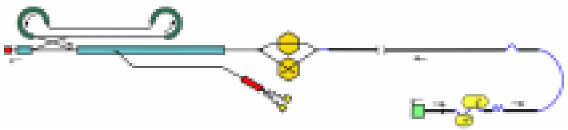
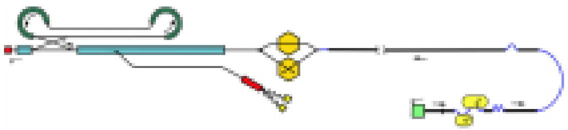


Linear Collider Luminosity

R. Brinkmann, DESY

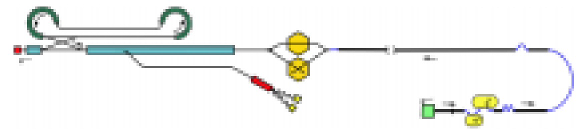
LC Workshop Chicago, Jan. 7-9, 02



Acknowledgement

- Most of what will be presented here is work done by other colleagues in the different LC design groups worldwide. I am grateful for numerous fruitful discussions and exchange of information and ideas over the past years.

- This is a brief summary of some aspects regarding luminosity for both “warm” and “cold” LC’s. A much more comprehensive performance comparison is presently worked out by the International Linear Collider Technical Review Committee (“Greg Loew Committee”).

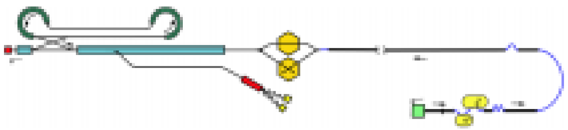


Basic limitations and scaling

- Beam power – determined by reasonable max. wall plug power $\boldsymbol{P_W}$ and transfer efficiency $\eta_{AC\rightarrow beam}$
- Beamstrahlung – energy loss δ_B and background at IP
- Beam emittance – need to ***generate*** and ***preserve***!

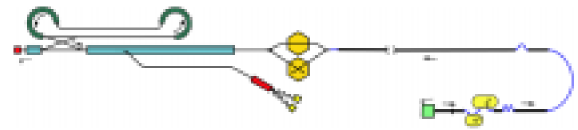
$$L = f_{coll} \cdot \frac{N_e^2}{4\pi\sigma_x\sigma_y} = \frac{1}{4\pi E_{cm}}\left[f_{rep} n_b N_e E_{cm}\right] \cdot \frac{N_e}{\sigma_x} \cdot \frac{1}{\sigma_y}$$

$$\propto P_W \cdot \eta_{AC\rightarrow beam} \cdot H_D \cdot \left. \frac{\sigma_z}{\beta^*} \right|^{1/2} \cdot \sqrt{\delta_B} / \sqrt{\varepsilon}$$



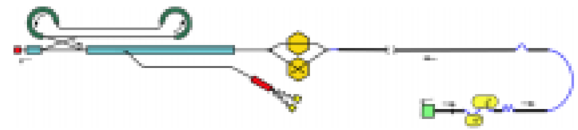
Luminosity challenge: it's only 4 orders of magnitude from the SLC…

	SLC	**X-band / TESLA**	
Energy E_{cm}	100	500 (→ ~1000)	GeV
Beam Power	0.04	6.6 / 11	MW
Spot size at IP	500 (~50 FFTB)	2.7 / 5	nm
Beamstrahlung	0.03	4.7 / 3.2	%
Luminosity	$3{\cdot}10^{-4}$	2 / 3.4	10^{34} cm^{-2} s^{-1}



Efficiency: “warm vs. cold”

	TESLA	NLC
η wall plug → RF	46.8 %	29.8 %
η RF → beam	63.0 %	33.5 %
η wall plug (RF) → beam	29.5 %	10 %
$P_{wallplug}$ for cooling	19.7 MW	(15 MW)
two-linac $P_{wallplug}$	95 MW	132 MW (+15)
two-linac P_{beam}	22MW	13.2 MW
total η wall plug → beam	23.3 %	10% (9)

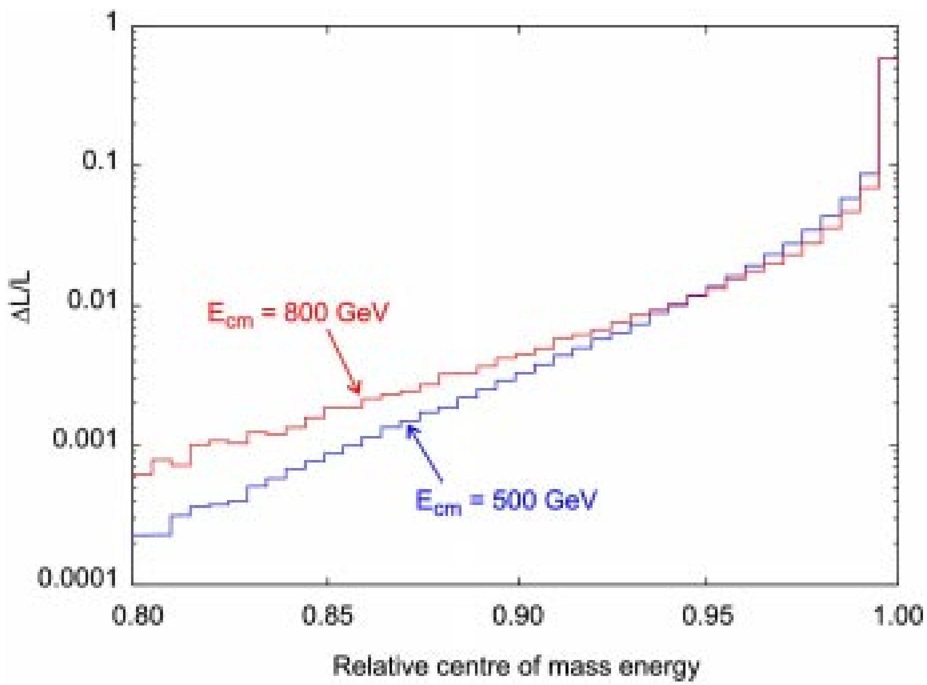


Beamstrahlung and lumi spectrum

$$\delta_B \propto \frac{N_e^2 \gamma}{(\sigma_x + \sigma_y)^2 \sigma_z} \cdot U_1(E_c^{ph} / E_{beam}) \rightarrow \frac{N_e^2 \gamma}{\sigma_x^2 \sigma_z}$$

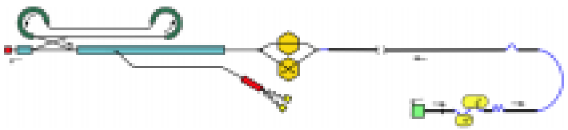
(Flat beam, low E_c^{ph})

Small # γ's per e$^{\pm}$: **$\langle n_\gamma \rangle \approx$ 1…2 ($\propto N_e/\sigma_x$)**

