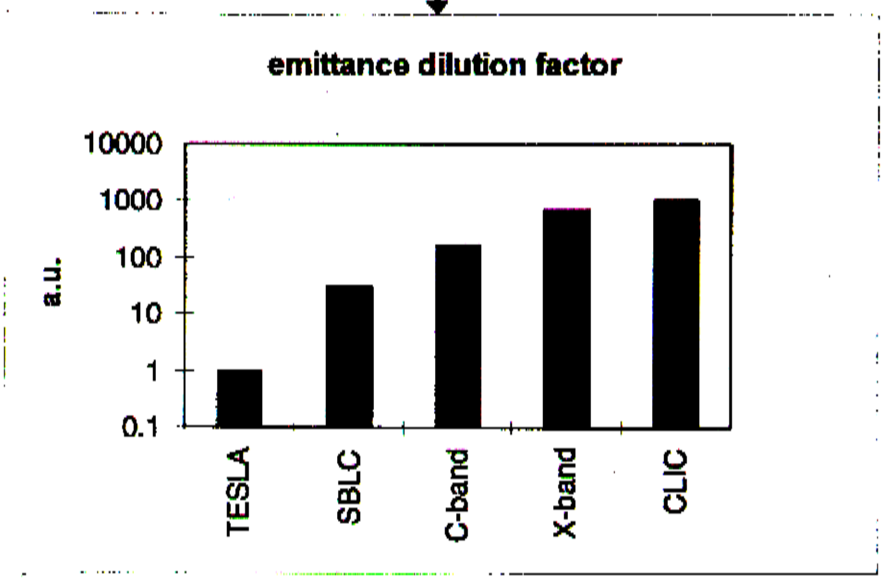
$$\frac{\Delta\varepsilon}{\varepsilon} \propto \frac{N_e^{2} f^{6}_{rf} F_{geom}^{2} \sigma_z}{g^2 \varepsilon_y} \times \delta y^2_{align} \langle\beta\rangle$$



81 7/99

After Recognition, that this is a Driving term!

$$\frac{\Delta\varepsilon_y}{\varepsilon_y} \propto \frac{N_e^2 f_{rf}^6 (\lambda / a)^7}{g^2 \varepsilon_y} \times dy_c^2 < \beta >$$



Alignment and stability tolerances:

	TESLA	SBLC	X-band/CLIC
acc. structures [µm]	**500**	50	~5 … 10
BPM-to-quad [µm]	**10**	5	1 … 2
quad pos. drift (no corr.) [nm]	**500**	100	~5…10
time between orbit corretion (ATL ground motion model)	**½ h**	5 min	~1 s

CLIC

$\frac{\Delta E}{E}$ 0.04 % 0.3 % 0.3 % ~1 %

remember also: smaller $<\beta>$ means more focusing

→ larger spurious Dispersion

→ $\Delta x \sim D_{Error} \times \frac{\Delta E}{E}$

What else do Wake Fields do ?

- Population of Tails :

  - presently:
    - TESLA : ~ 10^{-3} of charge in Tails
    - NLC : ~ 10^{-1} of charge in Tails

→ both are assumptions at this point!

- SLC - Tails have not been understood
- the population of tails in the linac can come from:
  - beam gas scattering
    → low T: - pumping speed
    - SC → cold!
  - Wakefields
    - F^3
  - non linear motion ? → no!
    ΔX_{rms} << Aperture
- no progress in understanding since many years and it is a difficult problem!

→ if you want to do work → please

collimation:	TESLA	NLC	
at	$12\,\sigma_x$	$6\,\sigma_x$	↓ close to the beam
	$48\,\sigma_y$	$40\,\sigma_y$	σ_x, σ_y small

Wakefields and Tails

Why worry:

crossing angle :

Electrons / Positrons in the Tails :
- will hit the Quad → huge em shower
- will generate very Photons → Detector

→ thats one reason for the big tungsten masks

The less collimation to be done →

- easier to build collimator
- handle Wakefields from collimators
- less muons produced which hit the detector
- shorter the collimation region !

