Main Linac Beam Dynamics

Kiyoshi KUBO

2006.05.22

(Some slides will be skipped in the lecture, due to the limited time.)

ILC Main Linac Beam Dynamics

- Introduction
- Lattice design
- Beam quality preservation
  - Longitudinal
  - Transverse
    - Wakefield
      - Single bunch, Multi-bunch
      - BBU, Cavity misalignment
    - Dispersive effect
  - Errors and corrections
    - Initial alignment, fixed errors
    - Vibration, ground motion, jitters, etc.

Note

- The hard copy is from very old version, having a lot of mistakes. Please look at the latest version.
- Basics will not be lectured here.
  - Beam optics: What are Emittance, Beta-function, Dispersion function, etc..
  - Wakefield: Definition of wake-function, etc..

  (See lectures yesterday.)
- Numbers quoted here and simulation results shown here may be preliminary.

About Home Work

- There are five exercises
  - Shown as “**HMWK-1**”, “**HMWK-2**”, , , “**HMWK-5**” in the slides
- Choose at least one.
  - two, if possible.

Introduction

- Main Linac is very simple, compare with most of other part of LC.
  - Basically many iteration of a simple unit.
- Some statistical calculations are useful because of the large number of identical components.
- Still, analytical treatment is very limited. And most studies are based on simulations.
  - Even in simulations, approximations are necessary for reasonable calculation time.
    - e.g., 2E10 particles cannot be simulated individually. Detailed treatment of edge fields of magnets and cavities may not be necessary. Space charge can be ignored for high energy beams.
    - “What can be ignored?” is important in simulation.

SKIP

Note on Simulation Codes

A lot of codes exist.

Probably, two kinds:

1. Track macro particles, each have 6 parameters, [x, y, z(or t), px, py, E(or pz)]
2. Track "slices", each have 14 parameters, [x, y, z(or t), px, py, E(or pz), <xx>, <yy>, <xy>, <xpx>, <ypy>, <xpy>, <ypx> <pxpx>, <pxpy>, <pypy>]

Some codes cannot change z of particles in tracking.

(This makes wakefield calculation significantly fast.)

"How accurate" and "How fast" may be correlated. (?)

Code bench marking for ILC is being performed.

Parameter of ILC Main Linac (ECM=500 GeV)

Beam energy	13~15 GeV to 250 GeV
Acc. gradient	31.5 MV/m
Bunch Population	1 ~ 2 $x10^{10}$ /bunch
Number of bunches	<= 5640 /pulse
Total particles	<=5.64 $x10^{13}$ /pulse
Bunch spacing	>= 150 ns
Bunch Length	0.15 ~ 0.3 mm
Emittance x (at DR exit/IP) Emittance y (at DR exit/IP)	8/10~12 $x10^{-6}$ m-rad 2/3~8 $x10^{-8}$ m-rad

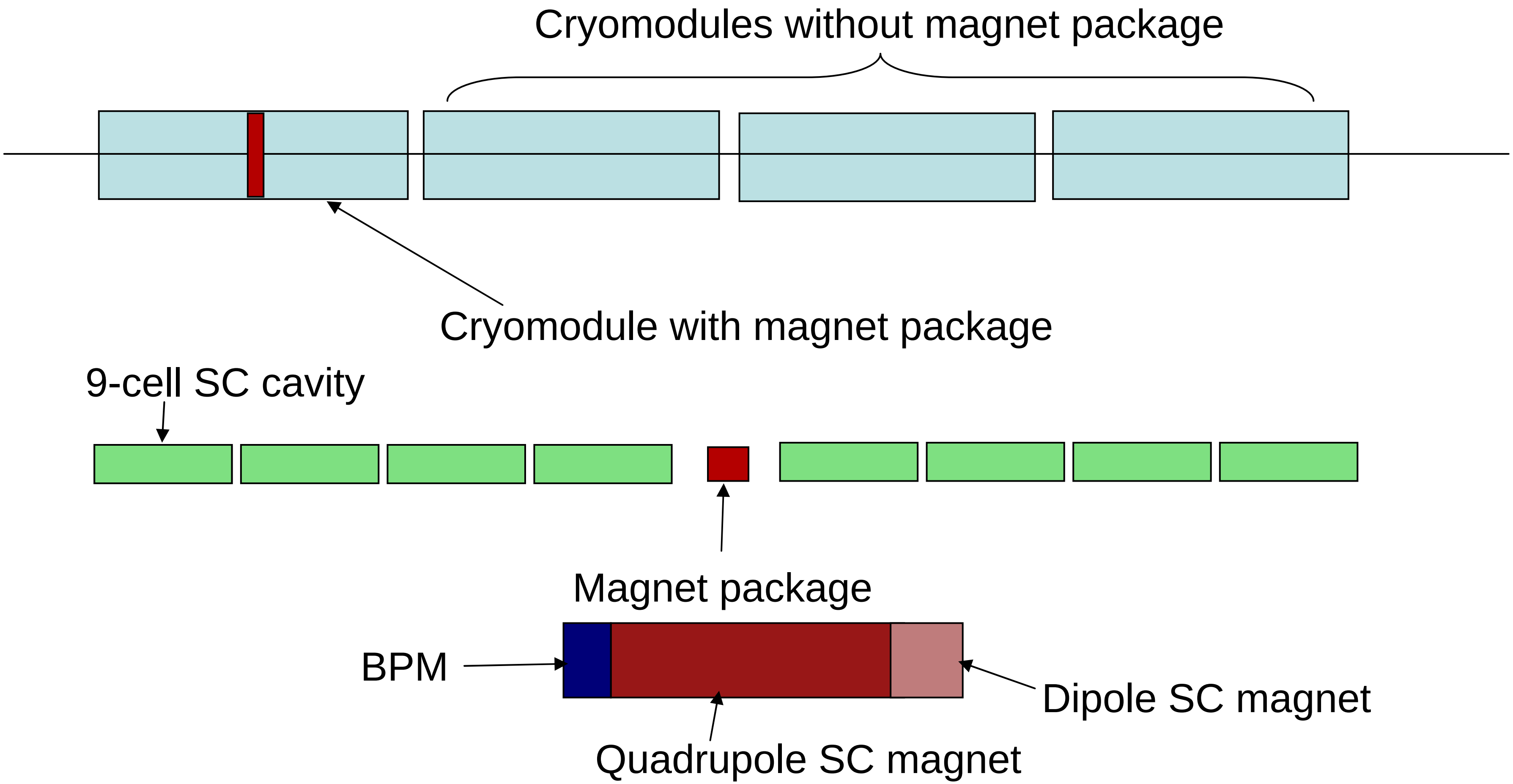
Lattice design

- Basic layout
  - One quad per four cryomodules
    - May be changed to one quad/three modules
  - Simple FODO cell

    x/y = 75/65 degree phase advance/cell

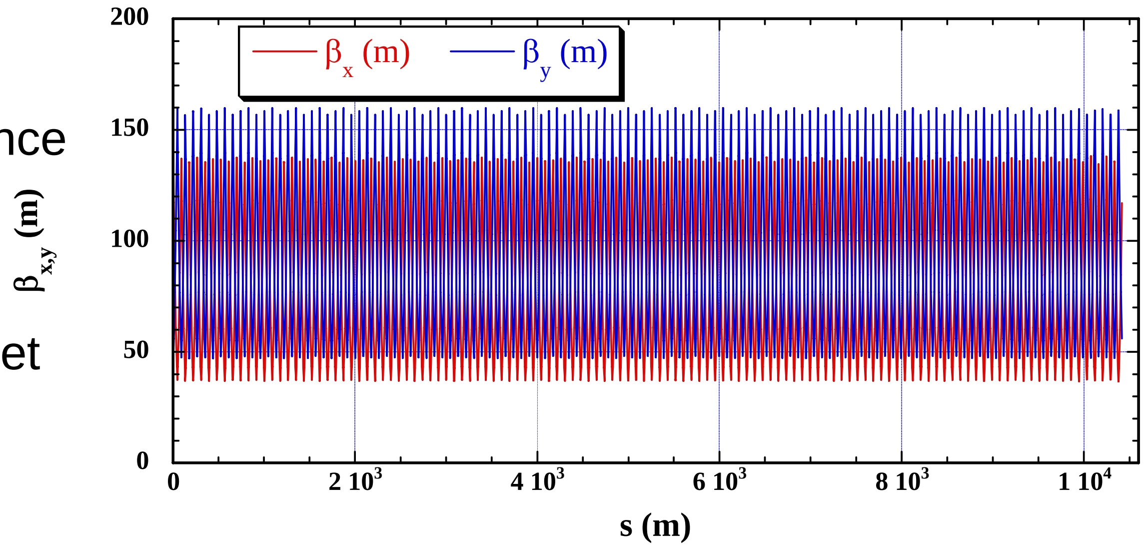
    Other possible configurations: change along linac
    - Higher the energy, larger the beta-function
    - FOFODODO, FOFOFODODODO, etc., in high energy region
- Vertically curved, following the earth curvature

Unit of main linac
about 240 units/linac



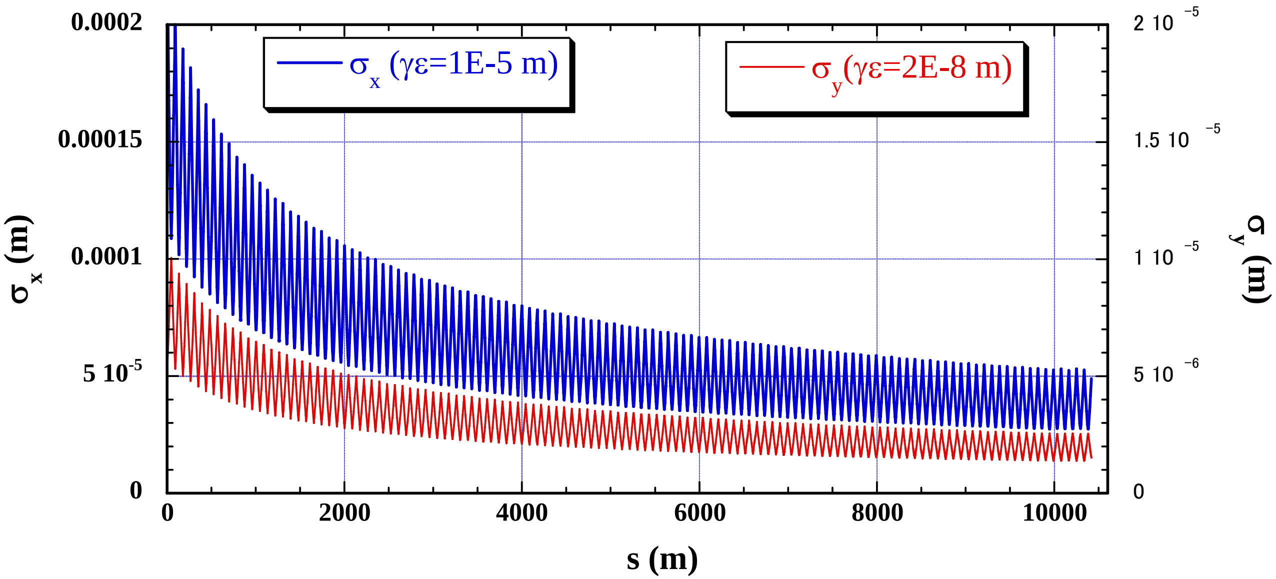
Beta-function

Baseline design
Constant phase advance



Strength of quad magnet is proportional to beam energy.

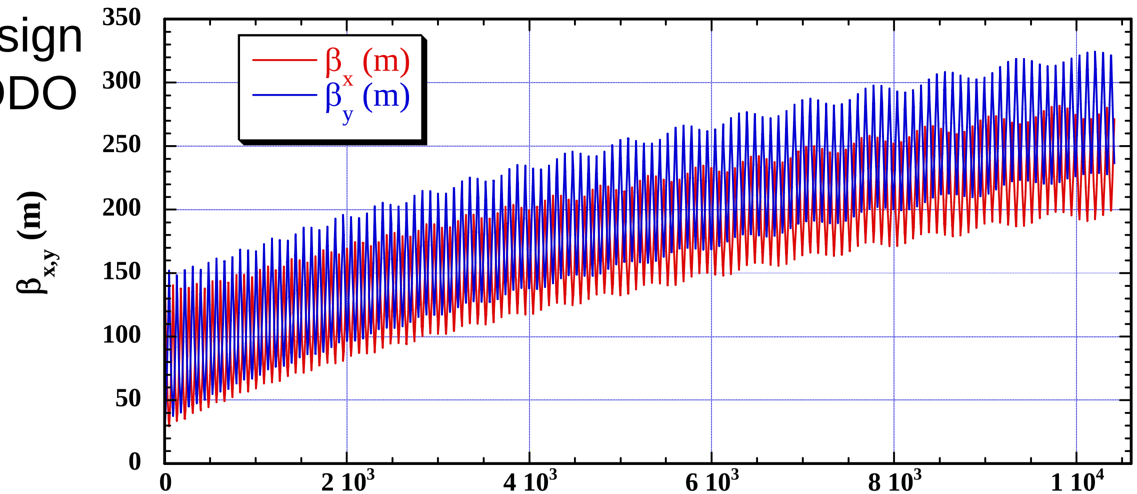
Beam size



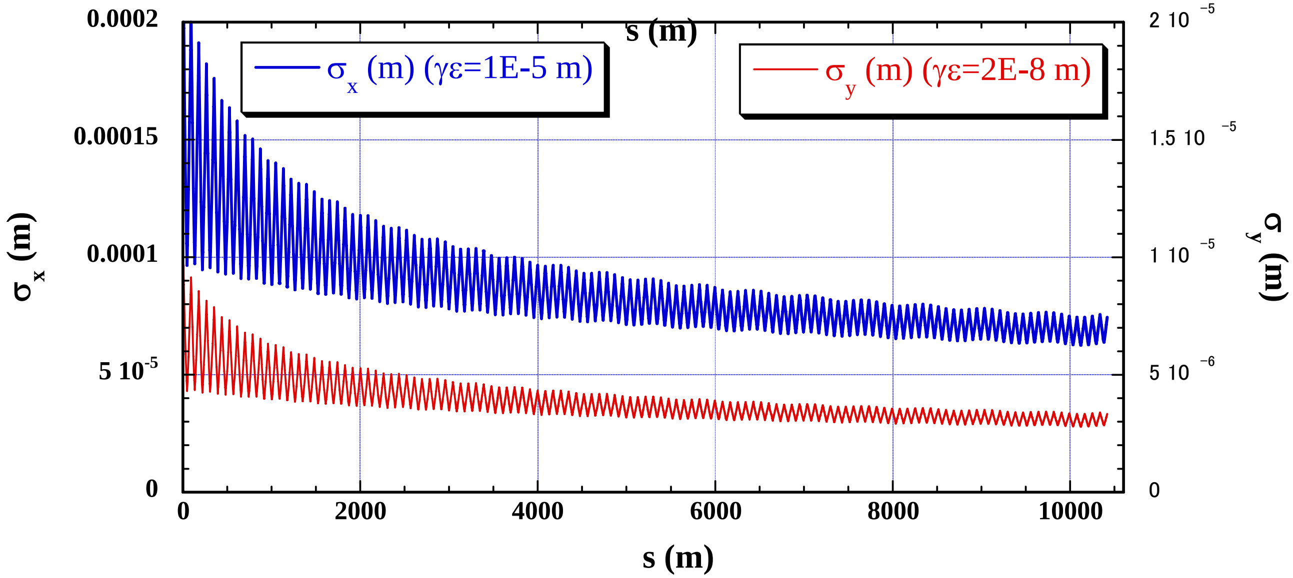
Vertical:
5~10 μm
at 15 GeV
1.5 ~ 2.5 μm
at 250 GeV