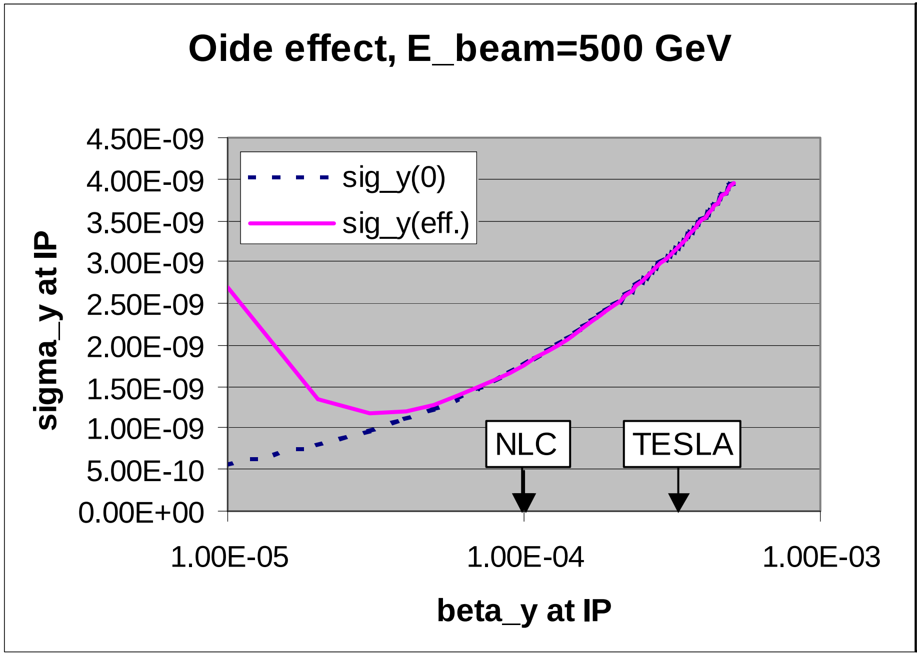


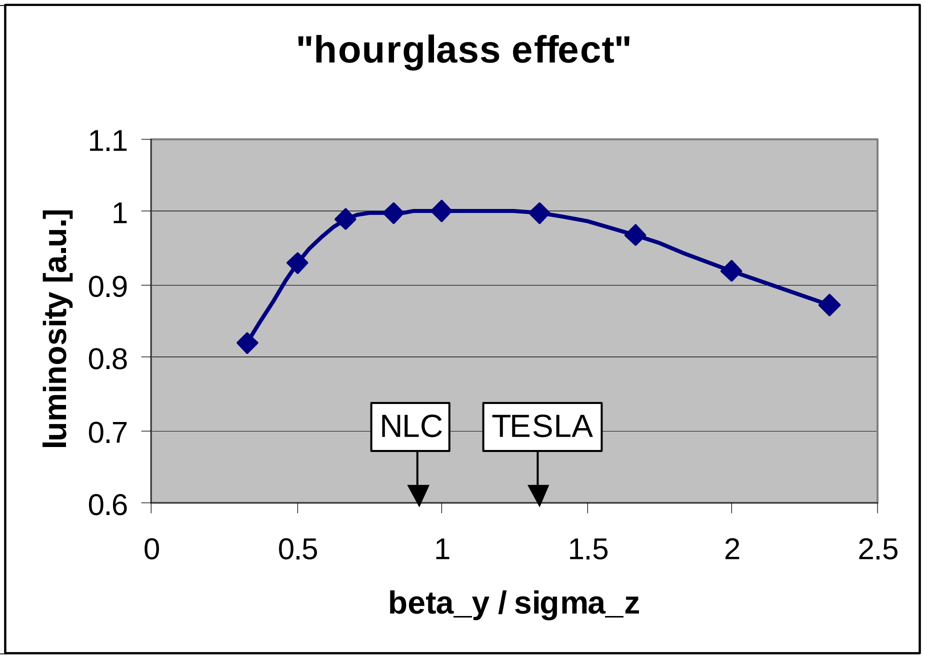
	TESLA500	NLC500
δ_B [%]	3.2	4.7
$\langle n_\gamma \rangle$	1.6	1.2
$\langle \Upsilon \rangle$	0.06	0.11
$L_{99\%}$ [10^{34}]	2.3 (68%)	1.4 (65%)

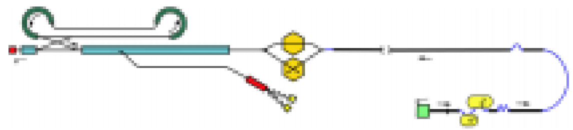
(ISR and $\sigma_{E,beam}$ not included)



Lower limit on β_y^*: synchr. rad. in quads (Oide 1988) and bunch length







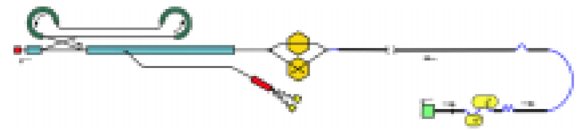
Side remark: all LC's have flat beams – round beams might be nice, too!

- Suppose we could get small hor. emittance $\varepsilon_x = \varepsilon_y$, but with ***unchanged phase space density N_e/ε_x*** , i.e. low bunch charge
- $\rightarrow$ collide round beams with $\beta_x = \beta_y$
- Better relation L vs. δ_B (ideally factor 2 higher L at same δ_B)
- Larger enhancement factor ***$H_D(round) \approx H_D^2(flat)$***
- Single bunch wakefields ***strongly reduced***

Main challenge:

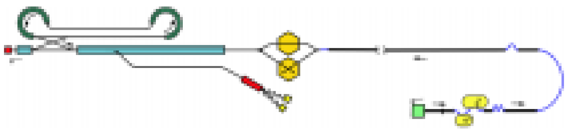
injection system (conventional damping ring doesn't work)

(other issues: very small bunch spacing, triplet at IP, …)

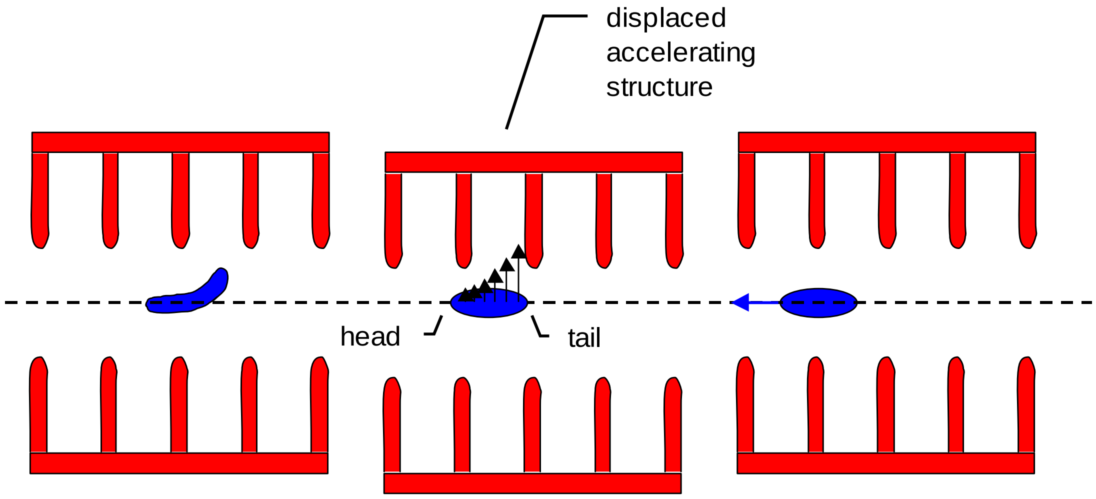


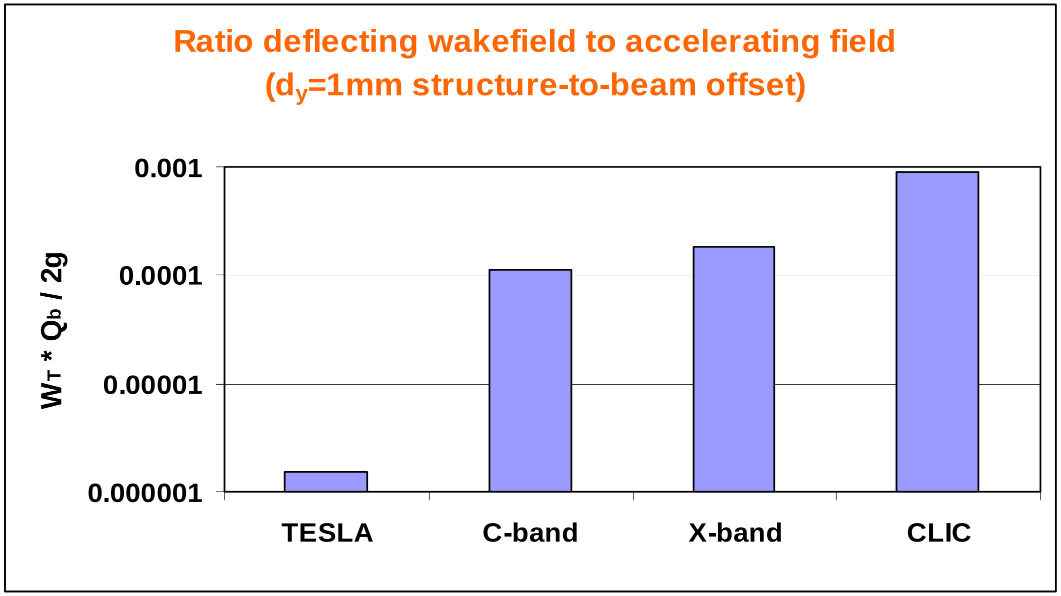
Example round beams: CLIC 3TeV

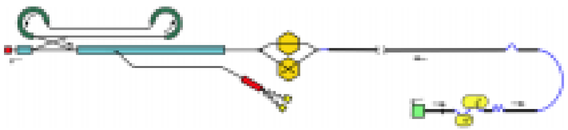
	flat	**round**
N_e	$4\cdot10^{9}$	$2\cdot10^{8}$
Δt_b	0.667ns	0.033ns
$\varepsilon_{x,y}$	$0.68\cdot10^{-6}$m, $2\cdot10^{-8}$m	$2\cdot10^{-8}$m
$\beta_{x,y}$	8mm, 0.15mm	0.6mm
$\sigma_{x,y}$	43nm, 1nm	2nm
σ_z	0.03mm	0.1mm
$D_{x,y}$	0.1, 5.2	4.7
δ_B	31%	28%
$<\Upsilon>$	8.3	2.5
H_D	2.1	4.1
L	$9.6\cdot10^{34}$	$10\cdot10^{34}$
$\Delta\varepsilon/\varepsilon$ single bunch (scaled)	100% (?)	2%