1.4km versus 5km

Beam Delivery System for the NLC

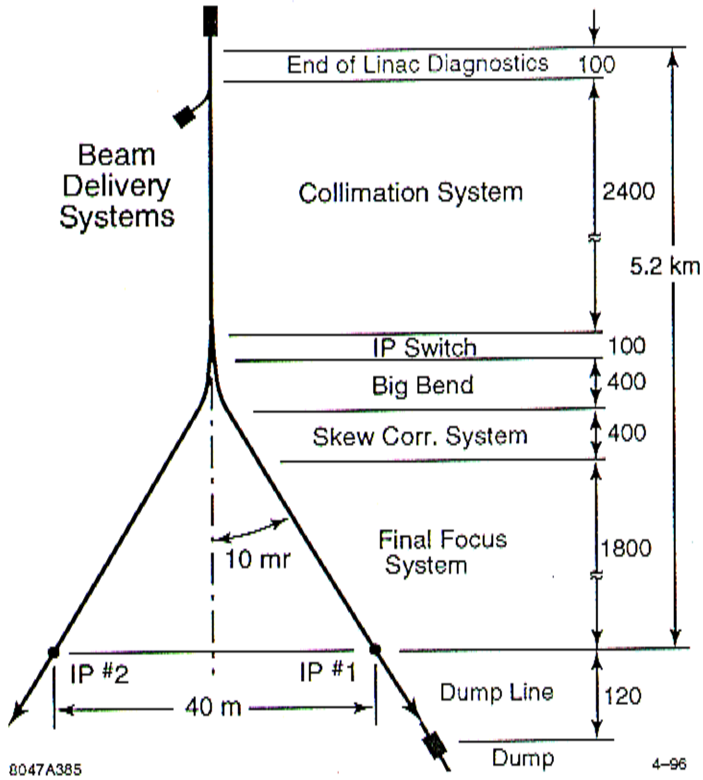


Figure 9-1. *A schematic layout of the beam delivery systems.*

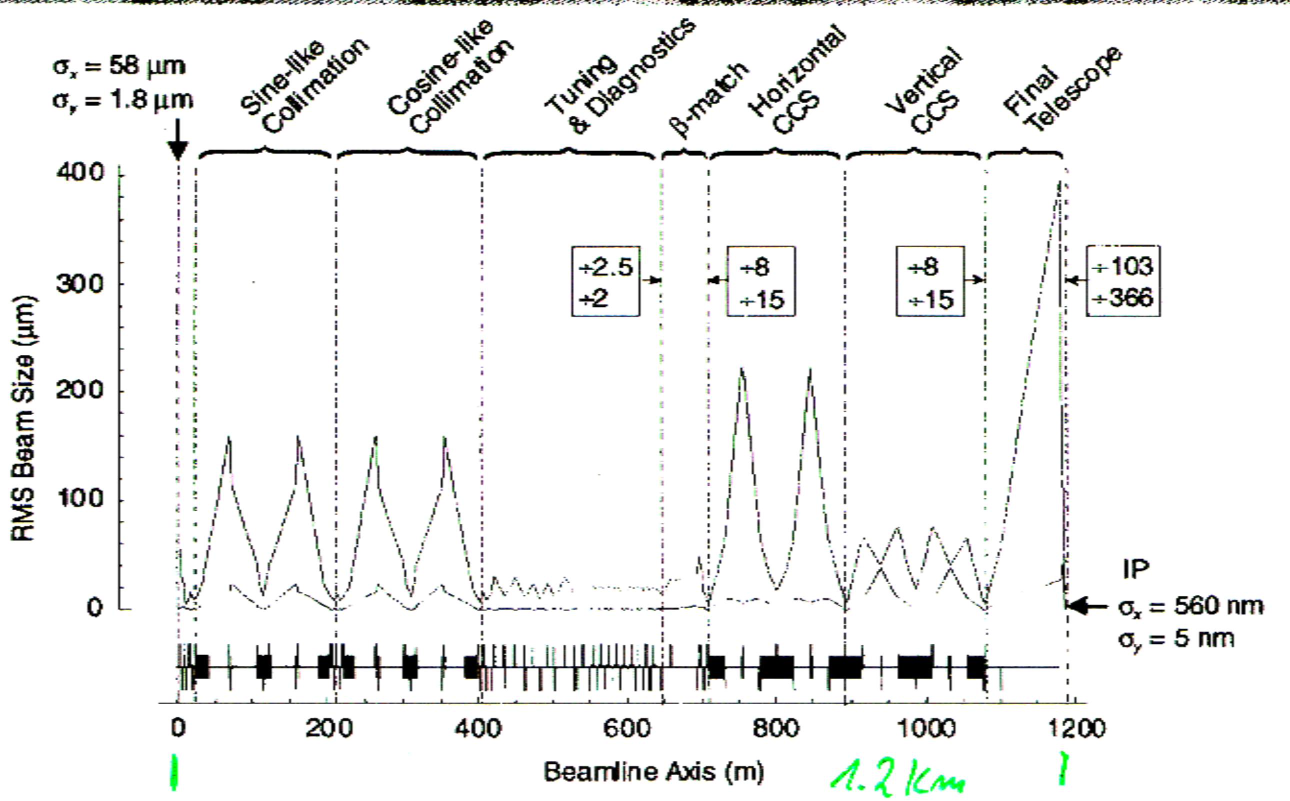
- collimation system is 2.4 km
  → thats the whole BD for TESLA S-Band

→ not quite fair because designed for 1.5 instead of 0.8 TeV

BDS for TESLA + S-Band ~ up to 800 GeV cms

24

Structure of TESLA-500 BDS



\WALKER@MPYNTWALKER, AUG20/16:42

Up TRC Home Page Next Table 1.2

ILC-TRC

Table 1.1
Linear Colliders: Overall and Final Focus Parameters - 500 GeV (c.m.)

>

Click here to update your machine information for Table 1.1.	TESLA TRC 12/95	TESLA Updated* 8/98	SBLC TRC 12/95	SBLC Updated* 10/96	JLC (C) TRC 12/95	JLC (C) Updated* 9/99	JLC (X) TRC 12/95	NLC TRC 12/95	JLC/NLC** Updated* 12/98	VLEF TRC 12/95	Up 10
Initial energy (c.m.) (GeV)	500		500		500		500	500	500	500	
RF frequency of main linac (GHz)	1.3		3		5.7		11.4	11.4	11.4	14	
Nominal luminosity (10^{33} cm^{-2} s^{-1})†	2.6	16.2	2.2	3.16	7.3	5.02	5.1	5.3	5.1(4.2)	12.3	11
Actual luminosity (10^{33} cm^{-2} s^{-1})†	6.1	30	3.75	5.3	6.1	7.18	5.2	7.1	6.54(5.45)	9.3	9.
Linac repetition rate (Hz)	10	5	50		100		150	180	120(100)	300	
No. of particles/bunch at IP (10^{10})	5.15	2	2.9	1.1	1	1.11	.63	.65	.95	20	
No. of bunches/pulse	800	2820	125	333	72		85	90	95	1	
Bunch separation (nsec)	1000	337	16	6	2.8		1.4		2.8	2.8	-
Beam power/beam (MW)	16.5	11.3	7.26	7.25	2.9	3.07	3.2	4.2	4.5(3.7)	2.4	
Damping ring energy (GeV)	4	3.2	3.15		2	1.98	2	2	1.98	3	
Unloaded/loaded††(MV/m)	25/25	21.7/21.7	21/17		40/32	44/34	73/58	50/37	72.3/55	100/91	
Total two-linac length (km)	29	30	33	32	18.8	16	10.4	15.6	10.5	7	
Total beam delivery length (km)	3	2.5	3		3.6		3.6	4.4	NA	3	
$\gamma\varepsilon_x / \gamma\varepsilon_y$ (m-rad × 10^{-6})	20/1	10/.03	10/.5	5/.25	3.3/.05		3.3/.05	5/.05	4.5/0.1	20/.08	
β^*_x / β^*_y (mm)	25/2	15/.4	22/.8	11/.45	10/.1	15/.2	10/.1	10/.1	12/0.12	100/.1	