Beta-function Possible alternative design

Possible alternative design
Phase advance per FODO
~ sqrt(1/E)



Beam size



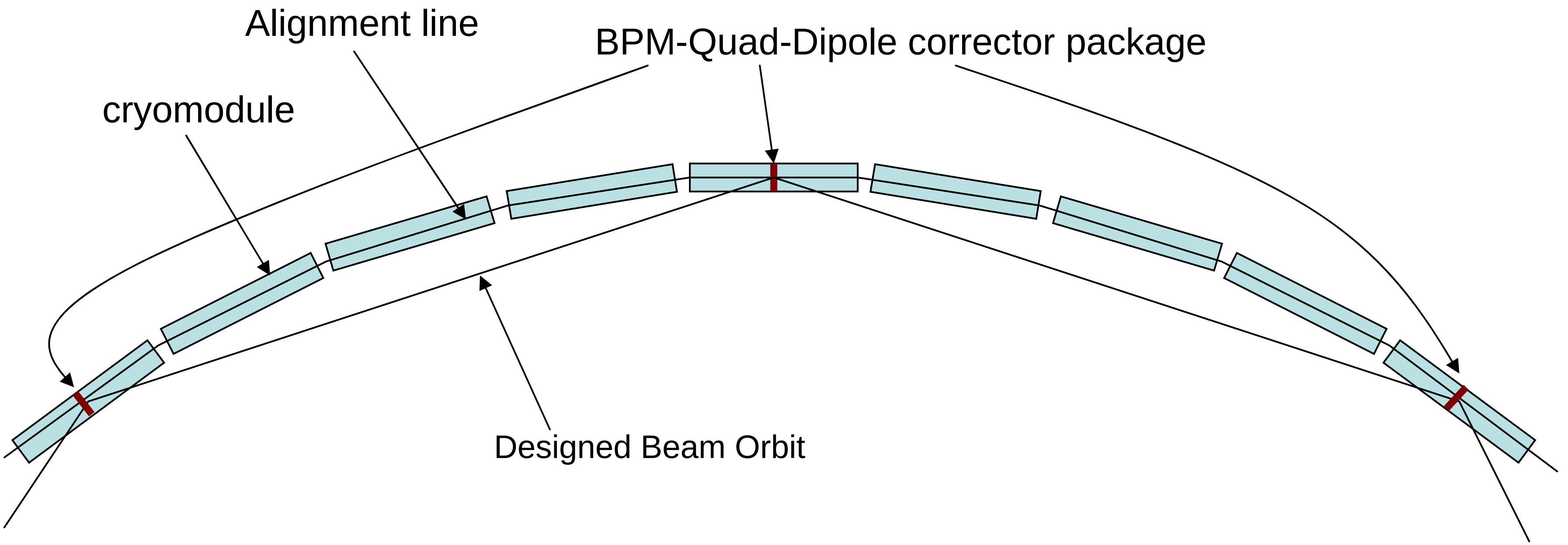
Tolerances depend on optics

$$\text{Tolerance of Quad magnet vibrations} \propto \sqrt{\overline{\beta}}$$

$$\text{Tolerance of Acc. Cavity offset} \propto 1 \Big/ \sqrt{\overline{\beta}}$$

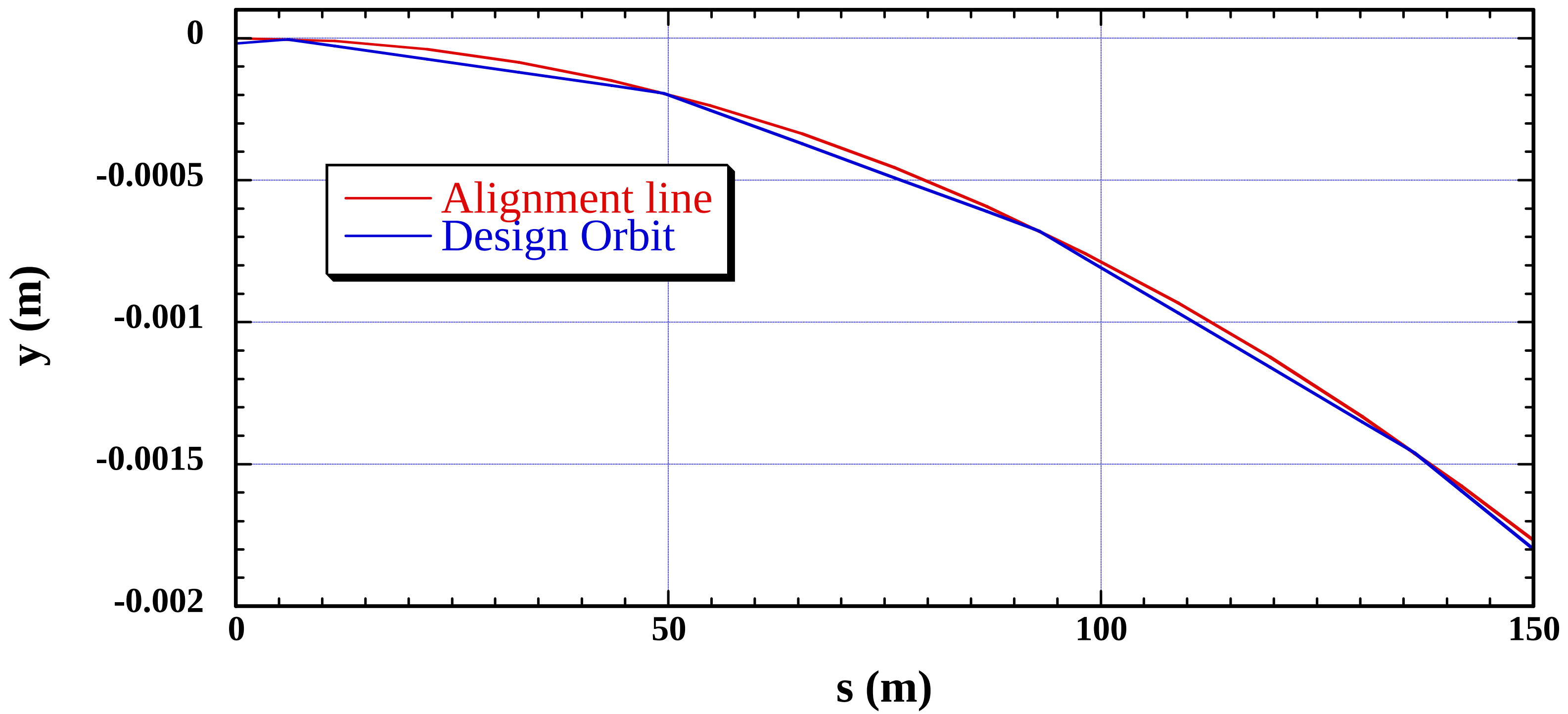
(See later discussions.)

Alignment and Beam Orbit in Curved Linac, Following earth curvature

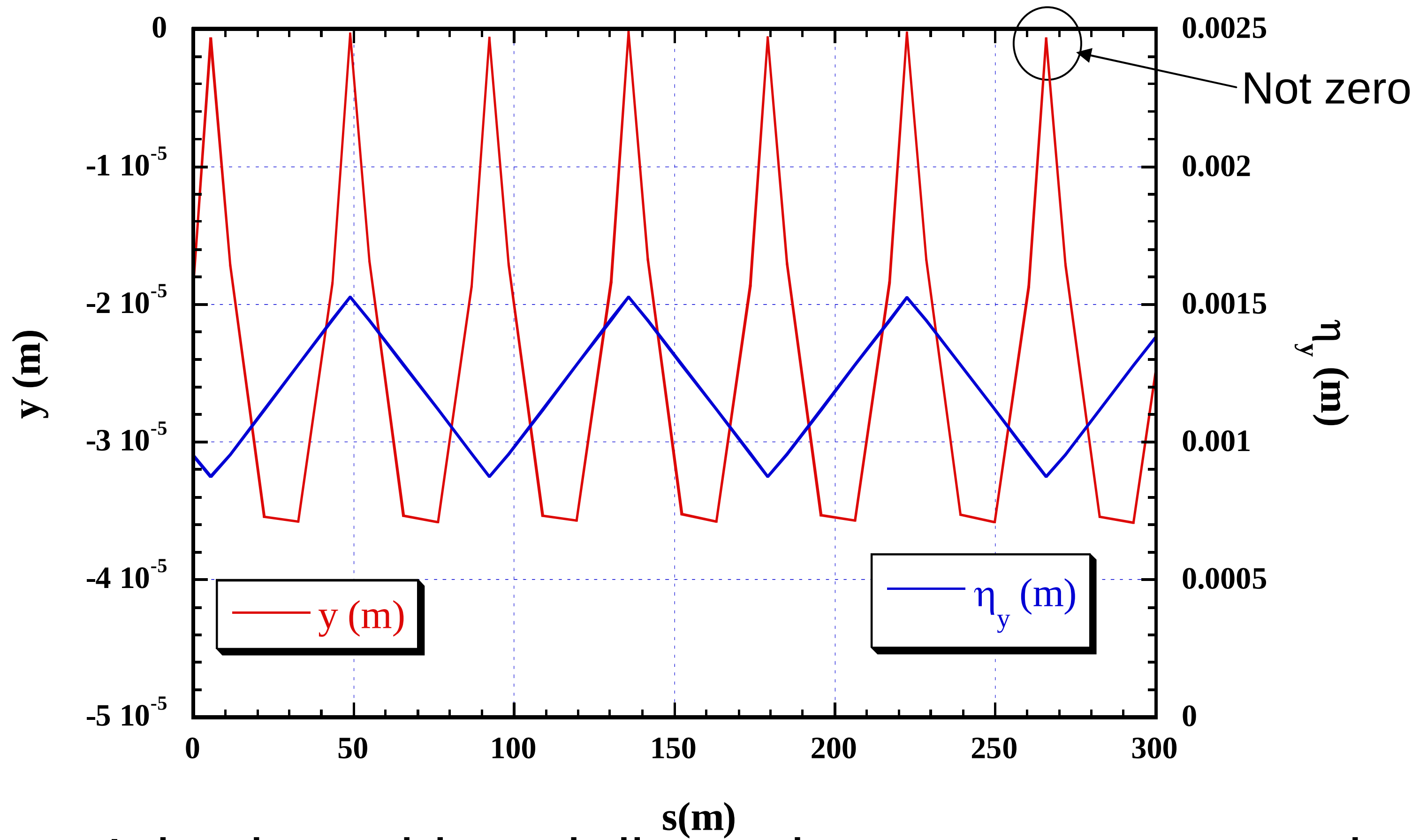


(Vertical scale is extremely exaggerated)

Alignment and Beam Orbit in Curved Linac, Following earth curvature



Design orbit w.r.t. the reference line and dispersion



Injection orbit and dispersion are non-zero, and should be matched to the optics.

Beam Quality Preservation

Beam Quality

- Longitudinal particle distribution
  - Energy and arriving time, or longitudinal position
    - E and t, or z
- Transverse particle distribution
  - Horizontal and vertical position and angle
    - x, x', y, y' (or x, px, y, py)

Generally,

"Stable and small distributions at IP"

is preferable.

Exception:

x and z distribution at IP should not be too small.

(→ beam-beam interaction)

Longitudinal Beam Quality

Longitudinal beam quality

- Beam energy stability
- Small energy spread.