Emittance preservation: main linac

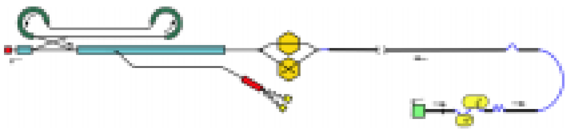






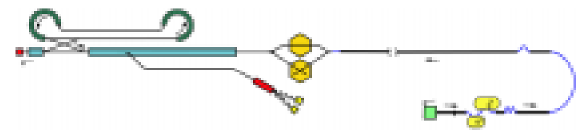
Scaling of W_{trans} helps to understand differences in tolerances – insufficient to understand beam dynamics in detail!

- Accurate alignment inside a cryostat is more difficult than outside
- diagnostics equipment can have better resolution in high-freq. than in low-freq. Linac (BPM's in small vs. large beam pipe)
- Effects causing emittance growth which are not (or not strongly) related to linac frequency (RF kicks, initial beam energy spread)
- High linac rep. rate helps to cope with mechanical vibrations (higher frequency – lower amplitude)
- Limitations on making and preserving small emittance from subsystems other than main linac (e.g. beam delivery)
- More subtle differences: → "banana" effect at IP



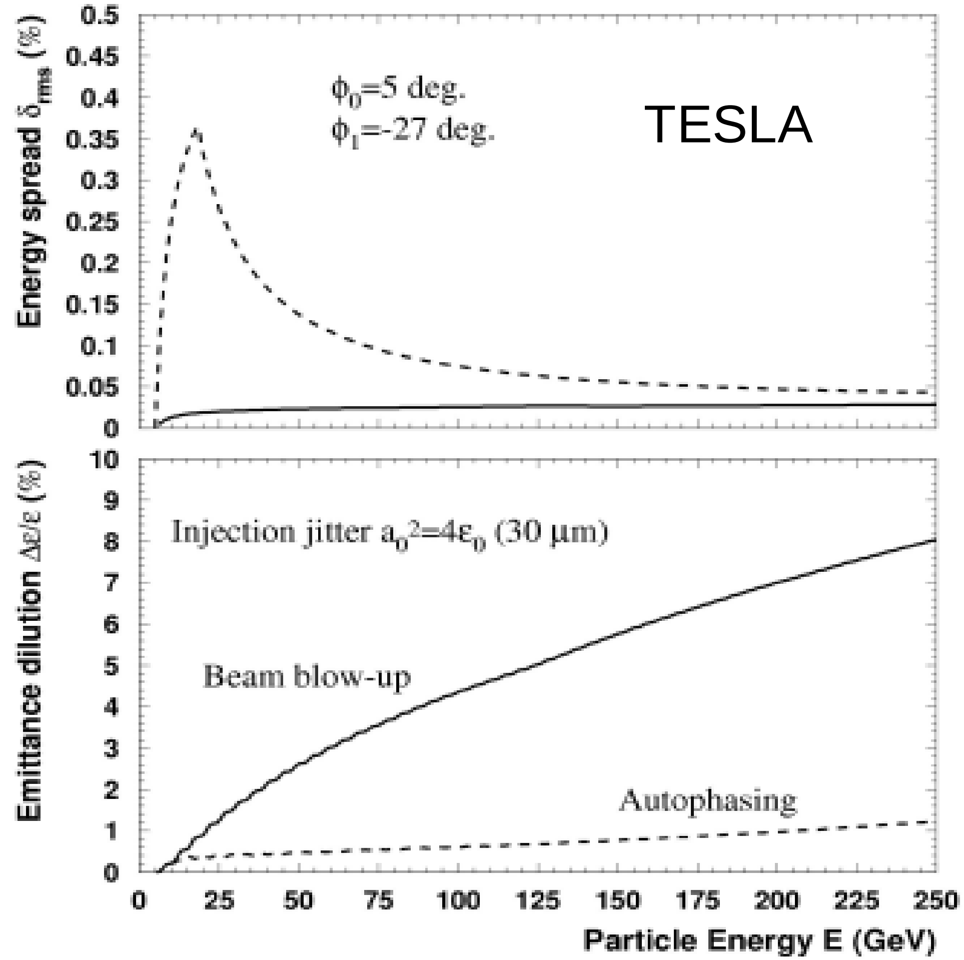
Beam Break-up

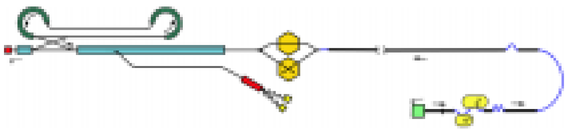
- Head-to-tail defocusing effect of W_{trans} can lead to exponential growth of betatron oscillation amplitude (BBU instability) → apply BNS damping with correlated energy spread dE/E vs. z (autophasing condition cancels wakefield defocusing with chromatic focusing of quadrupole lattice)
- Remaining emittance growth from free oscillation is due to uncorrelated dE/E, filamentation and non-perfect autophasing



• TESLA is not in BBU regime – autophasing still helps to reduce sensitivity to orbit jitter: with expected ~0.5σ pulse-to-pulse jitter → correlated emittance growth $\Delta\varepsilon/\varepsilon$ ~ 0.1%

• NLC requires 0.6% correlated energy spread to avoid BBU

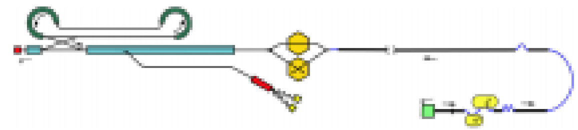




Beam based alignment

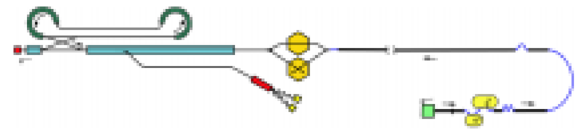
- BPM's can't be pre-aligned along a straight (or: smooth) line with sufficient accuracy → need beam based methods to reduce dispersive emittance growth from random orbit kicks (BPM-to-quad with "shunt" method, DF steering by varying quad strengths or beam energy, …) → effectively replace BPM offset error by ***BPM resolution***

- In strong wakefield regime, active alignment of ***accelerator structures*** is also required (***RF-BPM's*** and ***micro-movers***)