Bunch Train Differences

Linear Collider Pulse Structures

TESLA: $t_{pulse} = 950\mu s$ (285 km), $\Delta t_b = 337ns$ = 100 m — 2820 bunches, $f_{rep} = 5Hz$, duty cycle 0.5 %

→ Accelerator is only 15 km long ≙ 150 bunches → Accident?

X-Band: $t_{pulse} = 0.27\mu s$ (81 m), $\Delta t_b = 2.8ns$ = 84 cm — 95 bunches, $f_{rep} = 120$ Hz, duty cycle 0.003 %

CLIC: $t_{pulse} = 0.1\mu s$ (30 m), $\Delta t_b = 0.7ns$ = 21 cm — 150 bunches, $f_{rep} = 200$ Hz, duty cycle 0.002 %

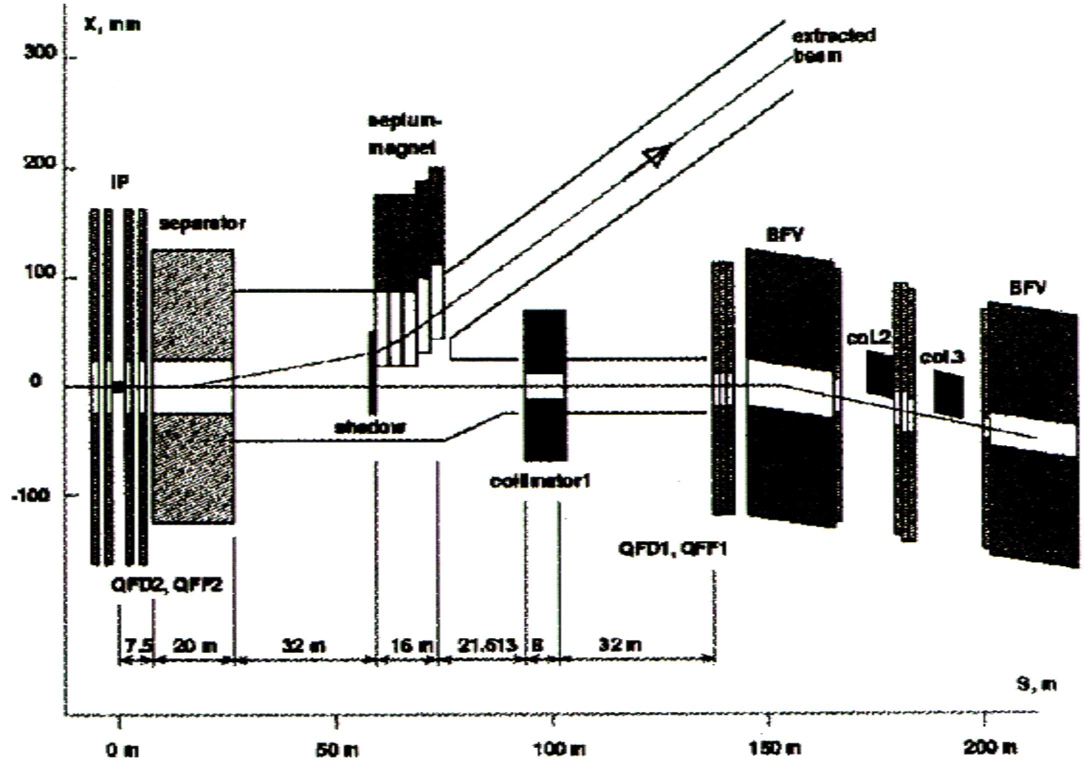
→ See number of photons per crossing!

hadrons/jets per crossing

Crossing Angle I

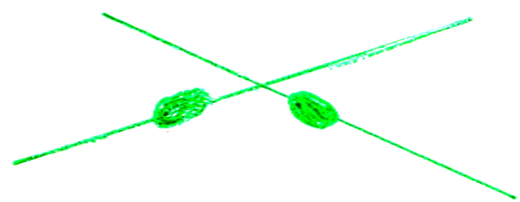
TESLA Interaction Region with Head-on Collision

→ the only accelerator which can do that



→ cheap crossing with crossing angle > 10 mrad

$$\sigma_{x\,eff} = \sqrt{\sigma_x^2 + \left(\frac{\Theta_{IP}}{2}\sigma_z\right)^2}$$