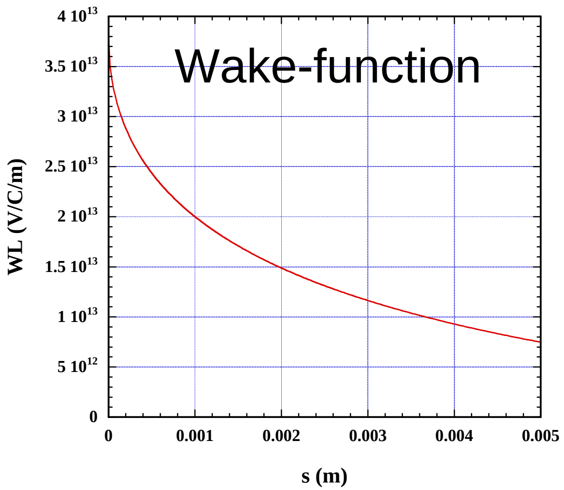
These require RF amplitude and phase stability, which rely on RF control.

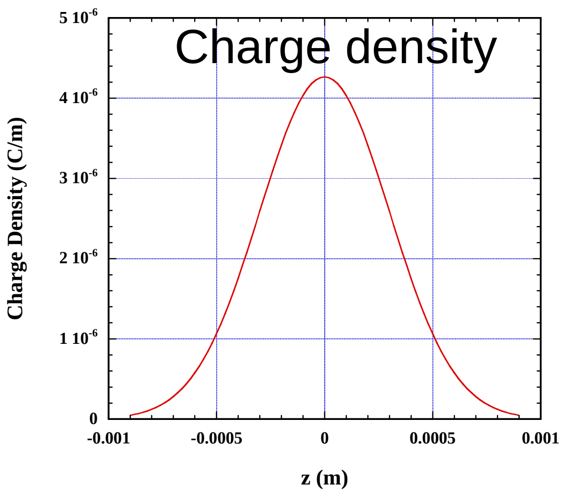
The stability requirement in main linacs is less severe than in bunch compressors.

Main Linac does (almost) nothing to the timing and bunch length.

(→ Bunch Compressor)

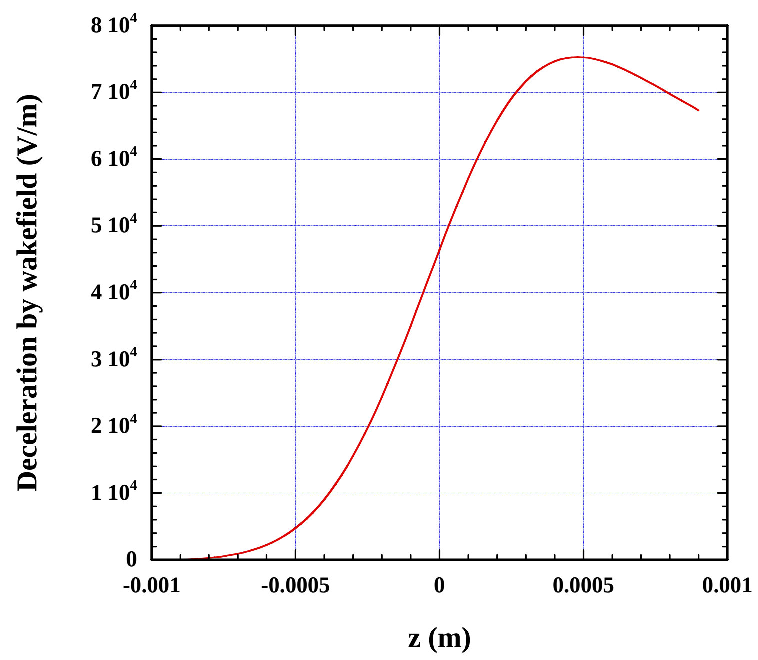
Single bunch:
Longitudinal short range wakefield





Deceleration by wakefield

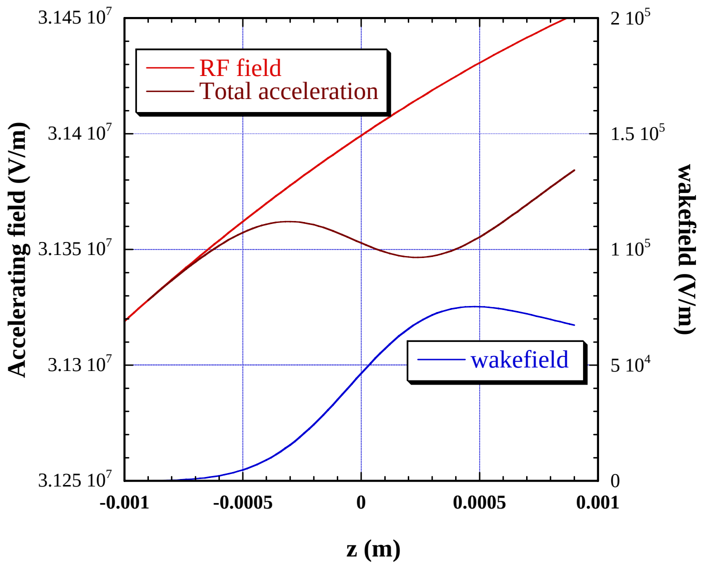
$$E(z) = \int_{-\infty}^{z} dz' \lambda(z') W(z - z')$$



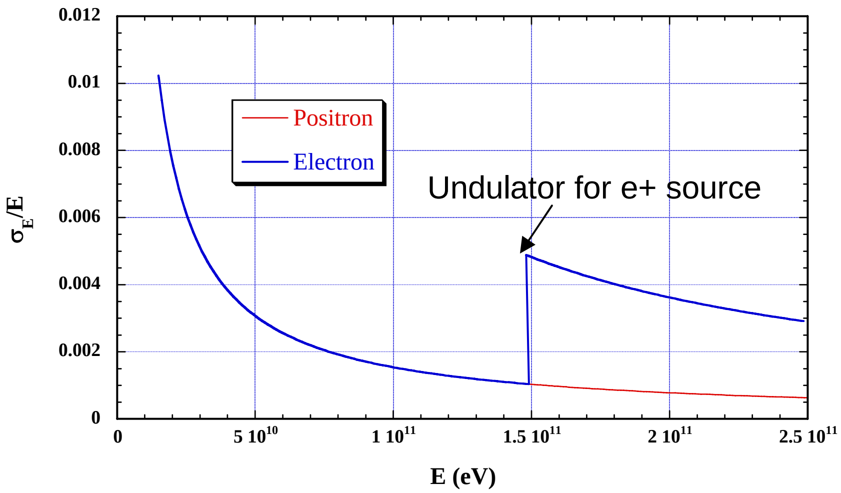
calculated from TESLA-TDR formula

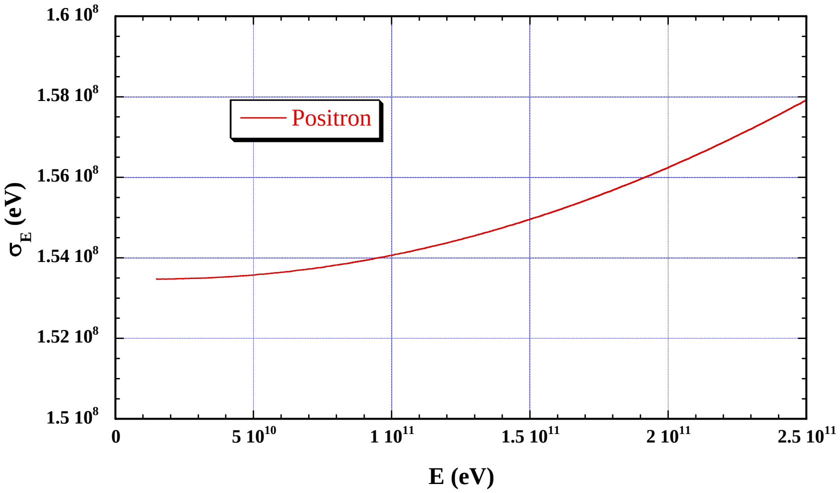
Total acceleration

(RF off-crest phase 4.6 deg. minimizing energy spread.)



Energy spread along linac. Initial spread is dominant.





Bunch by bunch energy difference

- Should be (much) smaller than single bunch energy spread
- Accurate RF control will be essential
  - Compensation of beam loading
  - Compensation of Lorentz detuning
- Longitudinal higher order mode wakefield will not be a problem.

Energy Fluctuation, Required RF Stability

Independent, random fluctuations of each klystron.

$$\delta E \approx \frac{1}{\sqrt{n_{\text{kly}}}}\left(\delta_{\text{amplitude}} e V_0 \cos\phi_0 + \delta_{\text{phase}} e V_0 \left|\sin\phi_0\right|\right)$$

Common error of all klystrons

$$\Delta E \approx \Delta_{\text{amplitude}} e V_0 \cos\phi_0 - \Delta_{\text{phase}} e V_0 \sin\phi_0$$

$$\begin{pmatrix} V_0 : \text{total voltage} \\ \phi_0 : \text{off - crest phase} \end{pmatrix}$$

For stability $< 0.1\sigma_E$ from each error,

$$\delta_{\text{amplitude}} < 0.1\sqrt{n_{\text{kly}}}\,\sigma_E / E \approx 2\times 10^{-3}$$

$$\delta_{\text{phase}} < 0.1\sqrt{n_{\text{kly}}}\,\sigma_E / E \left|\sin\phi_0\right| \approx 2\times 10^{-2}\,\text{rad}$$

$$\Delta_{\text{amplitude}} < 0.1\sigma_E / E \approx 10^{-4}$$

$$\Delta_{\text{phase}} < 0.1\sigma_E / E \left|\sin\phi_0\right| \approx 10^{-3}\,\text{rad}$$

Fluctuations faster than feedback are relevant.

Transverse Motion

Transverse beam quality

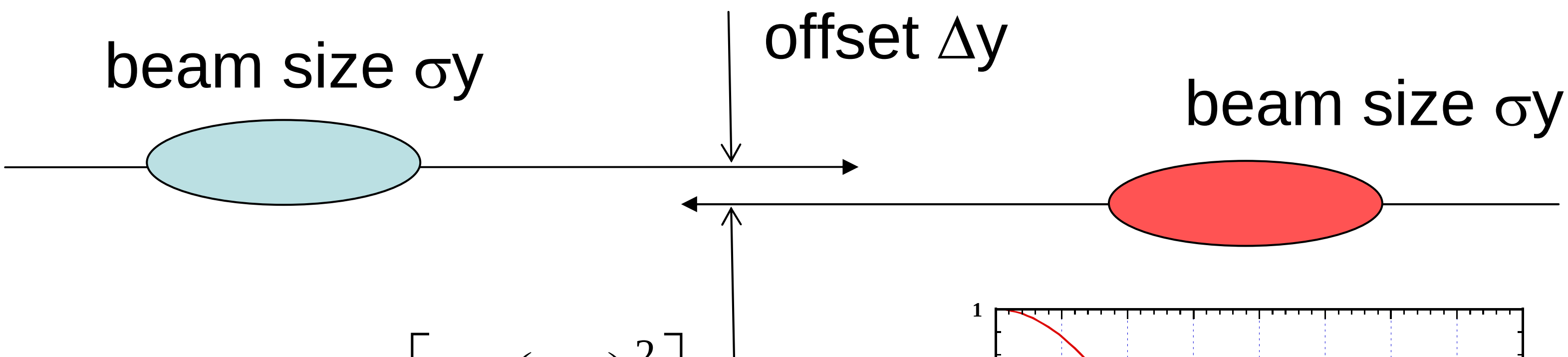
- Beam position at IP
  - Offset between two beams should be (much) smaller than the beam size
- Beam size at IP, Emittance
  - From consideration of beam-beam interaction, ‘flat’ beam is desirable.
    - vertical size is much smaller than horizontal size
  - Beam size at IP is limited by emittance
    - Hour glass effect and Oide limit
  - Then, vertical emittance need to be very small.
- Vertical position stability and vertical emittance preservation are considered

Beam position jitter

- There will be position feedback in Main Linac, BDS, then, at IP, and feed-forward in RTML (turnaround).
- In Main Linac, only fast jitter (faster than the feedback) should be important, unless it causes emittance dilution.
- The dominant source can be:
  - vibration of quadrupole magnets.
  - Strength jitter of quadrupole and dipole magnets (instability of power supplies)

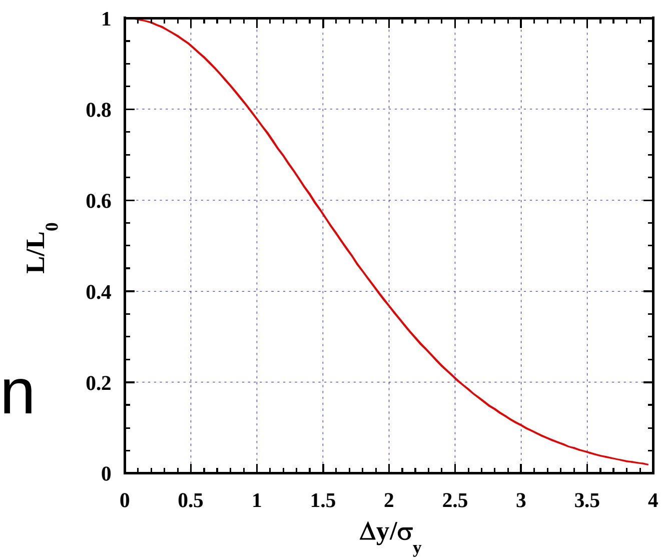
Beam position offset vs. luminosity

- estimation without beam-beam force



$$L(\Delta y) = L(0)\exp\left[-\frac{1}{4}\left(\frac{\Delta y}{\sigma_y}\right)^2\right]$$

→ Offset between two beams should be (much ?) smaller than the beam size



beam-beam force will change this significantly

Estimation of beam position change due to quad offset change

Final position change due to offset of i-th quad:

$$\Delta y_f = -a_i k_i \sqrt{E_i / E_f} \sqrt{\beta_f \beta_i} \sin \varphi_i$$

a_i : offset of i - th quad, k_i : k - value (f^{-1}) of i - th quad,

E_i : beam energy at i - th quad, E_f : final beam energyk_i : k - value,

β_i : betafunction at i - th quad, β_f : final betafunction

φ_i : phaseadvance from i - th quad to final

Final beam position is sum of all quads' contribution. Assuming random, independent offset, expected beam position offset is:

$$< y_f^2 > \approx \beta_f \sum_{quad} \beta_i k_i^2 E_i \sin^2 \varphi_i / E_f \approx a^2 N_q \beta_f \bar{\beta} \bar{k}^2 \big/ 4$$

a : rms of offset, N_q : number of quads,

$\bar{\beta}$: average of betafunction, $\bar{k}^2$: average of k - value square

Please confirm or confute expressions in this page.