Linac tolerances & emittance growth

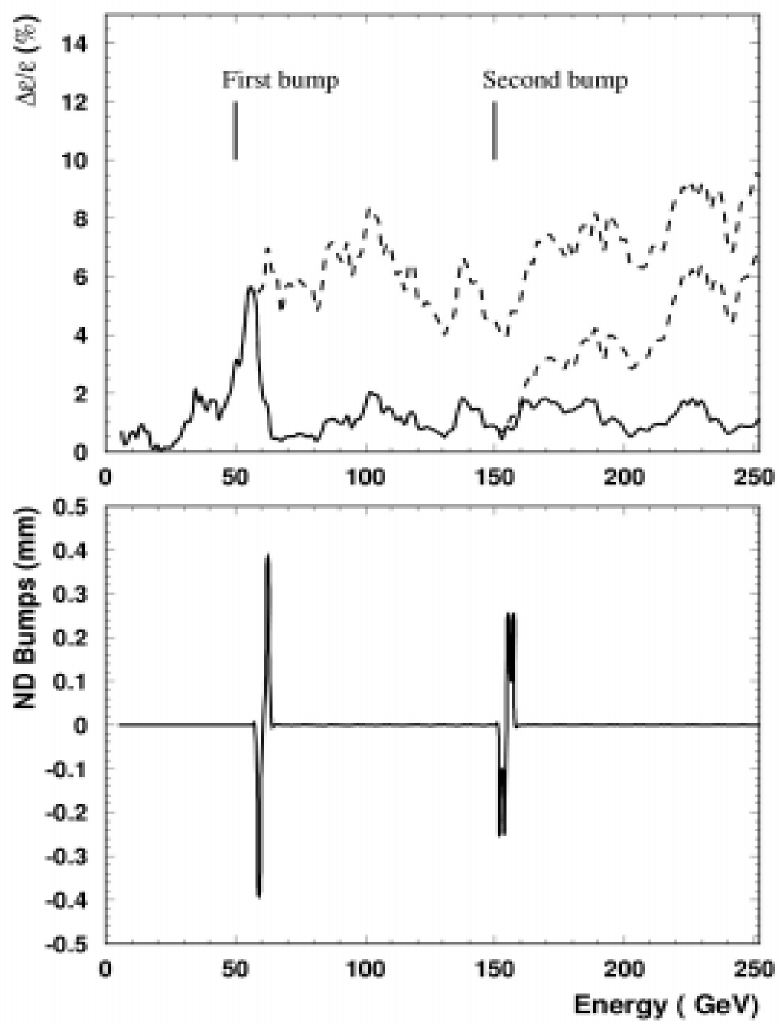
	TESLA	Δε/ε	NLC	Δε/ε
RF structures	300μm	4%	20μm	4%
Girders	200μm	20%	5μm	3%
# of RF BPM's p. linac	-		10,000	
# of micro-movers p. linac	-		1,700	
quad-BPM resolution	10μm	4%	0.3μm	25%
# of quads/BPM's p. linac	360		800	
total Δε/ε (budget DR→IP)		28% (50%)		32% (75%)

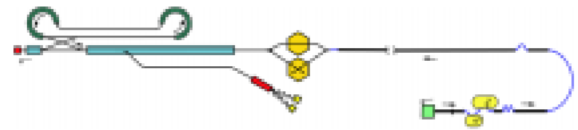


“Plan B”: wakefield and dispersion correction with steering bumps

	TESLA	NLC
Filamentation	~10%	full
# of ε-diagnostic stations	1 (+ lumi)	7 (+lumi)
reduce static emittance growth to	< 2%	< 10%

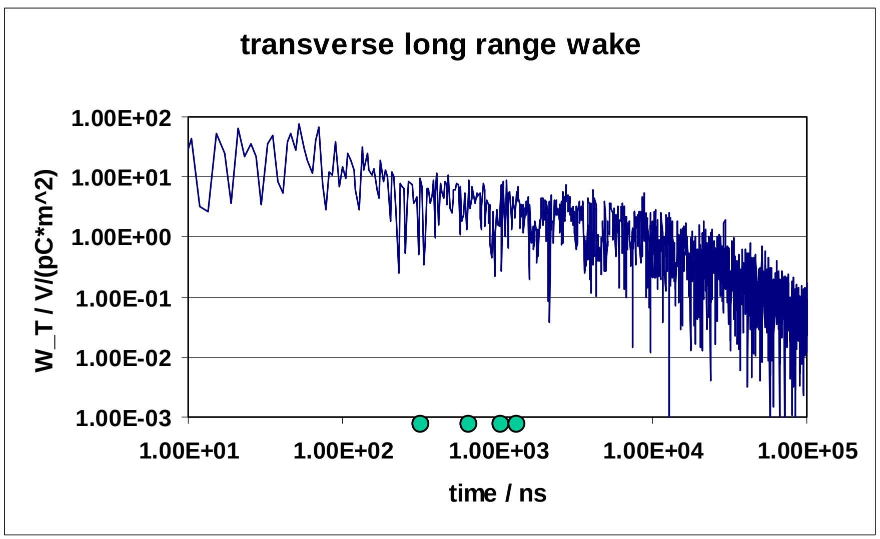
Simulation of wakefield bumps in TESLA →

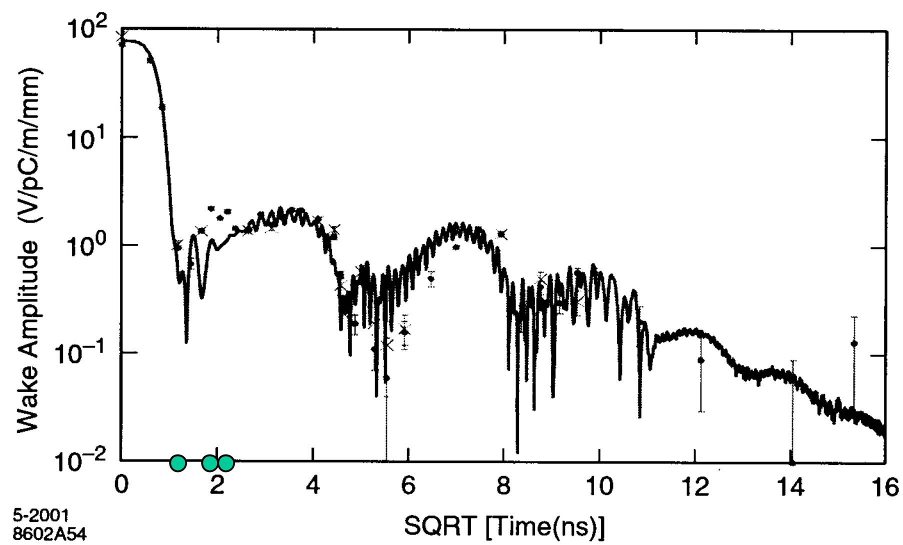




Multi-bunch effects

Avoid HOM-driven BBU by ***detuning*** and ***damping*** → beam stability OK with tolerances specified by single bunch effects

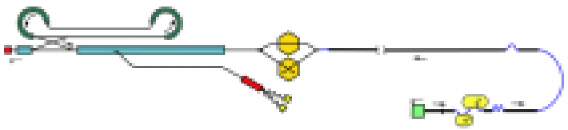




TESLA

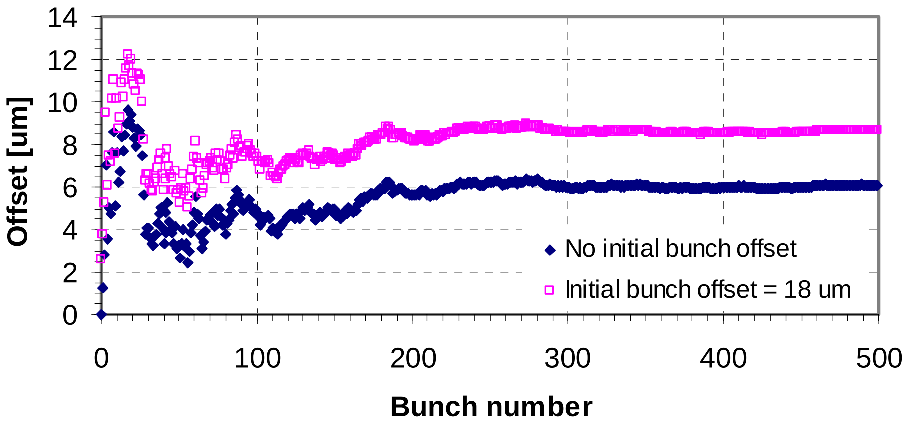
NLC

y-scale factor 10^3



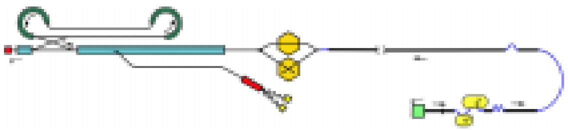
Static part of HOM driven orbit pattern can be removed with fast correctors

TESLA: just program feed-forward table of 3MHz bandwidth intra-train feedback system…



NLC: several stations (filamentation!) with fast kickers (few 100Mhz) required

Orbit motion in TESLA very small compared to cavity alignment errors → HOM pattern is static