	TESLA		SBLC		JLC (C)		JLC (X)	NLC	JLC/NLC**	VLEF	
	TRC 12/95	Updated* 8/98	TRC 12/95	Updated* 10/96	TRC 12/95	Updated* 9/99	TRC 12/95	TRC 12/95	Updated* 12/98	TRC 12/95	Up 10
σ_x^* / σ_y^* (nm) before pinch	1000/64	553/5	670/28	335/15.1	260/3	318/4.3	260/3.1	320/3.2	330/4.9	2000/4	
σ_z^* (μm)	1000	400	500	300	120	200	90	100	120	750	
Crossing Angle at IP (mrad)	0	0	3	6	6	8	6.1	20	20(6)	6	
Disruptions D_x / D_y	.56/8.7	.3/33	.36/8.5	.32/7.1	.2/18	.25/17.9	.096/8.3	.07/7.3	0.12/7.9	.4/215	
H_D	2.3	1.8	1.8	1.68	1.4	1.7	1.4	1.34	1.36	2	0.[illegible]
Upsilon sub-zero	.02	.02	.037		.14	.21	.12	.089	.11	.059	
Upsilon effective	.03	.03	.042		.144		.12	.09	.11	.074	
δ_B (%)	3.3	2.8	3.2	2.8	6.5	4.1	3.5	2.4	3.7	13.3	10
n_γ (no. of γs per e)	2.7	2.0	1.9	1.4	1.5	1.5	.94	.8	1.1	5	4.[illegible]
N_{pairs} (p_T^{min} = 20 MeV / c, Θ_{min} = 0.15)	19	31	8.8	7.1	10.3	20.1	2.9	2	9.8	1700	12
$N_{hadrons}$ / crossing	.17	.13	.1	.04	.23	.13	.05	.03	.07	45.9	11
$N_{jets} \times 10^{-2}$ (p_T^{min} = 3.2 GeV / c)	.16	.3	.14	.1	.66	.37	.14	.08	.2	56.4	28

Click here to update your machine information for Table 1.1.

*If a number does not appear in the updated column, this means that the number in the TRC column still holds.

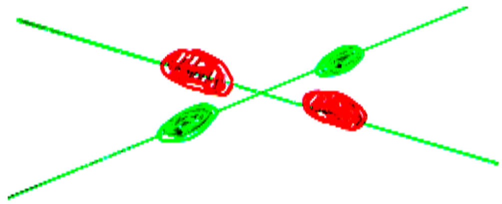
**Numbers in ( ) under JLC/NLC correspond to 100 Hz repetition rate; numbers in ( ) under CLIC correspond to a 20% dilution in σ_y^* and 5% in σ_x^*.

† For the sake of uniformity, the nominal luminosity is simply defined as $N^2 / 4\pi\, \sigma_x^* \sigma_y^*$ times the number of crossings per second, and in all cases assumes head-on collisions, no hour-glass effect and no pinch. The actual luminosity incorporates all these effects, including crossing angle where applicable. NLC calculations assume crab-crossing.

†† The loaded gradient includes the effect of single-bunch (all modes) and multibunch beam loading, assuming that the bunches ride on crest. Beam loading is based on bunch charges in the linacs, which are slightly higher than at the IP.

Crossing Angle II

„Kink Instability"



→ „residual" em interaction between bunches that have left, or are in front of the IP!

that depends on ΔT_{Bunch}

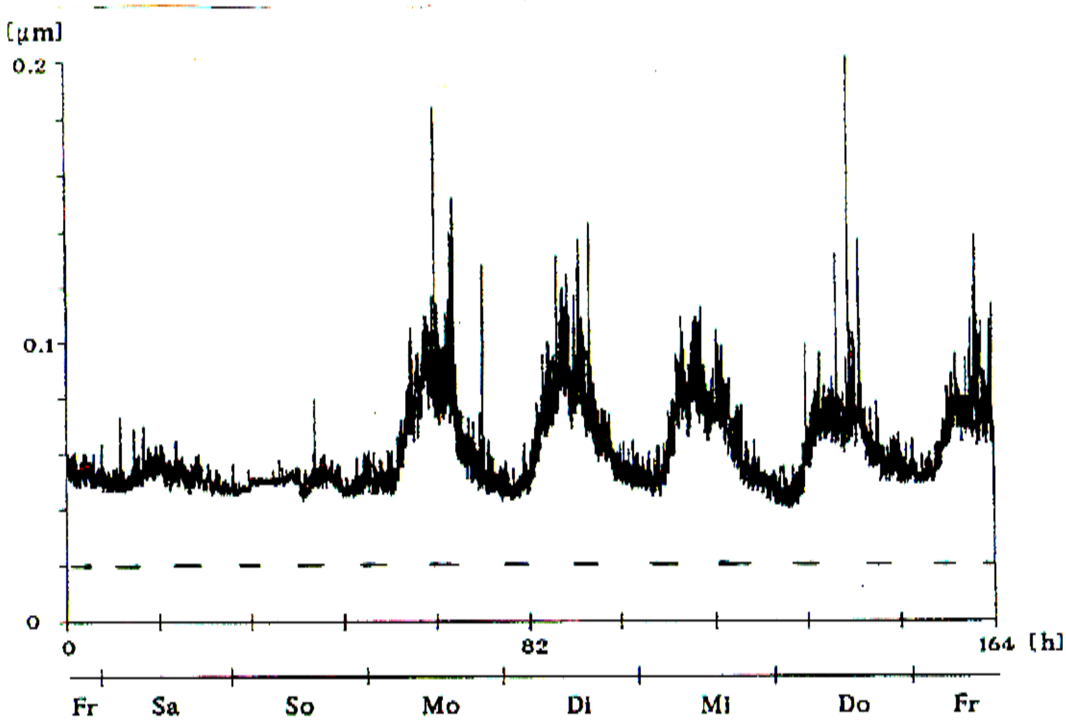
$$\Theta_{cros} \sim \sqrt{\frac{1}{\sigma_z} \times \frac{L_{IP}}{\Delta z_{Bunch}}}$$