HMWK-1

Estimation of beam position change due to magnet strength change

Final position change due to strength change of i-th quad:

Replace $a_i k_i$ in the previous page by $a_i \delta k_i$,

where δk_i, is the quad strength error.

Final position change due to strength change of i-th dipole:

Replace $a_i k_i$ in the previous page by $\delta k_{0,i}$,

where $\delta k_{0,i}$, is the dipole strength error.

Strength fluctuation is important especially for curved linac, because of non-zero designed dipole kicks, even without alignment errors.

Stronger focus optics make quad vibration tolerance tighter

Beam position jitter / beam size:

$$\frac{\sqrt{< y_f^2 >}}{\sigma_y} \approx \frac{a\sqrt{N_q \beta_f \overline{\beta}\overline{k}^2} \Big/ 2}{\sqrt{\varepsilon_y \beta_f}} =\sim \frac{a\sqrt{N_q}}{\sqrt{\varepsilon_y \overline{\beta}}}$$

proportional to:

- quad vibration
- square root of number of quads

inversely proportional to:

- square root of average beta-function
- square root of emittance

Beam quality - Emittance

- Our goal is high luminosity
- For (nearly) Gaussian distribution, emittance is a good measure of luminosity
  - We are usually interested in this case.
- But, ...
- We use emittance dilution as a measure of quality dilution in the main linac, anyways.

Luminosity, general definition

Instantaneous luminosity:

$$L \equiv \iiint dxdydz \left| \vec{v}_{-} - \vec{v}_{+} \right| \rho_{-}(x,y,z) \rho_{+}(x,y,z)$$

$\vec{v}_{+(-)}$: velocity of positron(electron) beam

$\rho_{+(-)}$: particle density of positron(electron) beam

Integrated Luminosity

$$L_{\text{int}} \equiv \int dt L(t)$$

Luminosity per bunch crossing for Gaussian beam

head on collision, no de-formation due to beam-beam force

$$L_{bc} = \int dt \int dz 2cN_- N_+ \lambda_{-,z} \lambda_{+,z} \int dx \lambda_{-,x} \lambda_{+,x} \int dy \lambda_{-,y} \lambda_{+,y}$$

$$= \frac{N_- N_+}{2\pi \sqrt{\sigma_{-,x}^2 + \sigma_{+,x}^2} \sqrt{\sigma_{-,y}^2 + \sigma_{+,y}^2}}$$

$\rho(x, y, z) = N \lambda_x \lambda_y \lambda_z$: density per volume

$$\lambda_{-(+),x(y)} \propto \exp\left(-\frac{x^2 (y^2)}{2\sigma_{-(+),x(y)}} \right), \quad \lambda_{-(+),z} \propto \exp\left(-\frac{(z-(+)ct)^2}{2\sigma_{-(+),z}} \right)$$

If e+ and e- beams are the same size, luminosity is proportional to inverse of beam’s cross section.

Example where emittance does not well correlated with luminosity -1

2E10 particles
σy=10 μm
$\sigma y'$=1 μrad

Luminosity: L_0
Emittance: 1E-11 m

1/1E6 of halo
Almost the same luminosity
Emittance increase by factor 2

2E10 – 2E4 particles
σy=10 μm
$\sigma y'$=1 μrad

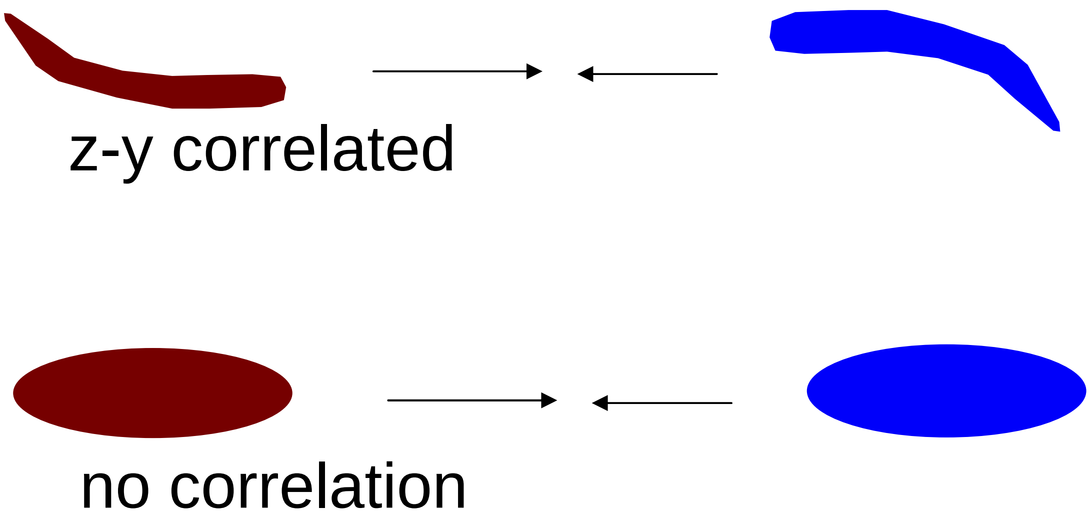
2E4 particles

Luminosity: 0.999999 L_0
Emittance: 2E-11 m

17 mm

Example where emittance does not well correlated with luminosity -2

So called “banana effect”



Same projected emittance.
Different luminosity

→ Beam-beam interaction

NOTE

- We use emittance as a measure of quality in the main linac.
- Halos, tails far from core should be ignored in calculating the emittance.
  - Effects of halos or tails should be considered in other context.
- Luminosity may not be well correlated to emittance, in some cases, because of Beam-beam force at IP
- Does any parameter represent luminosity better than emittance, which can be evaluated without collision simulations? **HMWK-2**

Dominant Sources of transverse Emittance dilution

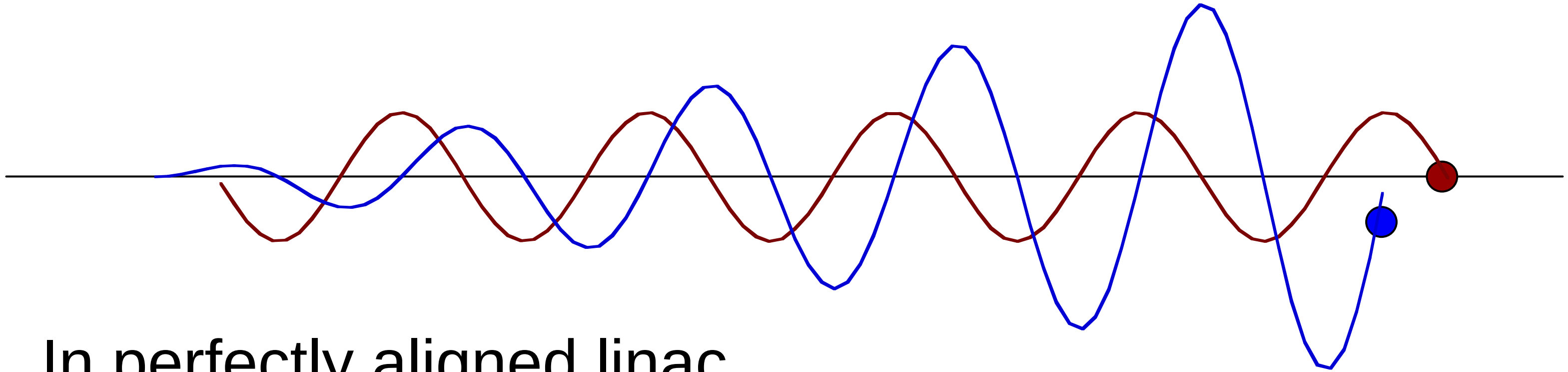
- Wakefield (transverse) of accelerating cavities
  - Electromagnetic fields induced by head particles affect following bunches.
    - z-correlated orbit difference
- Dispersive effect
  - Different energy particles change different angles by electromagnetic fields (designed or not-designed).
    - energy correlated orbit difference

Effects of Transverse Wakefield

Transverse Wakefield of Accelerating cavities

- Short range - Single bunch effect
  - Wakefunction is monotonic function of distance
  - Not seriously important for ILC
- Long range - Multi-bunch effect
  - Many higher order oscillating mode
  - For ILC
    - Need to be damped
    - Frequency spread is needed. (may naturally exist ?)
    - Need to be careful for x-y coupling
- BBU [Beam Break Up] (injection error)
- Effect of cavity misalignment

Rough estimation of BBU (Beam break up) (by two particle model)



In perfectly aligned linac.

The first particle oscillates with injection error.
Wake of the first particle excites oscillation of the following particle.

Amplitude of first particle oscillaion (initial a_{00})

$$a_0 \approx a_{00}\sqrt{E_0 / E}$$

Amplitude of 2nd particle oscillation (initial 0)

$$a_1 \approx \begin{cases} a_0\, e\, q\, W\, \beta\left(\sqrt{E / E_0} - 1\right)/g & (g > 0) \\ a_0\, e\, q\, W\, \beta\, s/2 & (g = 0) \end{cases}$$

q : cahnge of the first particle

W : wakefunction (assume constant)

β : beta - function (assume constant)

$E_0,\ E$: initial energy and energy at s

g : acc. gradient (assume constant)

s : distance from the entrance

Requiring $a_1/a_0 < 1, \quad W < g/\left[eq\beta\left(\sqrt{E/E_0} - 1\right)\right]$

Rough estimated requirement from BBU

Requiring $a_1/a_0 < 1, \quad W < g/\left[eq\beta\left(\sqrt{E/E_0} - 1\right)\right]$

For ILC,

$$g \approx 30\,\text{MeV/m}, \quad q \approx 3\,\text{nC}, \quad \beta \approx 100\,\text{m}, \quad E/E0 \approx 17$$

$$\Rightarrow W < 3\times 10^{13}\ \text{V/C/m}^2$$

This is barely satisfied for short range wake of TESLA design.

Short range wake of warm accelerating structure is much larger.
And special cure is necessary, such as BNS damping, or auto-phasing technique:

- Introduce z-correlated energy spread (tail has lower energy),
- Avoid 'resonance' between head and tail.

BNS, auto-phasing is good for BBU due to wake and necessary for warm LC.
But introducing energy spread causes dispersive effect and may not be used in ILC.

SKIP

Explanation of auto-phasing by 2 particle model

Continuous, constant focusing optics. No acceleration.

Leading particle: $y_0''(s) = -\frac{K}{E_0} y_0(s)$

Following particle: $y_1''(s) = -\frac{K}{E_1} y_1(s) + \frac{e q_0 W}{E_1} y_0(s)$

$E_{0,1}$: energy of leading and following particle, q_0 : charge of leading particle

W : wake function, K : const. focusing strength,

Solution of y_0, : $y_0(s) = y_0(0)\cos(ks) + y_0'(0)\sin(ks)/k$, $(k = \sqrt{K/E_0})$

If $E_1 = E_0$,

$$y_1(s) = y_1(0)\cos(ks) + y_0'(0)\sin(ks)/k + s\frac{e q_0 W}{2E_0}\sin(ks)/k$$

Amplitude of the 3rd term grows linearly with distance

If $-\frac{K}{E_1} + \frac{e q_0 W}{E_1} = -\frac{K}{E_0}$,

$y_1(s) = y_0(s)$ is a solution of the following particle.

No growth of induced oscillation

SKIP

Consider auto-phasing by 2 particle model, with acceleration, analytically.