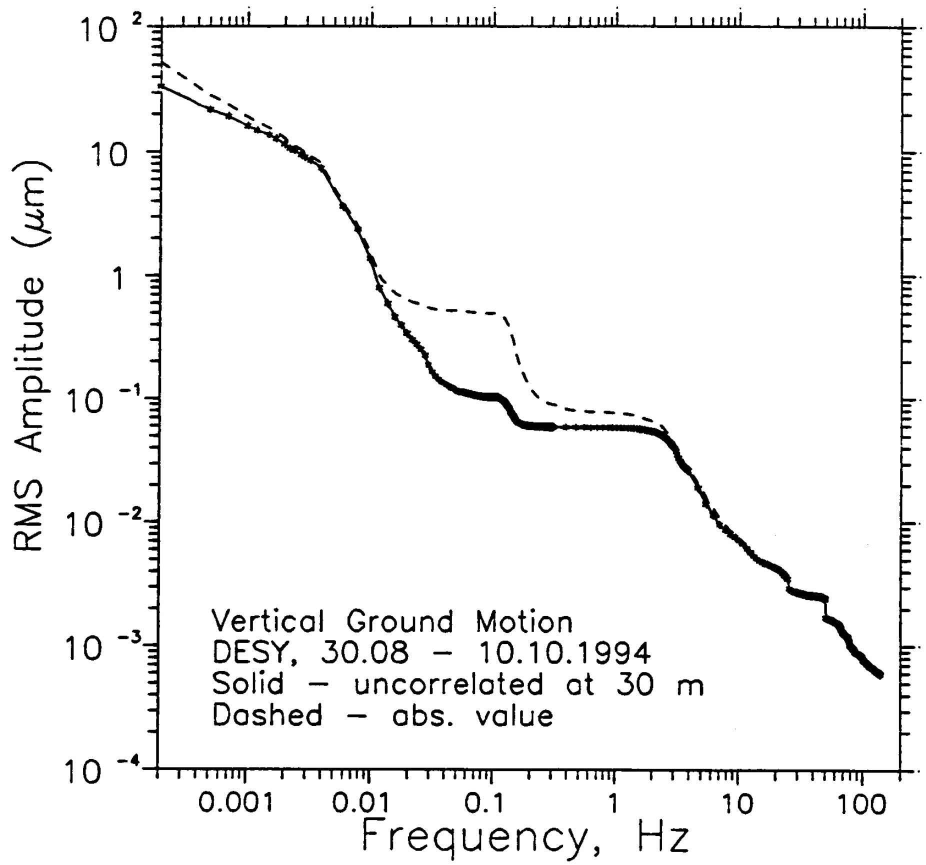


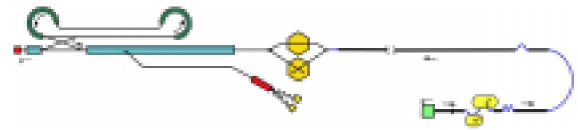
Ground motion

- Model for TESLA derived from HERA ground and orbit motion data

- rms amplitude ~70nm for f>1Hz, essentially uncorrelated

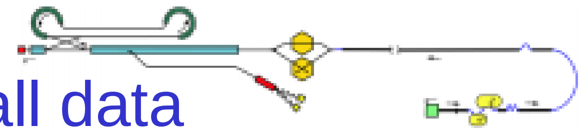
- Large amplitude for f<0.3Hz not critical because of large wavelength & strong correlation





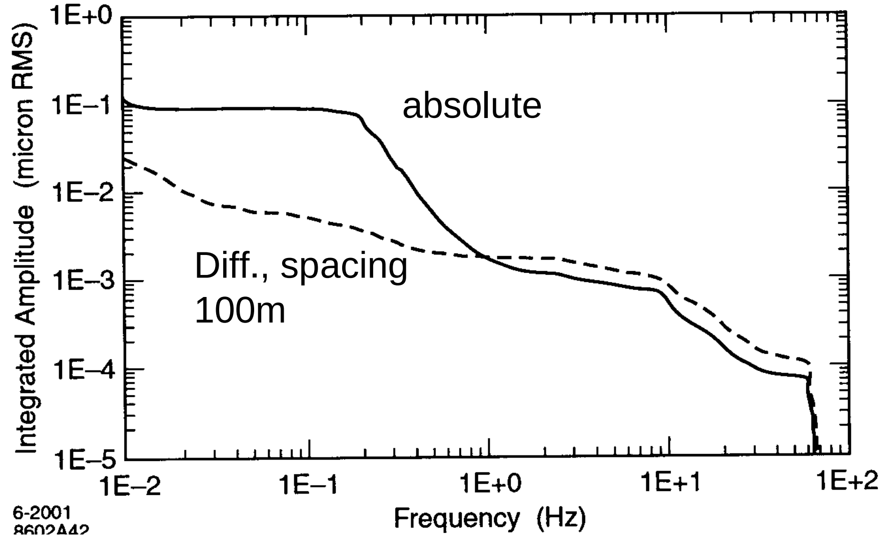
6.3 km HERA ring in Hamburg

Waste processing & power plant

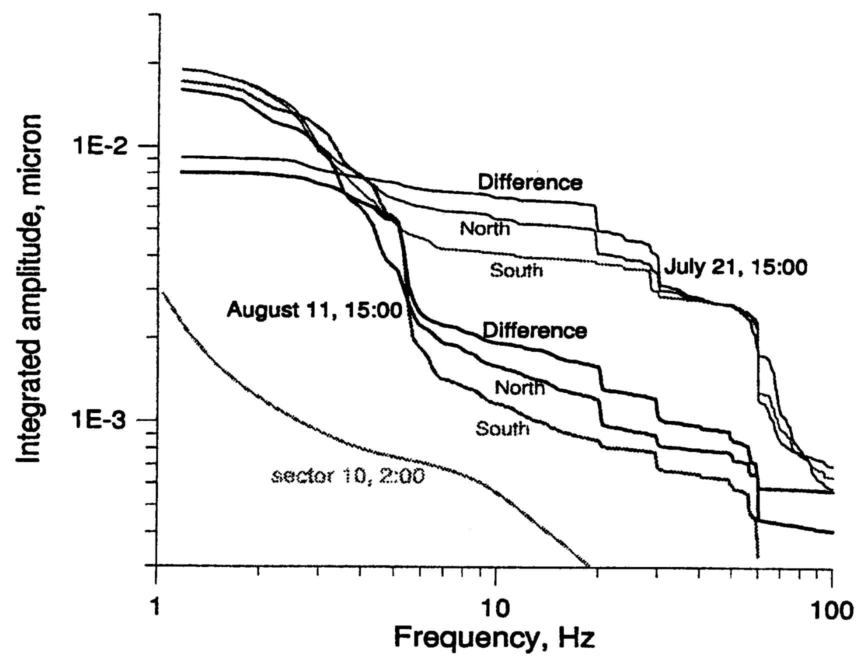


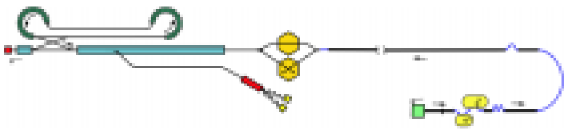
SLAC linac tunnel and SLD hall data

- Correlation vs. frequency similar as at HERA, but amplitudes smaller by factor 10…50



- Amplitudes increase in SLD hall by factor ~5 due to infrastructure (cooling, ventilation)





Slow diffusive motion

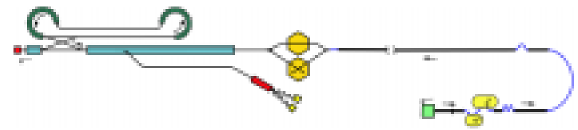
$$\langle \Delta y^2 \rangle \approx A \cdot T \cdot L$$

- HERA model, from orbit drift data (minutes to weeks):

$$A = 4 \cdot 10^{-6} \mu m^2 (m \cdot s)^{-1}$$

- SLAC model from linac tunnel and FFTB measurements:

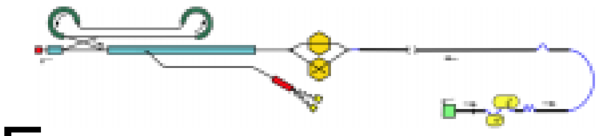
$$A = 5 \cdot 10^{-7} \mu m^2 (m \cdot s)^{-1}$$