$L_{IP} = \Delta$ IP-Quad

TESLA	NLC	CLIC
0	6-8	10 or more

Ground Motion and Quadrupole Vibration

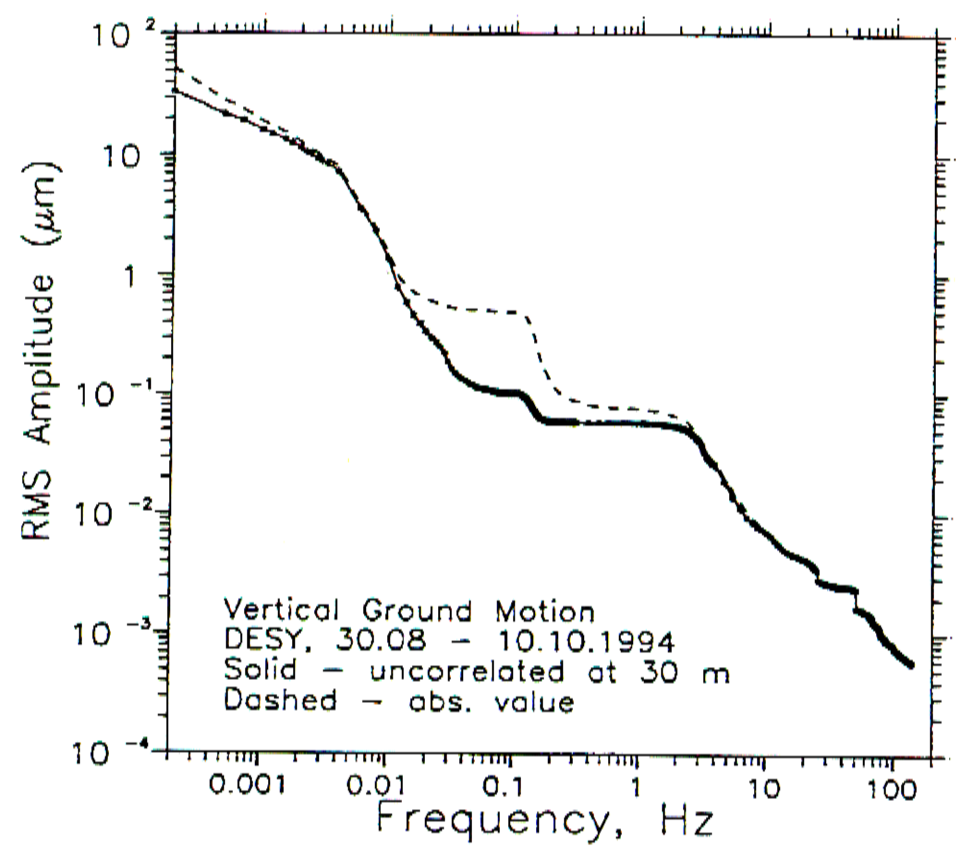
- **Ground motion detoriates the vertical emittance due to quadrupole vibration**
  - natural motion
  - cultural induced motion



Long term measurement of rms–ground motion in the HERA tunnel during 1 week.

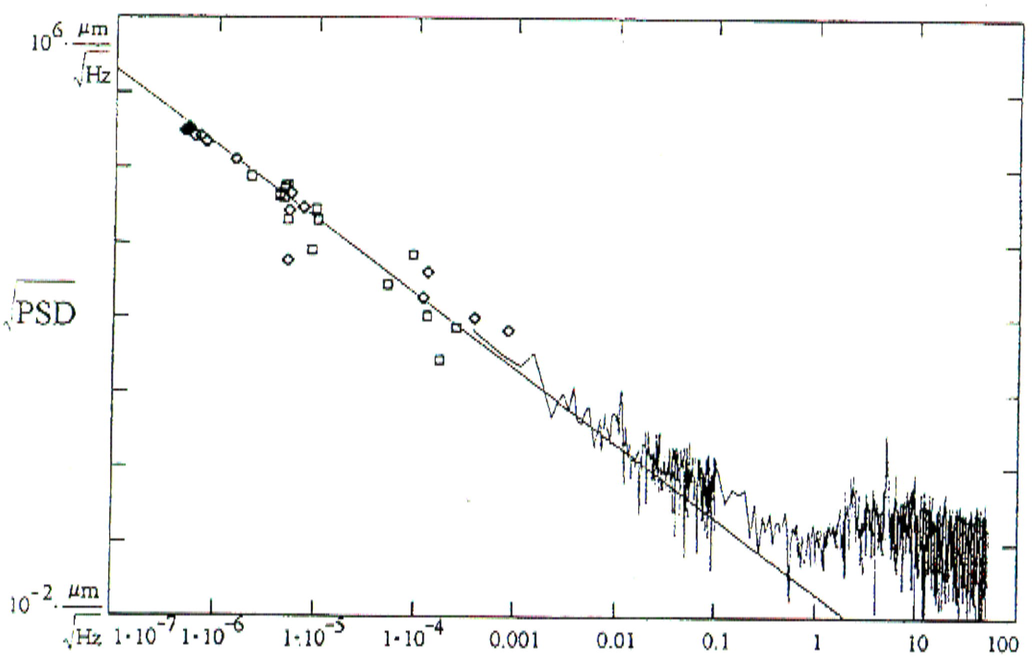
Amplitude & Frequency of Ground Motion

- **In addition to noise:**
  - resonances of supports
  - motion due to operation (water, air, temperature)
- **Possible Remedies depend on the frequency range**
  - passive
  - beam based
  - slow feedbacks



Operation and Long Term Behaviour

- **Is a S-Band Linear Collider operatable?**
  - Compare to operation of HERA in a 6 km long tunnel below the city:
  - data extracted from Orbit drifts and direct measurement over 8 decades in frequency (Brinkmann, Montag, Rossbach, Schiltsev etc)



— Fourier spectrum of one BPM reading at HERAe
◇ HERA rms electron orbit motion after certain time intervals
□ HERA rms proton orbit motion after certain time intervals
— spectrum density scaling as expected by ATL rule

$$\sigma_y = A * Time * Length$$

$$A \sim 4*10^{-6}\ \mu m^2 / m / sec$$

ATL says!