Continuous, constant focusing optics.

$$\text{Leading particle: } y_0''(s) = -Ky_0(s) - \frac{g}{E_0(s)} y_0'(s)$$

$$\text{Second particle: } y_1''(s) = -Ky_1(s) - \frac{g}{E_1(s)} y_1'(s) + \frac{eq_0W}{E_1(s)} y_0(s)$$

$$\text{Energy: } E_0(s) = E_0(0) + gs$$

$$K: \text{const. focusing strength}, \quad g: \text{const. acc.gradient}$$

$$\text{Solution of } y_0 \text{ assuming } (g/E_0)^2 << K = k^2$$

$$y_0(s) = [E_0(0)/E_0(s)][y_0(s)\cos(ks) + y_0'(s)\sin(ks)/k]$$

SKIP

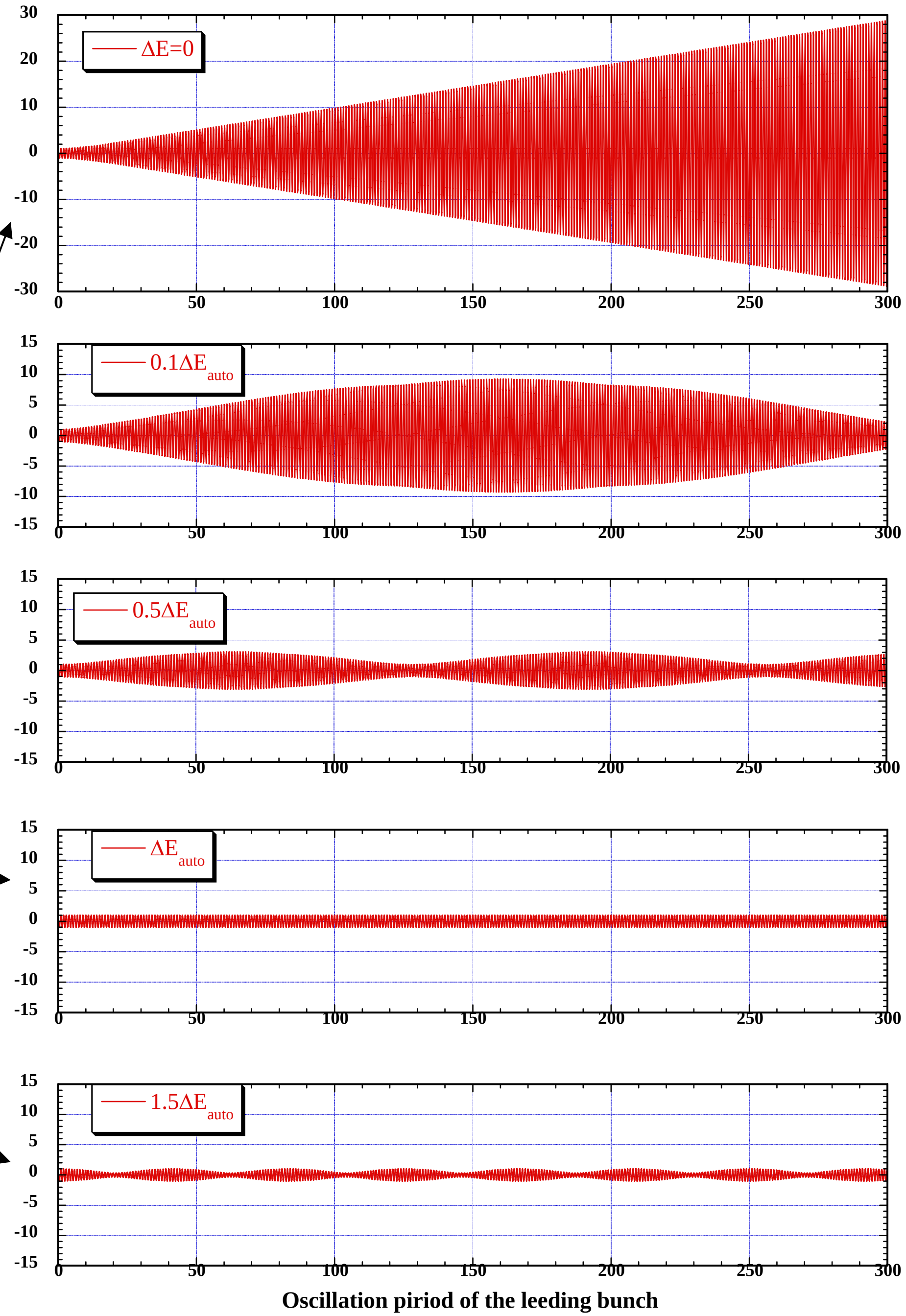
Oscillation of second particle.
Two particle model.
No acceleration

Unit of the amplitude of the leading particle .

No energy difference:
Amplitude grows linearly.

Auto-phasing:
Oscillate as same as the leading particle.

More energy difference:
BNS Damping



SKIP

Note on auto-phasing, BNS damping

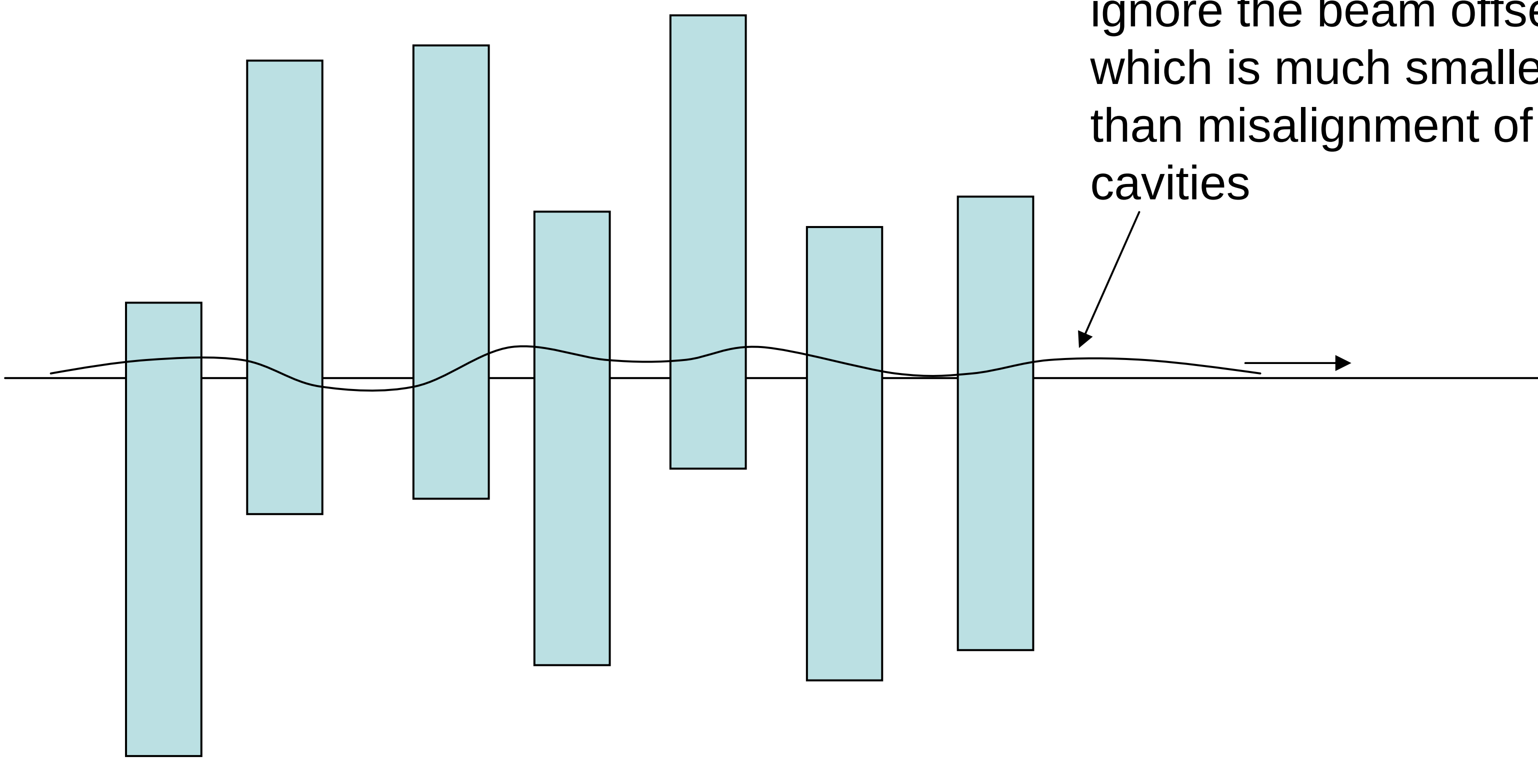
- It is impossible to maintain exact auto-phasing condition for all particles. But,
- Exact condition is not necessary to suppress BBU. Correlated energy difference close to the exact condition will work.
- Useful for single bunch BBU
  - Wakefunction is monotonic with distance
  - Longitudinally correlated energy difference can be introduced by controlling RF off-crest phase.
  - Warm LC must use this technique
  - Not strictly necessary for ILC
- Difficult to apply to multibunch BBU
  - Complicated wake function → need to introduce complicated bunch-by-bunch energy difference

Effect of misalignment of cavities

Assume

Beam offset << typical misalignment

Induced wake almost only depend on misalignment, not on beam offset.



Effect of misalignment of cavities-continued

Position change of *j*-th particle at linac end due to i-th cavity:

$$y_{i,f} = -e a_i W_{j,i} \sqrt{1/E_i E_f} \sqrt{\beta_f \beta_i} \sin\varphi_i$$

$$\text{"sum - wake": } W_{j,i} = \sum_{k<j} q_k W_i(z_j - z_k)$$

a_i : offset of i - th cavity,

E_i, E_f : energy at i - th cavity and final energy,

β_i, β_i : beta at i - th cavity and final beta,

φ_i : phase advance from i - th cavity to final,

q_k : charge of k - th particel,

L_{cavi} : cavity length, g : acc. gradient,

Position change at linac end:

$$y_{j,f} = -e \sum_i a_i W_{j,i} \sqrt{1/E_i E_f} \sqrt{\beta_f \beta_i} \sin\varphi_i$$

Expected Position change square of j-th particle:

assume all cavities have the same wakefunction

$$< y_{j,f}^2 >= \sum_i < a_i^2 > \frac{e^2}{E_i E_f} W_{j,i}^2 \beta_f \beta_i \sin^2 \varphi_i \approx \frac{e^2 a^2 L_{cav} \beta_f \overline{\beta} \overline{W_j^2} \log(E_f / E_0)}{2 g E_f}$$

Please confirm or confute expressions in this page.

HMWK-3

Stronger focus optics (smaller beta-function) make Effects of wakefield weaker

BBU:

Amplitude of first particle oscillaion (initial a_{00})

$$a_0 \approx a_{00}\sqrt{E_0 / E}$$

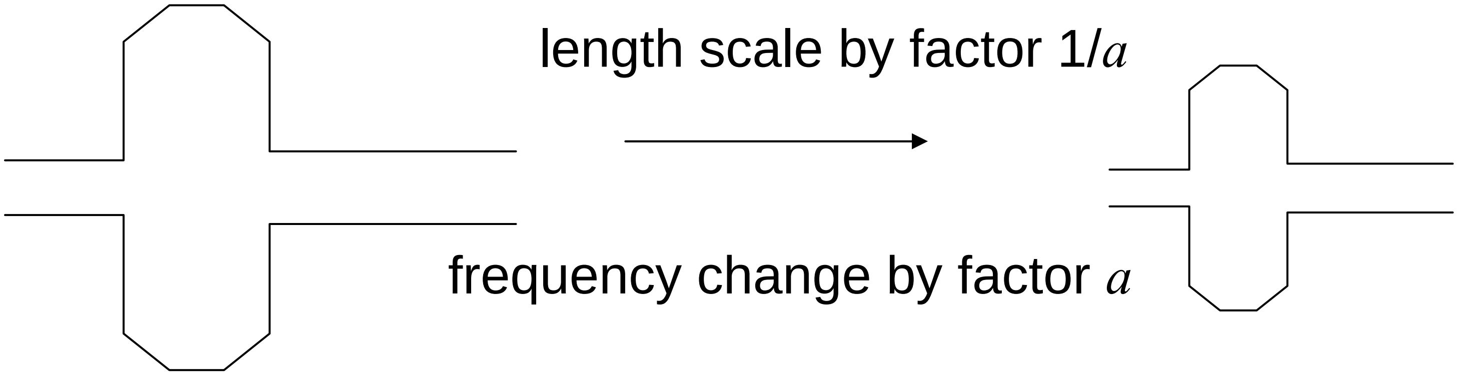
Amplitude of 2nd particle oscillation (initial 0)

$$a_1 \approx \begin{cases} a_0\, e\, q\, W\, \beta\left(\sqrt{E / E_0} - 1\right)/g & (g > 0) \\ a_0\, e\, q\, W\, \beta\, s/2 & (g = 0) \end{cases}$$

Misalignment:

$$< y_{j,f}^2 > = \sum_i < a_i^2 > \frac{e^2}{E_i E_f} W_{j,i}^2 \beta_f \beta_i \sin^2 \varphi_i \approx \frac{e^2 a^2 L_{cav} \beta_f \overline{\beta} \overline{W_j^2} \log(E_f / E_0)}{2 g E_f}$$

Due to low RF frequency of ILC, using superconducting cavity, wakefield is much less serious, compare with warm LC (X-band or higher frequency).