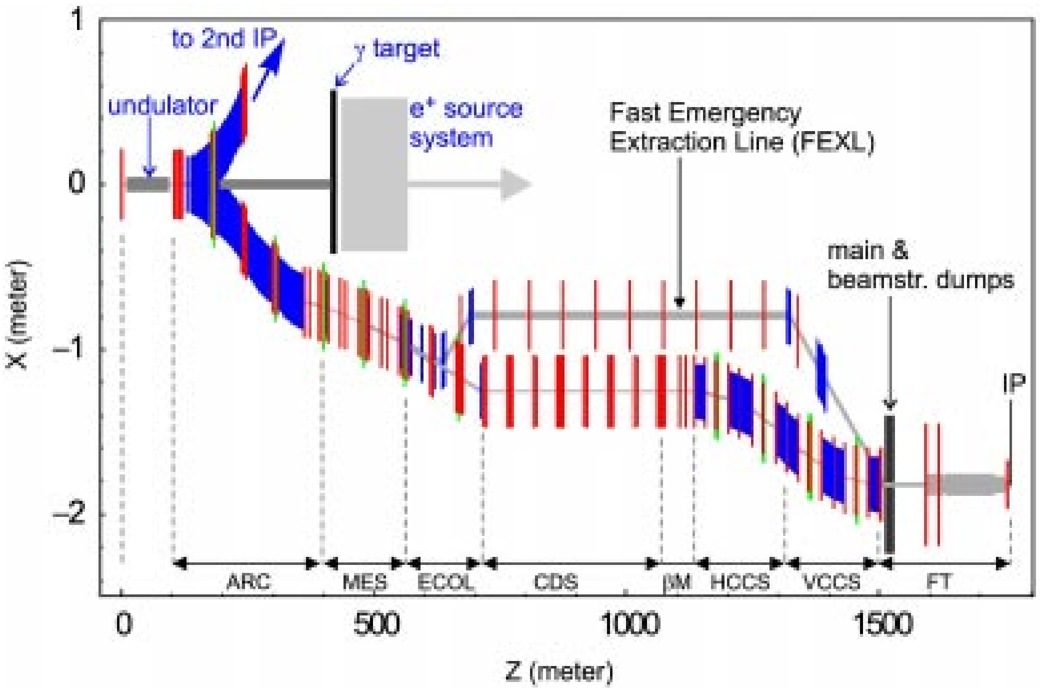
Linac quadrupole position errors from ground motion
(SLAC and HERA models)

	TESLA			NLC		
	HERA	**SLAC**	**tolerance**	**HERA**	**SLAC**	**tolerance**
quad jitter 10Hz	(not relevant)			8nm	0.5nm	10nm
quad jitter 1Hz	70nm	2nm	200nm	70nm	2nm	~few 10nm
quad alignment $1h^{-1}$	1.2µm	0.4µm	10µm	0.6µm	0.2µm	2µm
orbit feedback	intra-train at end of linac + pulse-to-pulse			pulse-to-pulse, 5 – 10 sections		

Note: temperature drifts, time varying stray fields, etc. may not be negligible!

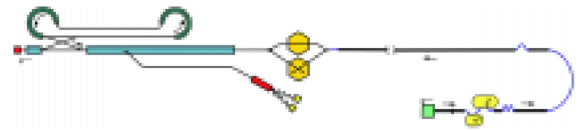


Beam Delivery and Final Focus



TESLA BDS

	TESLA	NLC
$\sigma_{x,y}$ at IP	553nm, 5nm	245nm, 2.7nm
$\beta_{x,y}$ at IP	15mm, 0.4mm	8mm, 0.1mm
type of FFS	FFTB-like	Raimondi
bunch spacing	337ns	1.4ns
correlated σ_E/E	0.05%	0.3%
uncorrelated σ_E/E	0.15% (e-), 0.05% (e+)	0.05%



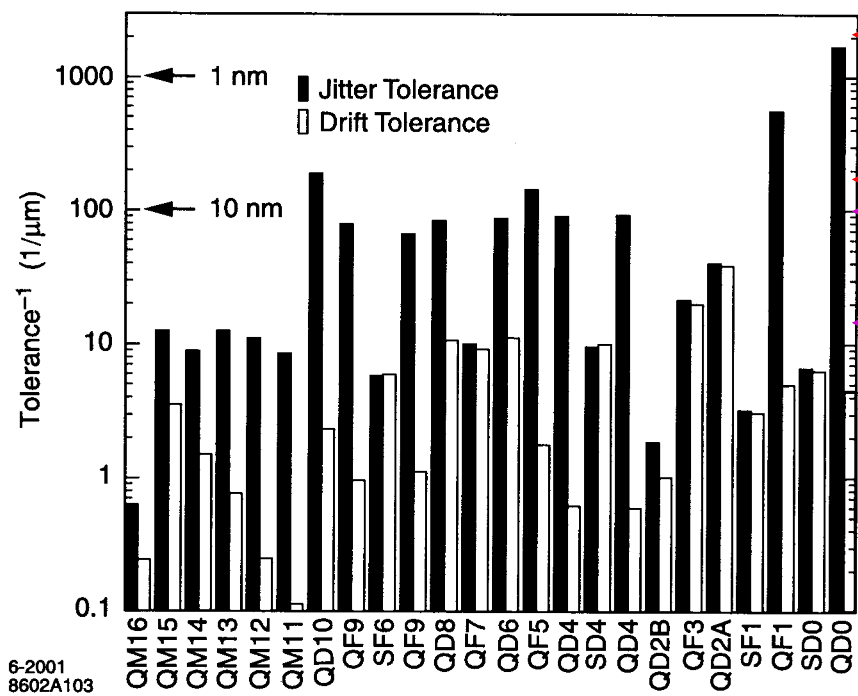
Luminosity Stability

"Jitter": steering at IP

"Drift": spot size at IP

Ground motion 10Hz:

NLC FFS tolerances

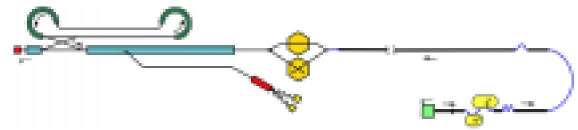


SLAC model

SLD "On"

HERA model

HERA 1Hz

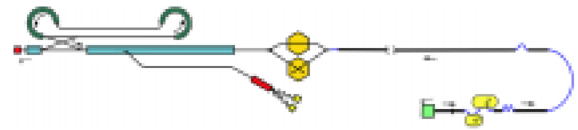


TESLA approach:

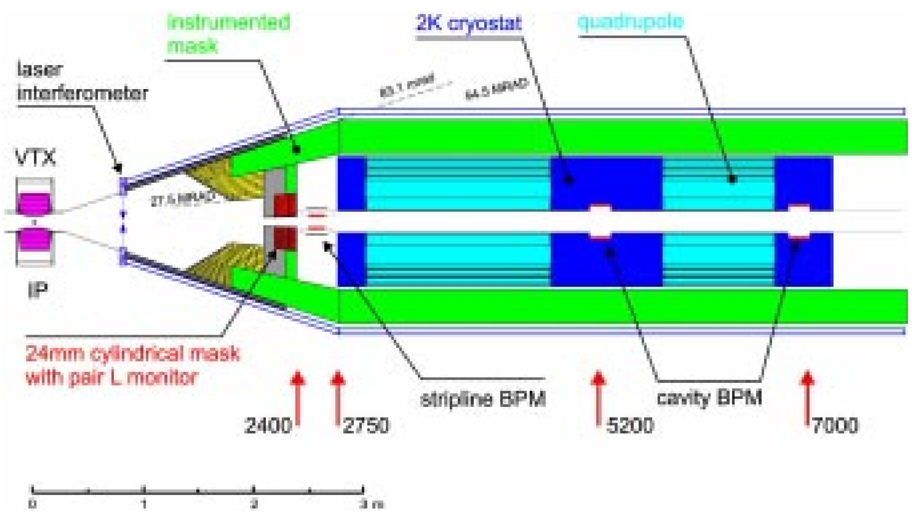
- Stabilize orbit at IP within 0.1σ in offset and angle with fast (3MHz) intra-train feedback
- Active stabilization of supports 70nm→20nm at ~1Hz for few quads *(spot size dilution 15%→1.5%)*
- Maintain spot size within few % with slow (pulse-to-pulse) orbit correction
- Luminosity tuning *(e+e- pair monitor)* by scanning orthogonal knobs within single bunch train ~once a day