$$\Delta y^2 = A \times T \times L$$

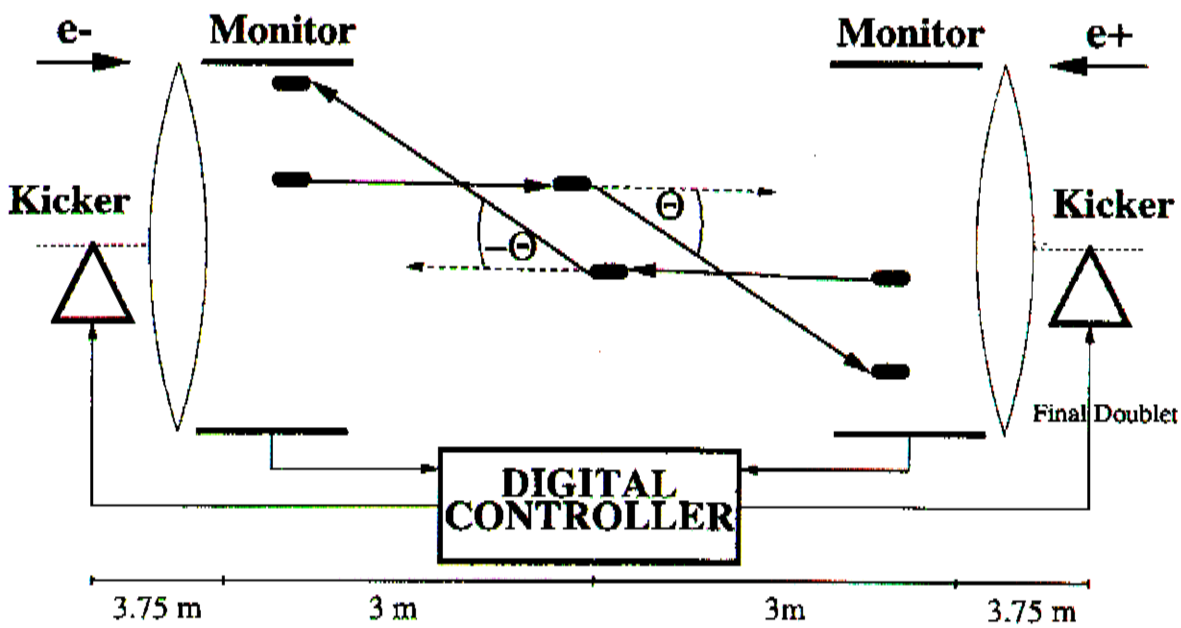
How to Determine The Mechancial Tolerance for the IP Magnets

- **Vibration Frequencies < (1/10 x) the repetition rate**
  - TESLA: < 0.5 Hz   S-Band: <5 Hz
  - slow drift from puls to puls
  - puls to puls feedback
- **Vibration Frequencies > (1/6 x) the repetition rate**
  - Amplitudes: TESLA: 70 nm   S-Band: nm
  - Correction within the bunch train
- **Method of Correction:**
  - Measure orbit kick due to beam - beam force at IP
  - Correction kicker in front of the IP
  - Assumption: Accelerator is mechanically stable (stiff) on the time scale of a beam puls !
  - TESLA: 800 μsec   S-Band: 2 μsec

TESLA System

even more fancy:

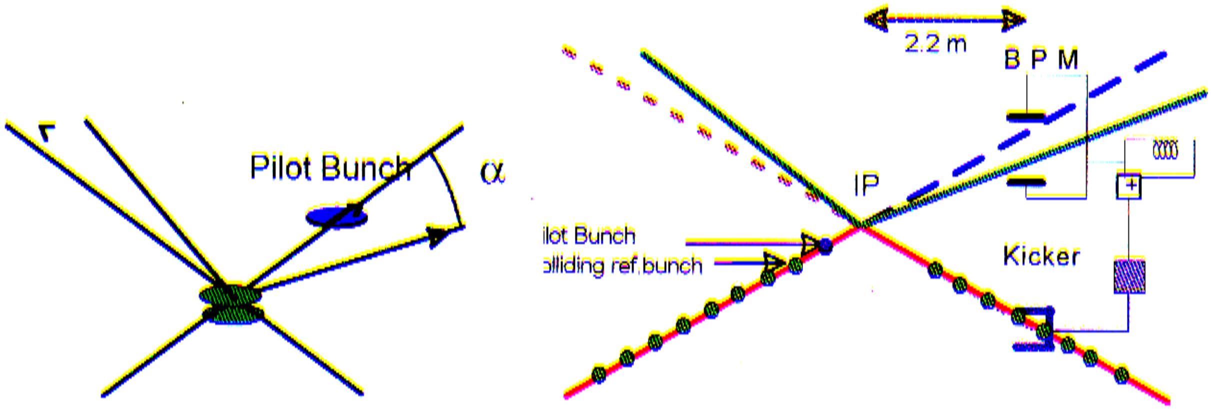
- 2 pick ups ⤳ does not need pilot bunch
- more precise ⤳ BW ⤳ „Peanuts"
  $\approx \frac{1}{300 ns} = 3 MHz$



Interaction Region Feedback

- **Bunch train length > travel distance between IP an Kicker**
  - use of pilot bunch
  - kicker close to BPM
- **To correct 10x σ_y=150nm x'~0.070μrad**

$$\alpha\,[\mathrm{mrad}] = \frac{\Delta y}{\sigma_y} \cdot 0.057 \cdot \mathrm{mrad}$$



ideal beam orbit
orbit due to beam beam kick

orbit of pilot bunch
orbit of colliding bunch; no feedback
orbit of colliding bunch with feedback

"Minimum" reaction time:

-> travel distance of signal -> 2x(IP <-> Pickup) + (Processing + Bandwidth of FB) + (Kicker Rise time)

-> $\Delta T_{react} \approx$ 20nsec + 20nsec + 10nsec ≈ 50 nsec! TESLA + S-Band!