Wakefunction of every dipole (transverse) mode

$$W_{\perp} \sin(\omega t) \rightarrow a^3 W_{\perp} \sin(a\,\omega t)$$

Amplitude of long range wake (multi-bunch effect)

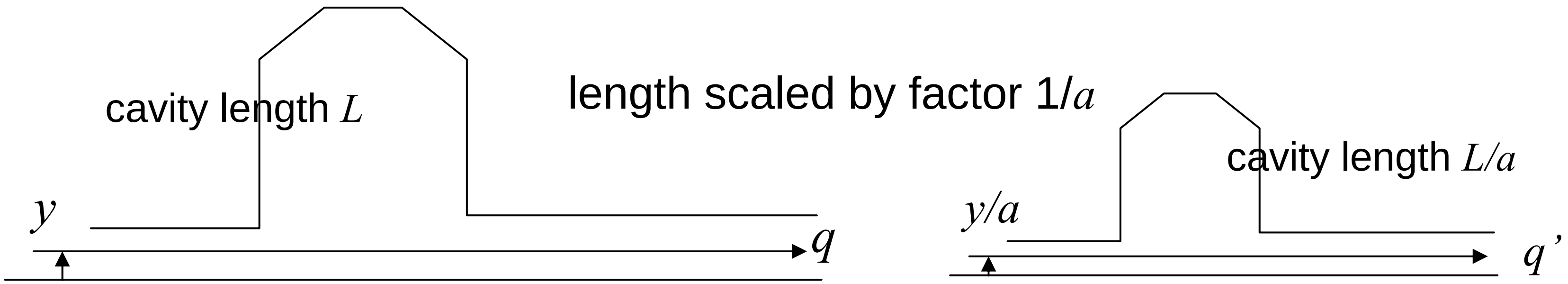
$$W_{\perp} \rightarrow a^3 W_{\perp}$$

Short range wake: Slope at the beginning (single bunch effect, $t \rightarrow 0$)

$$\omega W_{\perp} \rightarrow a^4 \omega W_{\perp}$$

Explanation of Wakefunction Scaling with size

Look at one dipole mode (justified by principle of superposition, for many modes)



Left cavity : Exited fielld by a drive charge q went through the cavity at offset y,

$$\text{Energy}: U_0,\ \text{Voltage}: V_0\ , \text{Average gradient}: E_0$$

The drive change 'feels' a one half of the voltage, then, from energy preservation,

$$U_0 = qV_0/2 \quad \text{and transverse wakefunction } W_0 = V_0/(q\,y\,L)$$

Right cavity : A drive charge q' went through offset y/a exited the same gradient, the same field distribution (length scaled)

$$\text{Energy}: a^{-3}U_0,\ \text{Voltage}: a^{-1}V_0\ , \text{Average gradient}: E_0$$

From energy preservation,

$$a^{-3}U_0 = q' a^{-1}V_0/2 \quad \Rightarrow \quad q' = a^{-2}q$$

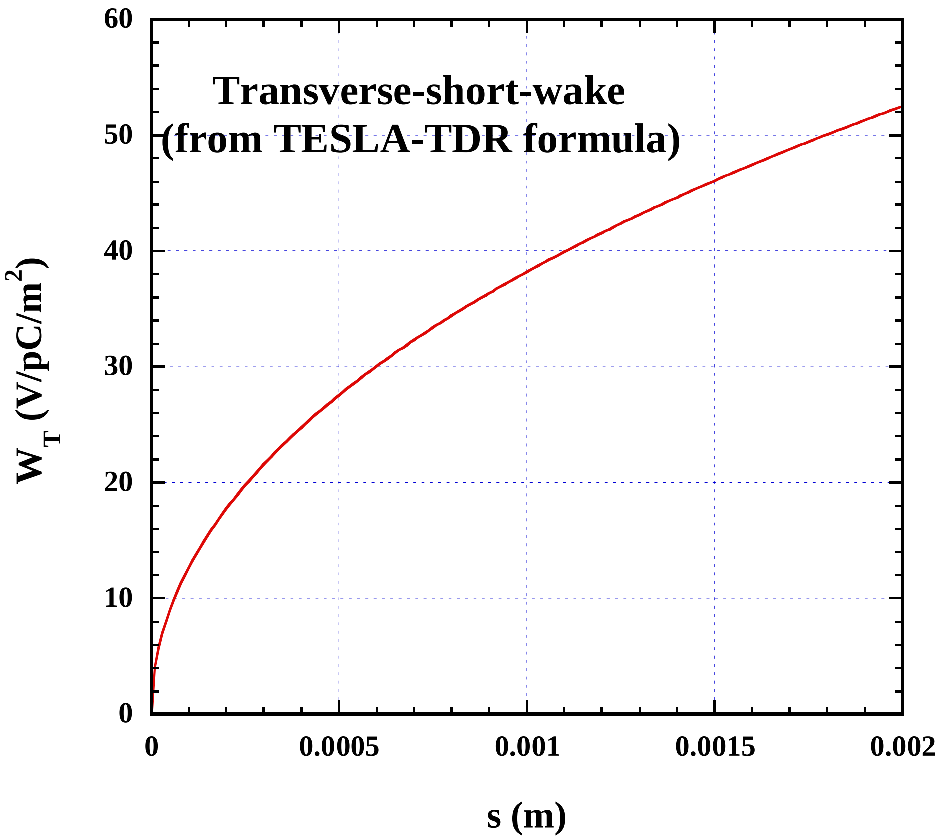
and transverse wake function $= a^{-1}V_0/(a^{-1}y\,q'\,a^{-1}L) = a^3 W_0$

Please confirm or confute expressions in this page.

HMWK-4

Example of Short range wakefunction

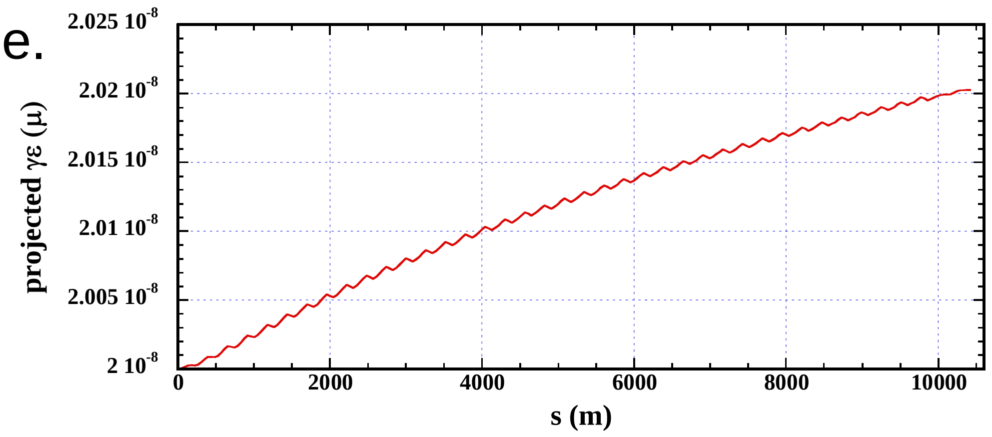
From TESLA-TDR



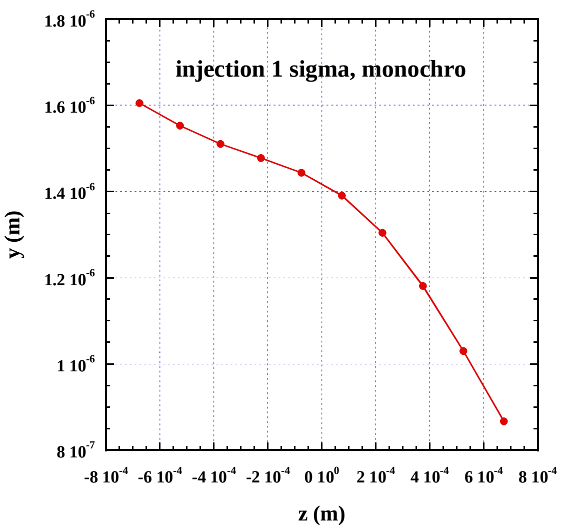
Example of simulation of short range wake effect-1

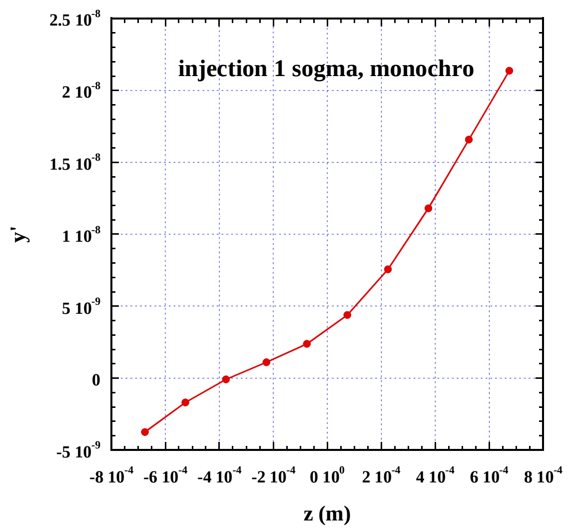
Single bunch BBU, with injection offset in perfectly aligned linac.

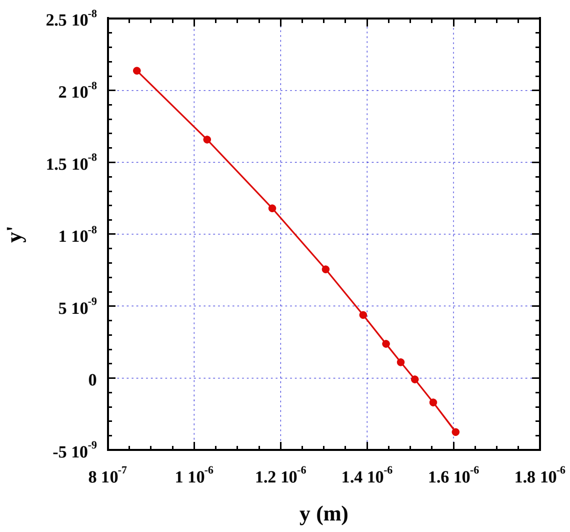
Emittance along linac,
injection offset 1 σ of beam size.
monochromatic beam.



y-z, y'-z, y'-y distribution
at the end of linac

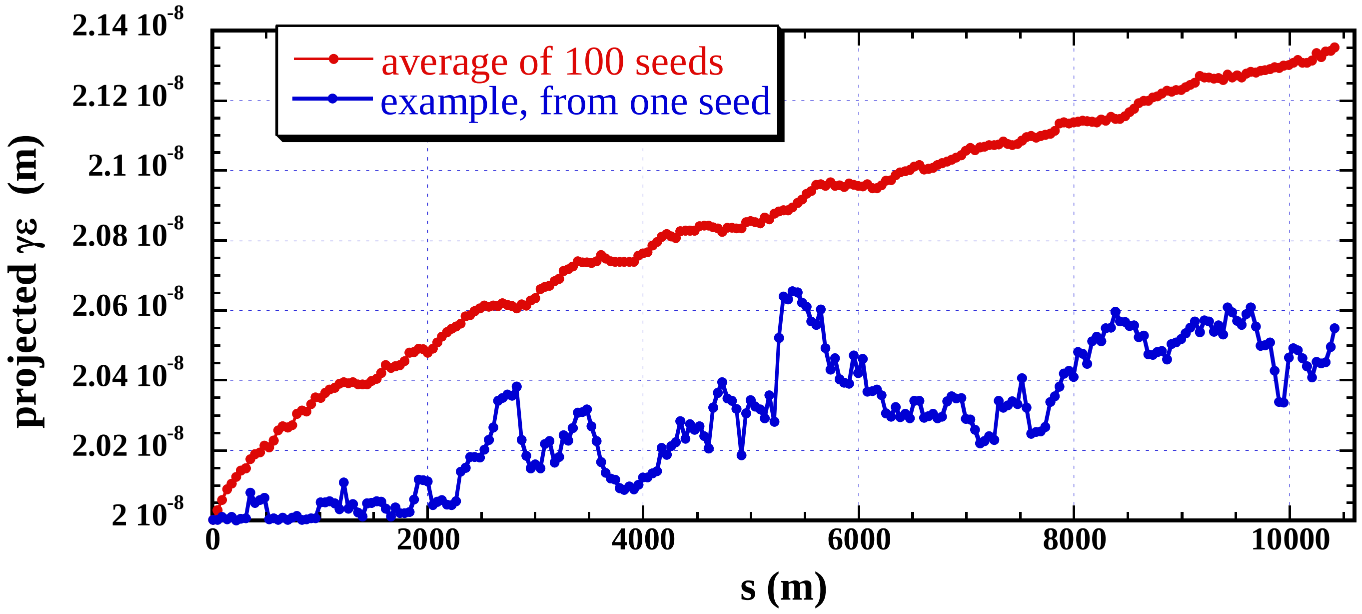






Example of simulation of short range wake effect-2

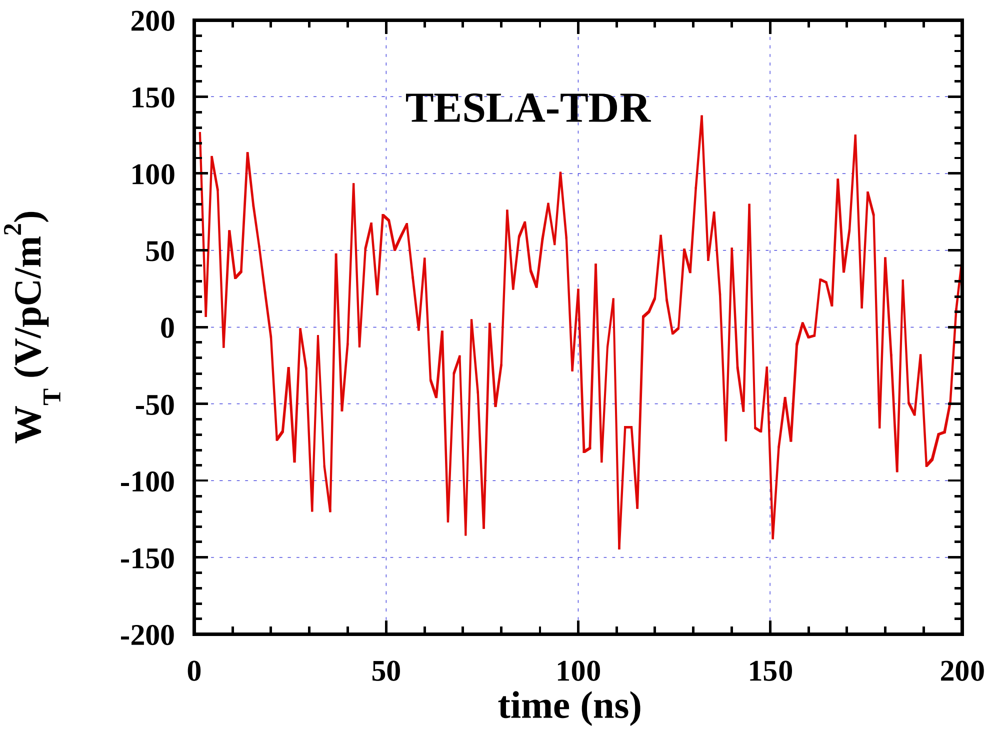
Single bunch, random misalignment of cavities, sigma=0.5 mm. Emittance along linac. One linac and average of 100 seeds. monochromatic beam.