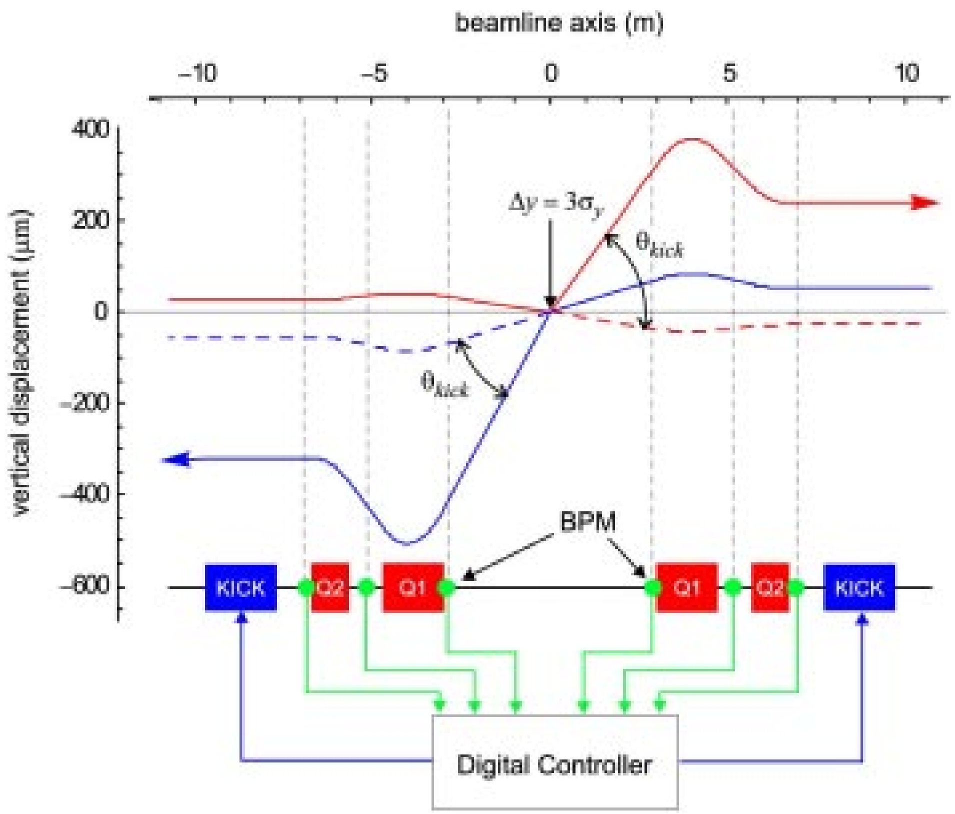
NLC approach:

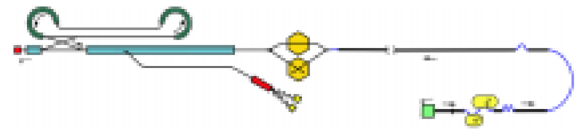
- Stabilize orbit at IP with pulse-to-pulse orbit feedback, rely on small ground motion amplitudes at relatively high frequency
- Maintain spot size within few % with pulse-to-pulse orbit correction *(easier due to rep. rate)*
- Luminosity tuning by scanning orthogonal knobs ~once every few hours
- “Plan B”: active stabilization of Final Doublet and/or very fast IP steering feedback



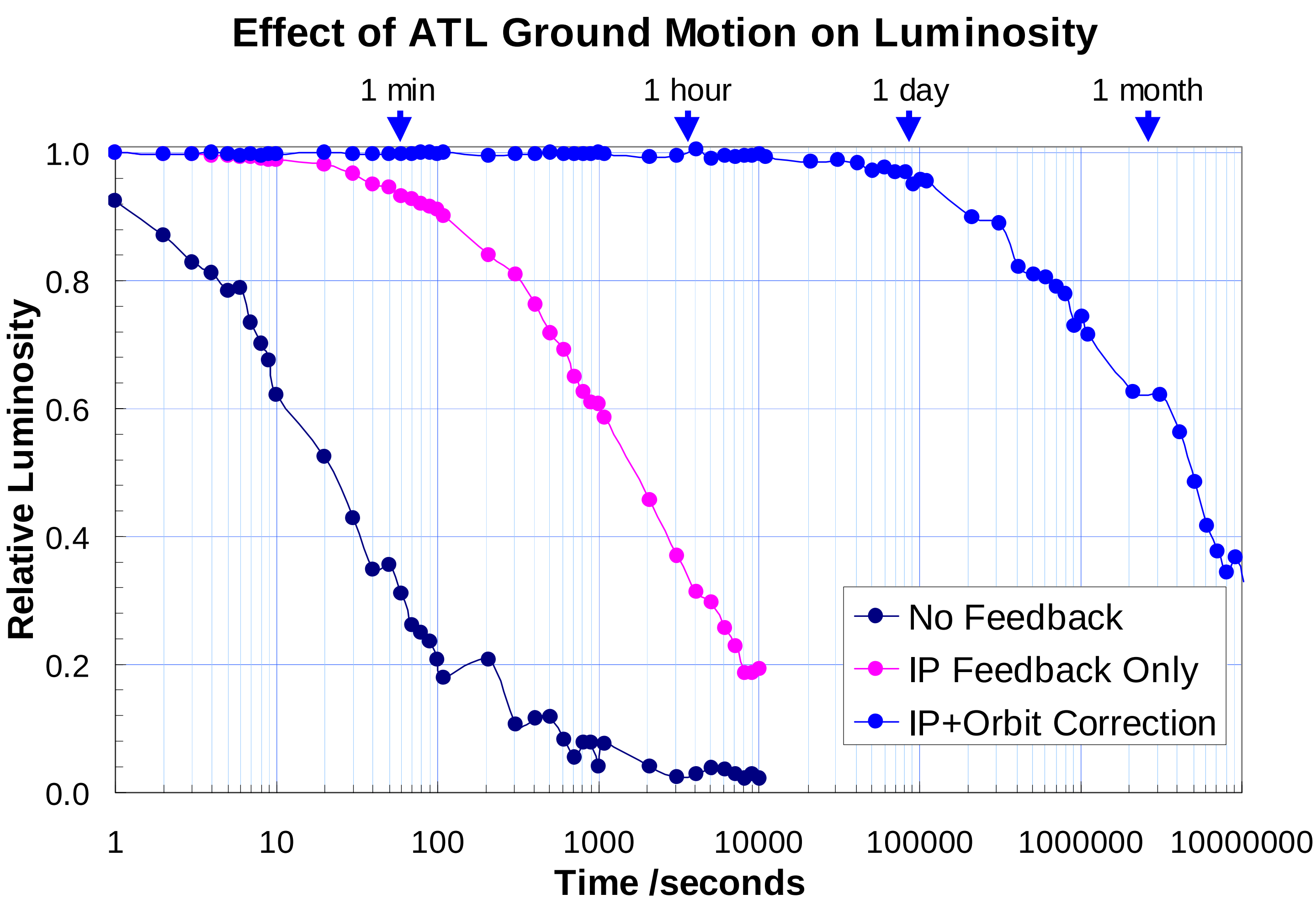
IP steering feedback (TESLA)

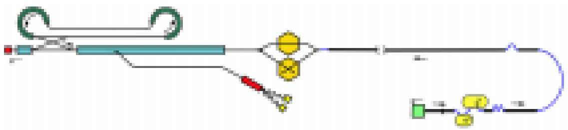






Lumi stability under ATL ground motion (TESLA)





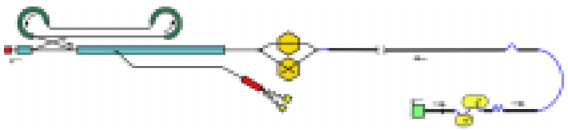
Kink instability and "banana" effect

Y. H. Chin 1987: two-stream instability leads to exponential growth of oscillation amplitude for beams colliding with an offset

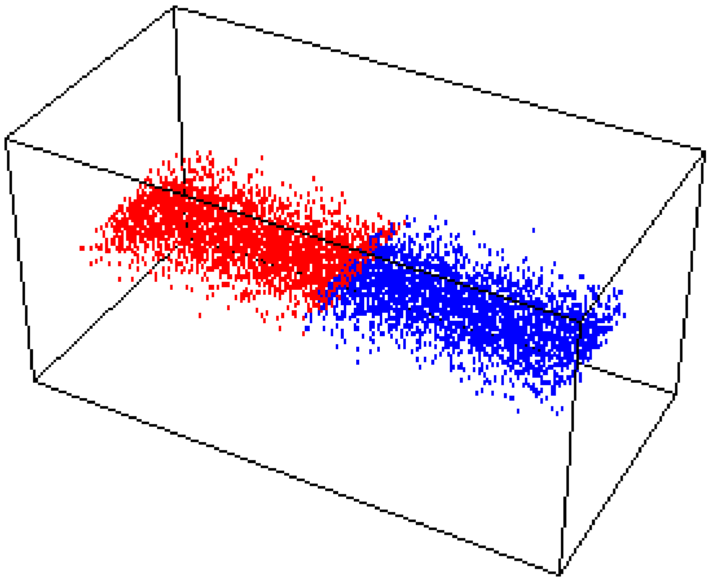
$$y_{e+(e-)}(t;z) = y_0 \exp\left[\omega t \pm i(\sqrt{3}\omega z - \pi/6)\right]$$

$$\omega = \frac{(2\pi)^{1/4}}{\sqrt{24}} \cdot \frac{\sqrt{D_y}}{\sigma_z}$$

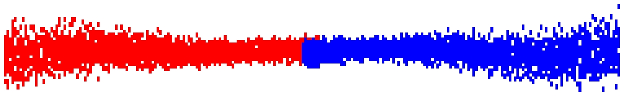
→ Tighter tolerance on IP steering, but even more annoying…