Beam Delivery System

Vertical spot size dilution at IP from spurious vertical dispersion in the Final Focus system:

$$\frac{\Delta\sigma_y}{\sigma_y} \approx \frac{1}{2} \cdot \frac{\sigma_E^2 D_y^2(IP)}{\sigma_y^2} = \left(\frac{\sigma_E}{\sigma_y}\right)^2 \cdot \delta_y^2 \cdot F_{optics}$$

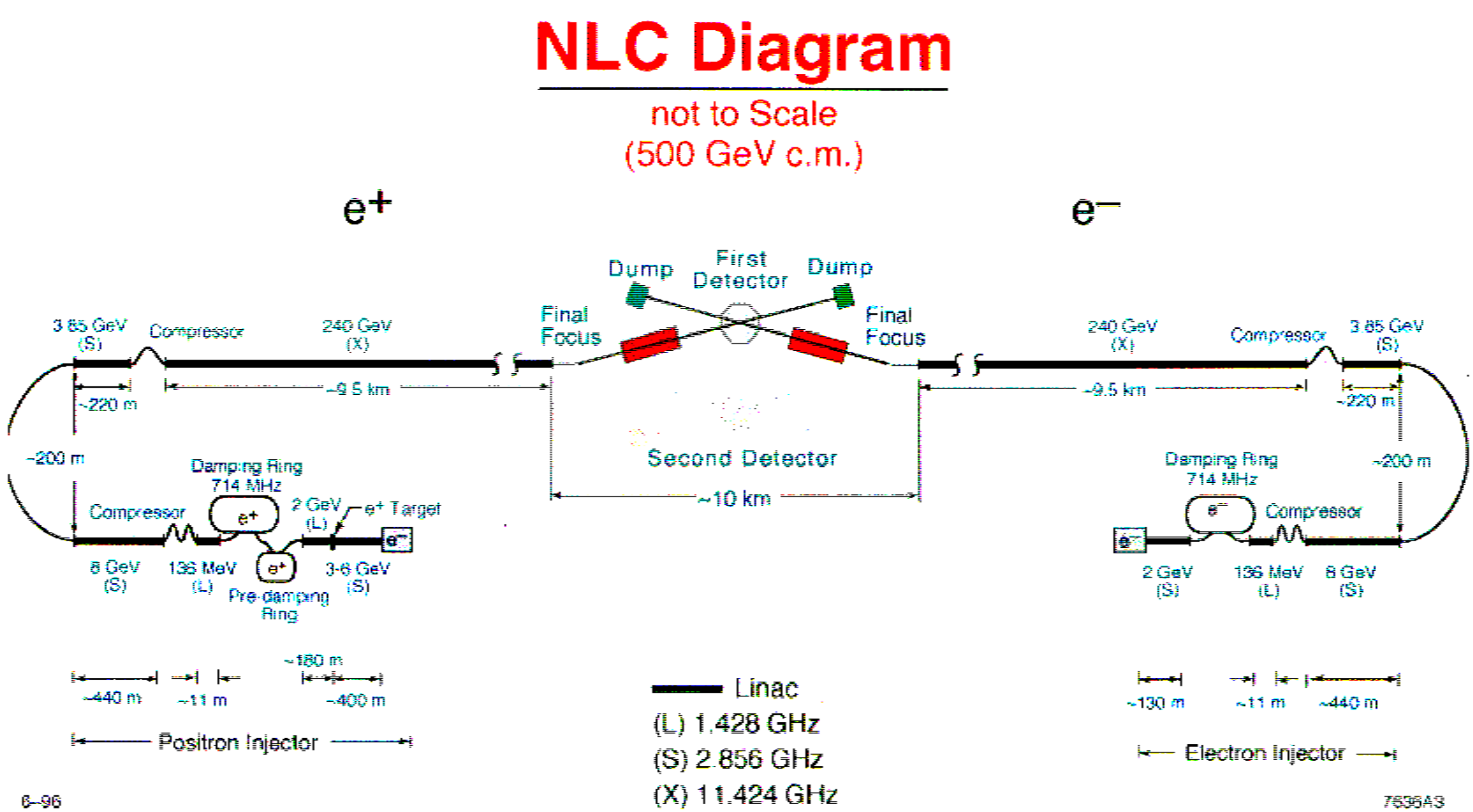
"figure of merit" → $\left(\frac{\sigma_E}{\sigma_y}\right)^2$

tolerances → δ_y^2

	TESLA	SBLC	X-band
energy spread σ_E [%]	**0.06**	0.3	0.3
spot size σ_y [nm]	**19** (5)	15	4…6
f.o.m. [a.u.]	**1** (15)	40	~400

CLIC ~ 1%

- position tolerances scale as 1/sqrt(f.o.m.)
- time between orbit corrections scales as 1/f.o.m.