Example of
Long range wakefunction

Sum of 14 HOMs from TESLA-TDR

Frequency (ave. meas.) [GHz]	Loss factor (simulation) [V/pC/m^2]	R/Q (simulation) [Ω/cm^2]	Q (meas.)
TE_{111}-like			
1.6506	19.98	0.76	$7.0 \cdot 10^4$
1.6991	301.86	11.21	$5.0 \cdot 10^4$
1.7252	423.41	15.51	$2.0 \cdot 10^4$
1.7545	59.86	2.16	$2.0 \cdot 10^4$
1.7831	49.20	1.75	$7.5 \cdot 10^3$
TM_{110}-like			
1.7949	21.70	0.77	$1.0 \cdot 10^4$
1.8342	13.28	0.46	$5.0 \cdot 10^4$
1.8509	11.26	0.39	$2.5 \cdot 10^4$
1.8643	191.56	6.54	$5.0 \cdot 10^4$
1.8731	255.71	8.69	$7.0 \cdot 10^4$
1.8795	50.80	1.72	$1.0 \cdot 10^5$
TE-like			
2.5630	42.41	1.05	$1.0 \cdot 10^5$
2.5704	20.05	0.50	$1.0 \cdot 10^5$
2.5751	961.28	23.80	$5.0 \cdot 10^4$

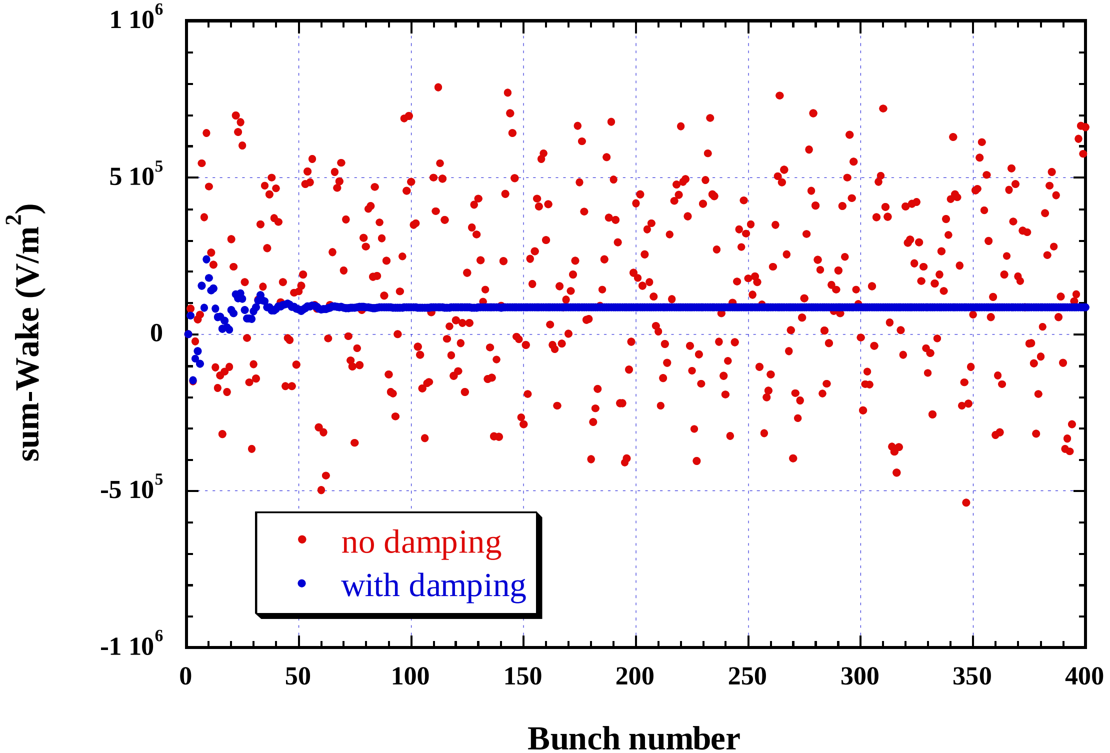


Mitigation of long range transverse wakefield effect

- Damping
  - Extract higher order mode energy from cavities through HOM couplers.
- Detuning
  - Cavity by cavity frequency spread.
    - Designed spread or
    - Random spread (due to errors)

- In LC, both will be necessary.

“Sum-Wake” from 14 HOM (from TESLA-TDR) with/without damping



Note: Bunch spacing is set as 219/650E6 s. The result strongly depend on the spacing.

$$W_j = \sum_{k<j} q_k W(z_j - z_k)$$

proportional to inverse of alignment tolerance

With damping, sum-wakes are almost the same for most of the bunches, except in the beginning of the beam pulse.
-->Orbit changes due to cavity misalignment are the same for most of the bunches. Please discuss implication of this. **HMWK-5**

Damping of Higher Order Mode Wakefield

Two HOM Couplers at both sides of a cavity

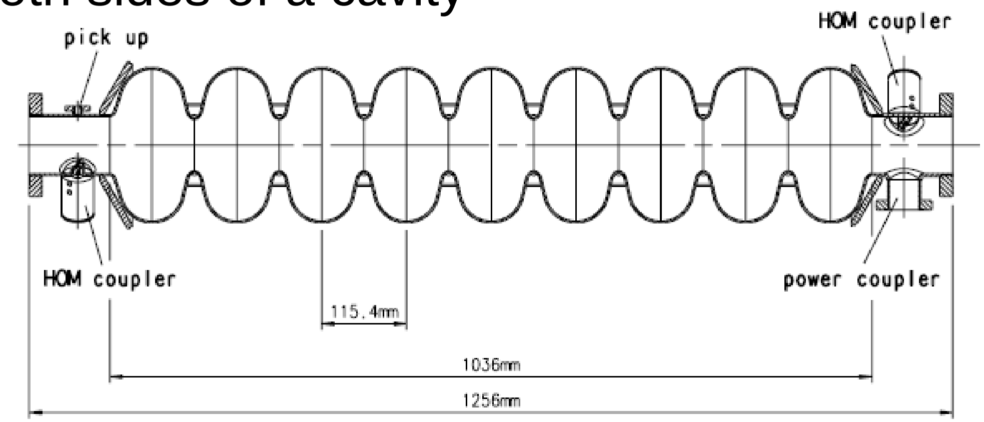
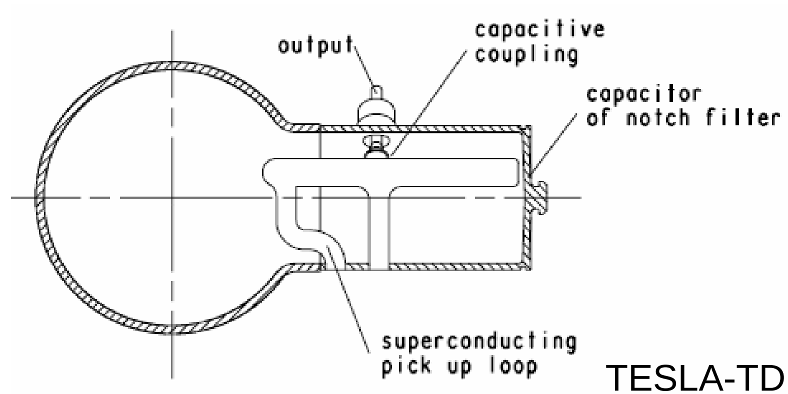


Figure 2.1.3: *Side view of the 9-cell cavity with the main power coupler port and two higher-order mode couplers.*

TESLA-TDR

Special shapes:

Accelerating mode should be stopped.
HOM should go through.
  - trapped mode may cause problem.



TESLA-TDR

Figure 2.1.20: *Cross-section of the higher order mode (HOM) coupler.*

Detuning of wakefield

For BBU: effective wake is from sum of cavities within length comparable to beta-function

n cavities in length comparable to beta-function,

$$W_{\text{effective}} \approx \sum_{i=1}^{n} W \sin \omega_i t$$

ω_i: HOM frequency of i-th cavity

If ω_i has no spread,

Amplitude of $W_{\text{effective}} \approx nW$,

If ω_i has spread δ_ω, for $t > 2\pi / \delta_\omega$,

Amplitude of $W_{\text{effective}} \approx \sqrt{n/2}\, W$.

In ILC Main Linac,

Typical HOM frequency ~ 2GHz, spread ≈ 0.1% $\rightarrow \delta_\omega \sim 2\text{MHz}$

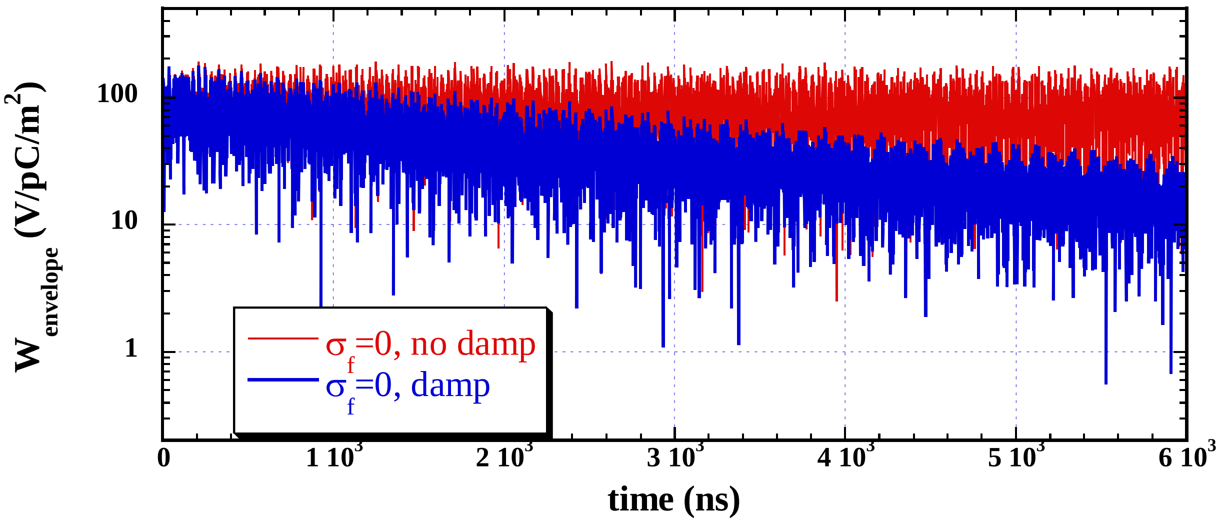
$\rightarrow$ Detuning becomes fully effective for $t \sim 500$ ns (next next bunch)

$n \approx 50 \rightarrow$ Wakefield reduction by factor of 10

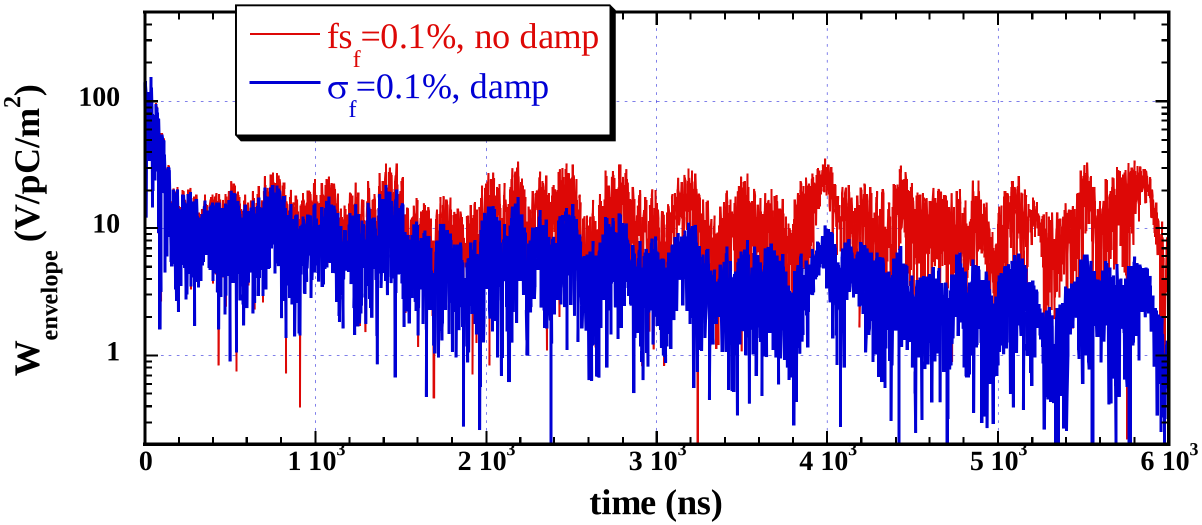
In X-band warm LC, carefully designed damped-detuned structures were necessary. Not for ILC.