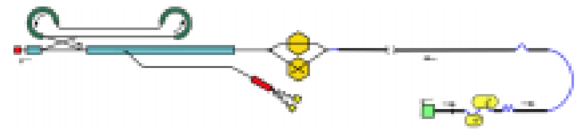
Internal bunch deformations are also amplified – even if initial offsets and angles are zero ***on average***



3-D

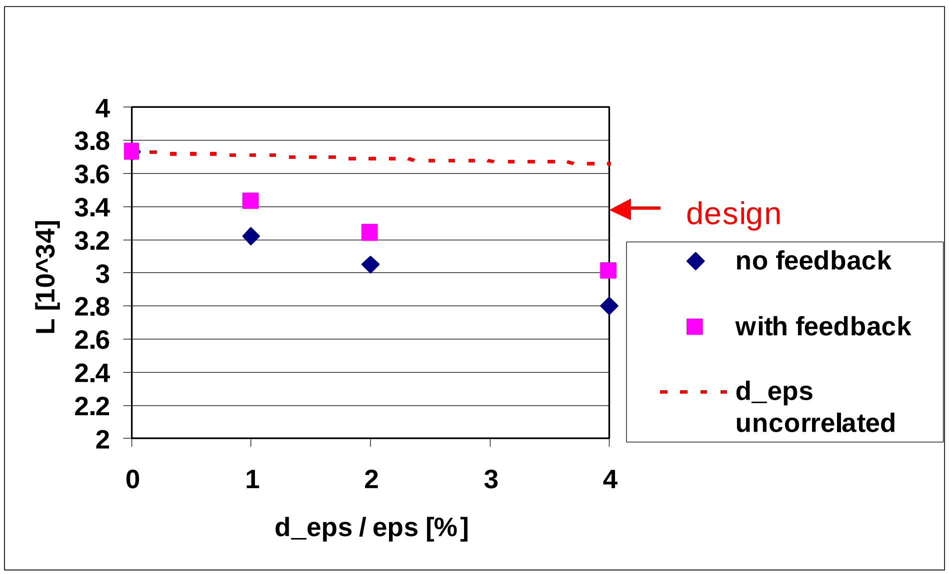


2-D
vertical

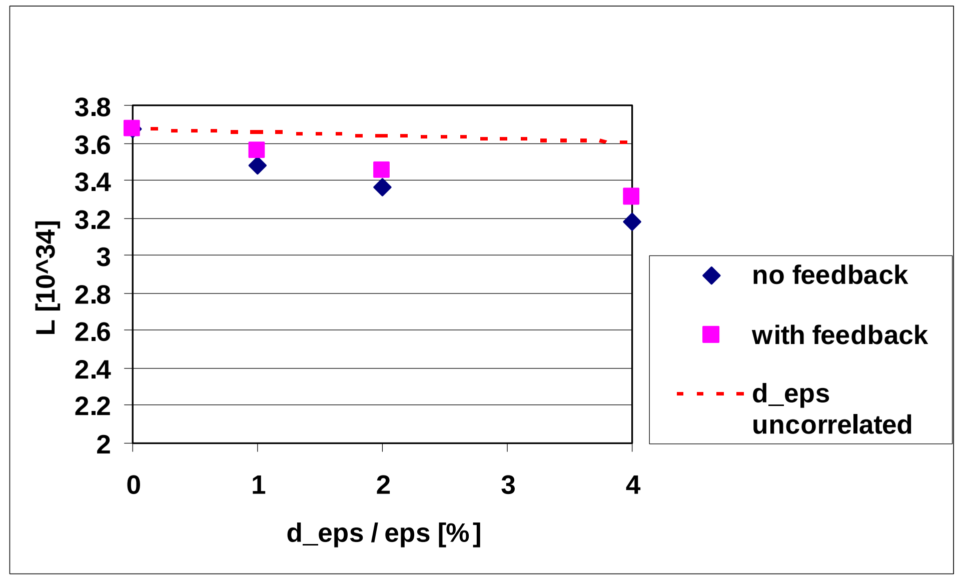


Effect on TESLA luminosity: enhanced sensitivity to ***correlated*** emittance growth

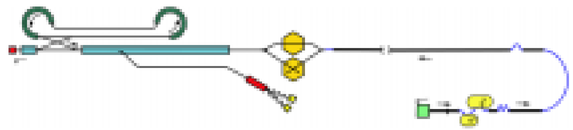
TDR, uncorr. Δε/ε=20%



Shorter bunch, D_y like NLC



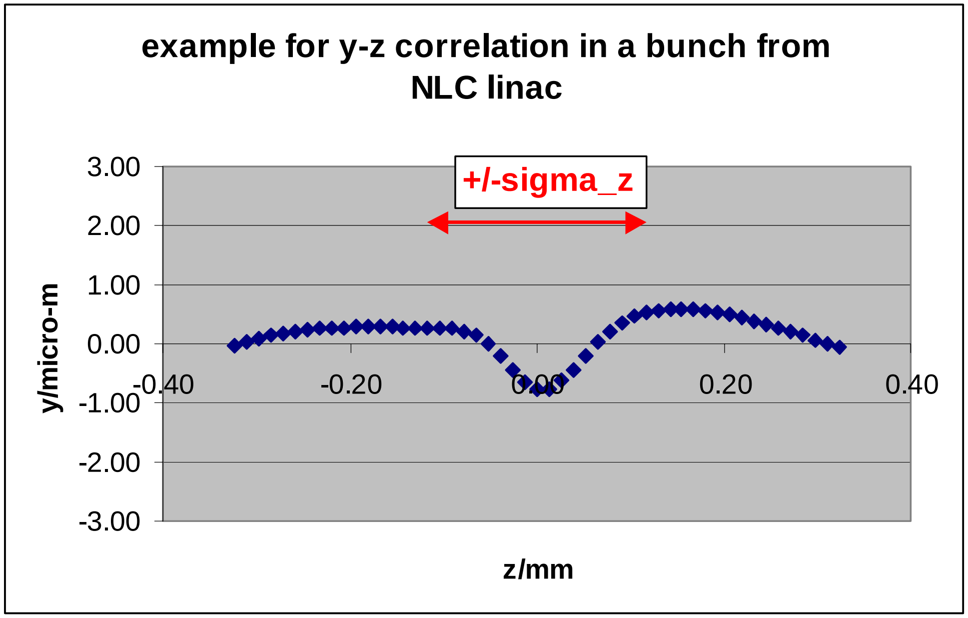
Feedback detects net bunch deflection, depending on relative phase & shape of distortion → steers beam ***as if*** there were an offset at the IP

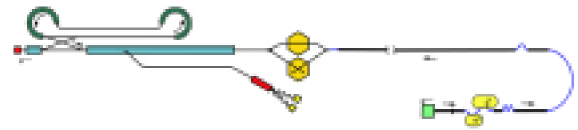


Kink instability could be reduced with shorter bunch 0.3mm → 0.15mm in TESLA; needs 2nd stage compressor, beamstrahlung 3.2% → 3.9%, D_y ~ 14 as in NLC

NLC linac "banana" has shorter "wavelength" → lumi less sensitive (?)

Dispersive aberrations from BDS entirely correlated → lumi more sensitive





Conclusion

- Luminosity goals for TESLA and NLC are both at a ***reasonable upper limit***
- The ***same*** value for *L* (say, NLC design value) is very likely easier to achieve for TESLA
- Beam dynamics in strong wakefield regime well understood, methods to guarantee beam quality well defined
- ***Complexity and accuracy*** of diagnostics and correction equipment for NLC substantially more demanding than for TESLA
- ***Higher rep. rate is a "+"*** for NLC regarding spot size stability in the FFS