NLC Diagram
not to Scale
(500 GeV c.m.)
e+
e−
Dump
First Detector
Dump
Final Focus
Final Focus
3.85 GeV (S)
Compressor
240 GeV (X)
~9.5 km
~220 m
~200 m
Damping Ring 714 MHz
Compressor
2 GeV (L)
e+ Target
8 GeV (S)
136 MeV (L)
3-6 GeV (S)
Pre-damping Ring
~180 m
~440 m
~11 m
~400 m
Positron Injector
Second Detector
~10 km
Linac
(L) 1.428 GHz
(S) 2.856 GHz
(X) 11.424 GHz
240 GeV (X)
Compressor
3.85 GeV (S)
~9.5 km
~220 m
Damping Ring 714 MHz
~200 m
Compressor
2 GeV (S)
136 MeV (L)
8 GeV (S)
~130 m
~11 m
~440 m
Electron Injector
6–96
7636A3

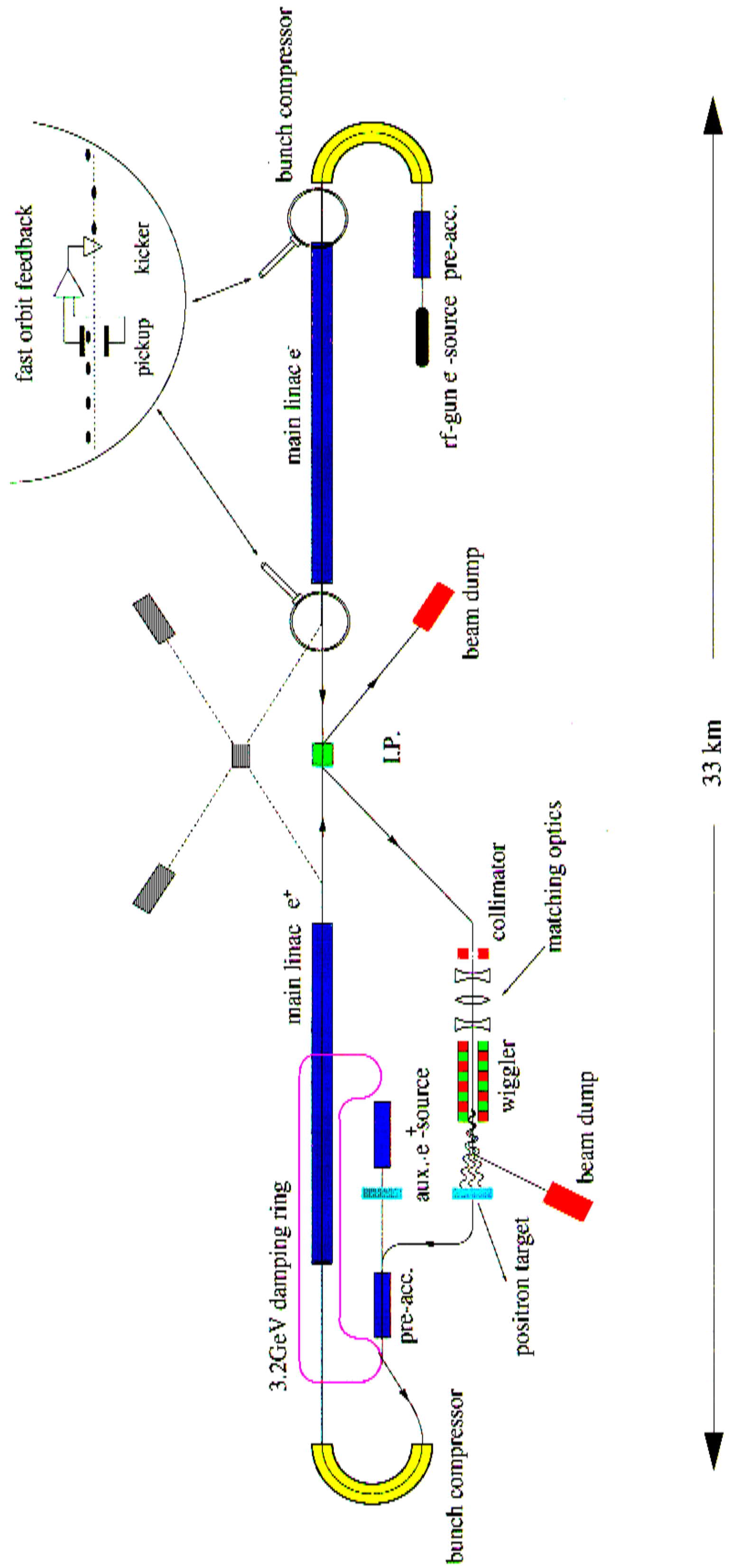


Figure 3.1.4: *Sketch of the overall layout of TESLA.*

Statement about Cost Optimisation

- very old and not from me !

$$V_{tot} = const. \sqrt{R'_{sh} \times \hat{P} \times L}$$

- R_{sh} = shunt impedance/m ; $\sim f^{1/2}$
  only F dependant Value
- $\hat{P}$ = total Peak Power ; $N \cdot \hat{P}_{klystron}$
- L

You can make more V_{tot} by: increasing $\hat{P}$ → RF cost
increasing L → linear cost tunnel, vacuum

Optimum for given V_{tot} : $\hat{P}_{cost} \equiv L_{cost}$

(1) "This statement is completely independent of frequency!"

(2) "This statement is true for any V_{tot}"

(1) → we are fighting this out right now

(2) „TESLA for low energy + CLIC for high energy" is a completely misleading statement
or there are other boundary conditions which do not care about cost!
- tunnel length, site boundary, crossing borders etc.....

"2nd Statement about Costs"

- As you go up in Frequency you have a lot more to do to:
  - make the beam
  - to keep it stable
  - to bring it to the IP

Upgrades + Upgrade Scenarios

... how do I get to: n x 1 TeV

(A) Straightforward: SLAC -> SLC
NLC I -> NLC II -> NLC III

"increase the peak power"

- SLED, better klystrons, more $\bar{P}$ ...

X-Band is probably ok.

(B) assume a: "two beam accelerator"

"take the "small" Linear Collider" and make a drive beam!

then: η for P_{rf} $\sim \left(\frac{F_{main\ Linac}}{F_{drive}} \right)^2$ (... stored energy)