Wakefunction envelope from HOMs (from TESLA-TDR) with/without random detuning (50 cavities) and damping

No detuning



Random detuning
σ_f/f=0.1%



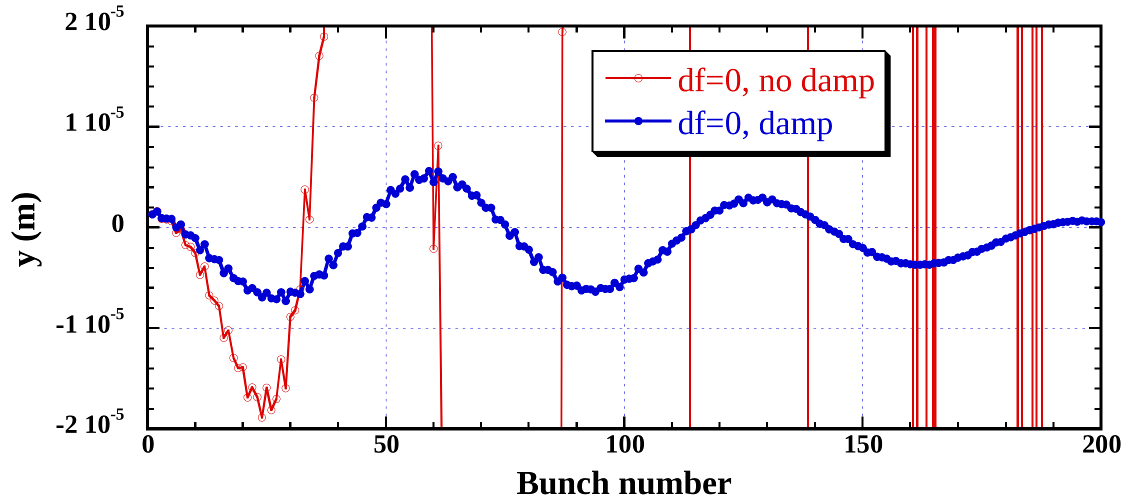
Example of simulation, long range wake effect-1

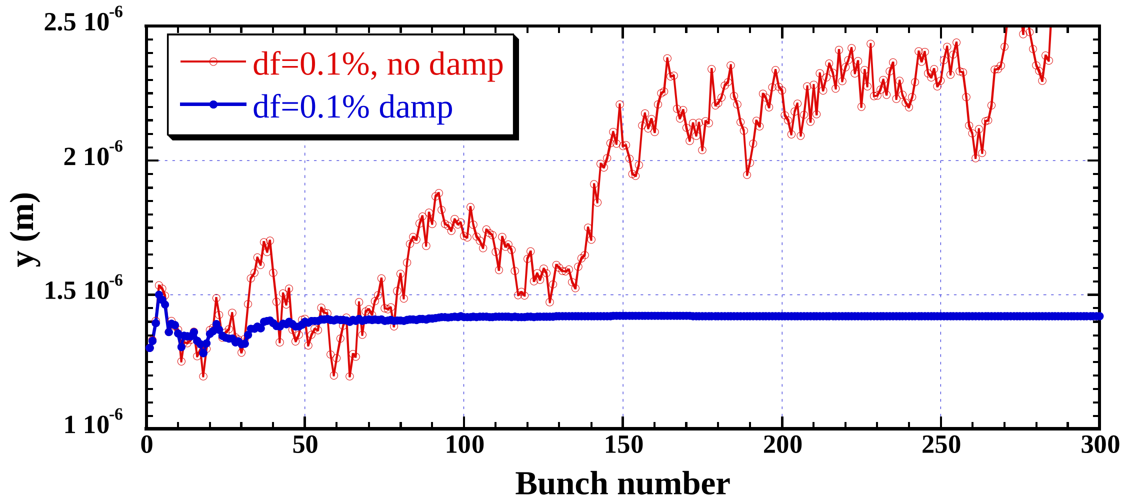
Multibunch BBU. Injection offset in perfectly aligned linac.

y vs. bunch number at the end of linac,

injection offset 1 sigma of beam size.

w/wo damping. w/wo frequency spread 0.1%.





(vertical scales are different by more than 1 order)

Detuning is very effective for BBU.

Example of simulation, long range wake effect-2

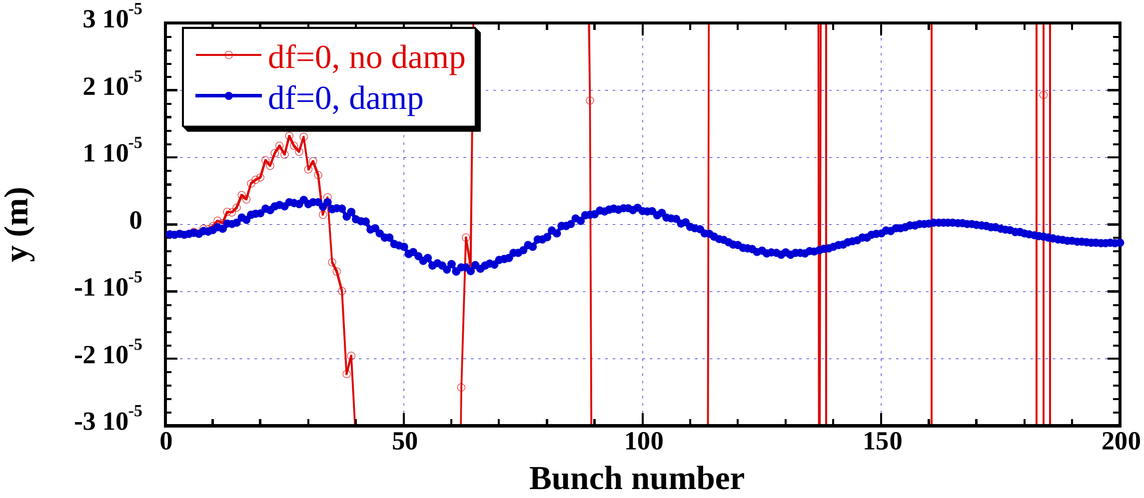
Multibunch, random misalignment of cavities

y vs. bunch number at the end of linac,

Misalignment of cavities, sigma=0.5 mm.

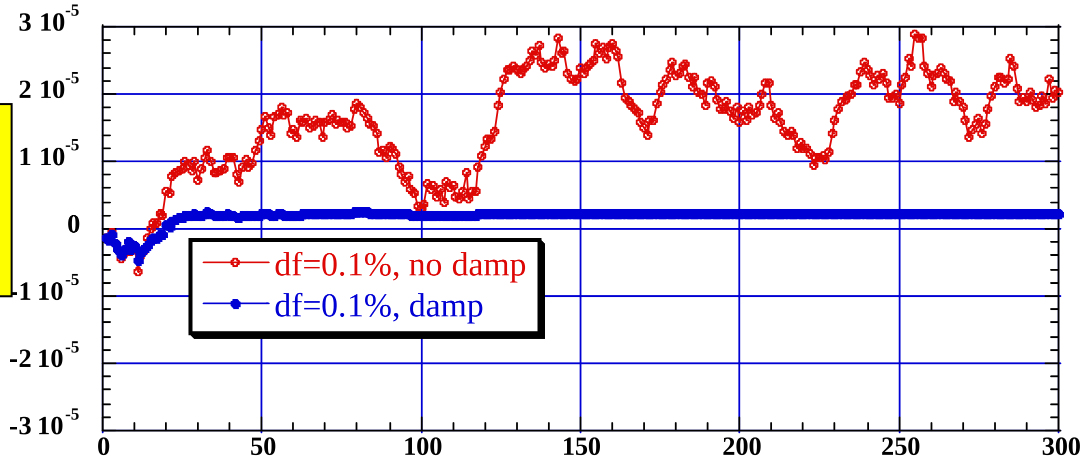
.

w/wo damping. w/wo frequency spread 0.1%.



(vertical scales are the same)

Detuning is not so effective for random misalignment as for BBU.



Possible vertical orbit induced by long range wakefield excited by horizontal orbit x-y coupling of wakefield mode

SKIP

- Horizontal beam orbit will be less stable than vertical. (Horizontal emittance is much larger than vertical, more than factor of 400 at the DR extraction.)
- Some dipole modes of wakefield may be x-y coupled
- Horizontal orbit may induce vertical orbit.

x-y coupling of long range wakefield

SKIP

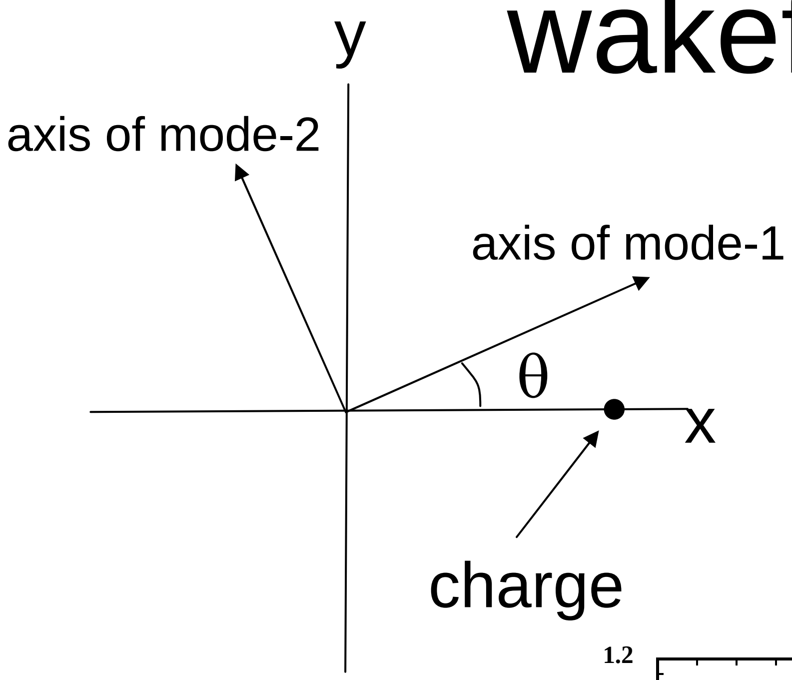
Consider dipole wakefield.

If cavity is perfectly x-y symmetric, two polarization modes has the same frequency (perfectly degenerated.)
Induced field by particles with horizontal offset kicks following particles only horizontally.

If symmetry is broken, two polarization have different frequency and their axis can be slant.
Induced field by particles with horizontal offset consists of two slant modes and can kick following particles vertically too.

x-y coupling of long range wakefield

SKIP



$$W_1(0) = eq\,xW\cos\theta$$

$$W_2(0) = -eqW\sin\theta$$

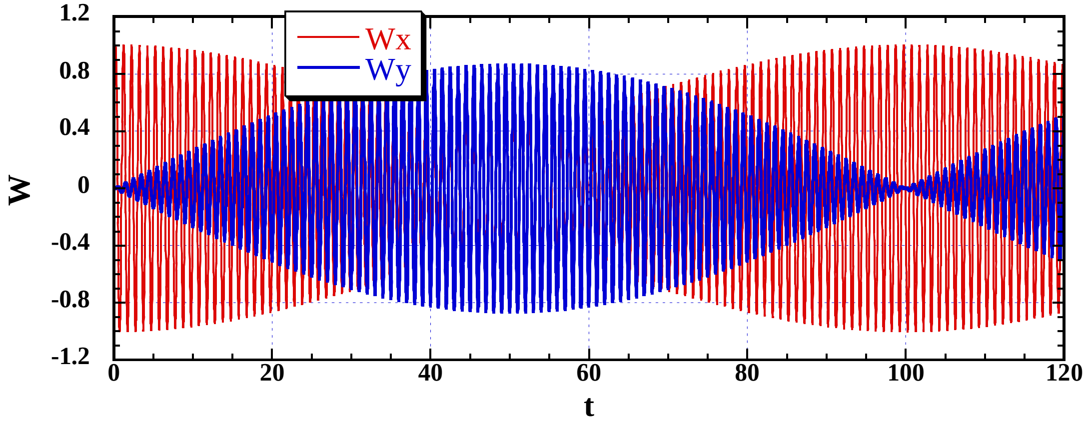
$$W_1(t) = W_1(0)\sin(\omega - \Delta/2)t$$

$$W_2(t) = W_2(0)\sin(\omega + \Delta/2)t$$

$$W_x(t) = W_1(t)\cos\theta - W_2(t)\sin\theta$$

$$W_y(t) = W_1(t)\sin\theta + W_2(t)\cos\theta$$

$$= -eq\,xW\sin 2\theta\,\sin(\Delta/2)t\,\cos\omega t$$



SKIP

Cures of x-y coupling due to long range wakefield

- Extremely good cylindrical symmetry of cavities. $\Delta \rightarrow 0$: difficult? and/or cost?
- Stronger damping : difficult?
- Intentionally broken symmetry. $\theta \rightarrow 0$: cost?
- x-y tune difference (Different phase advance per FODO cell). Suppress the effect of the coupling.
- etc. ???

Dispersive effect

Dispersive effect

- Dominant source of emittance dilution in ILC Main Linac
- Depend on initial energy spread
- Important errors:
  - Quad misalignment
  - Cavity tilt (rotation around x-axis)
- Need rather sophisticated corrections
  - DFS (Dispersion Free Steering)
  - Kick Minimum
  - etc.

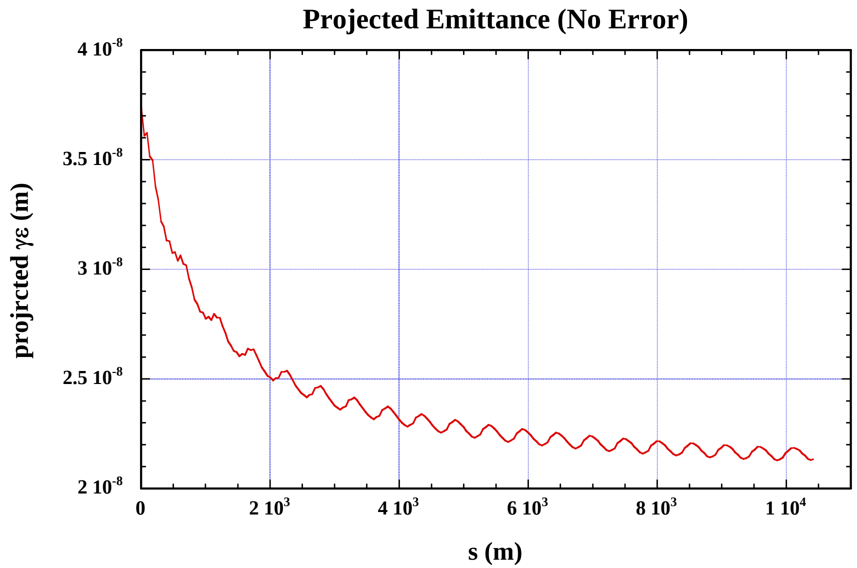
Note: Correction of Linear Dispersion -1

- Energy-position correlation will be measured after the main linac. And linear dispersion will be well corrected, (we assume).
- “Linear dispersion corrected emittance” should be looked, not projected emittance. (see appendix - 1)
- There is designed dispersion in curved linac. Even without errors, projected emittance is significantly larger than “linear dispersion corrected emittance”.

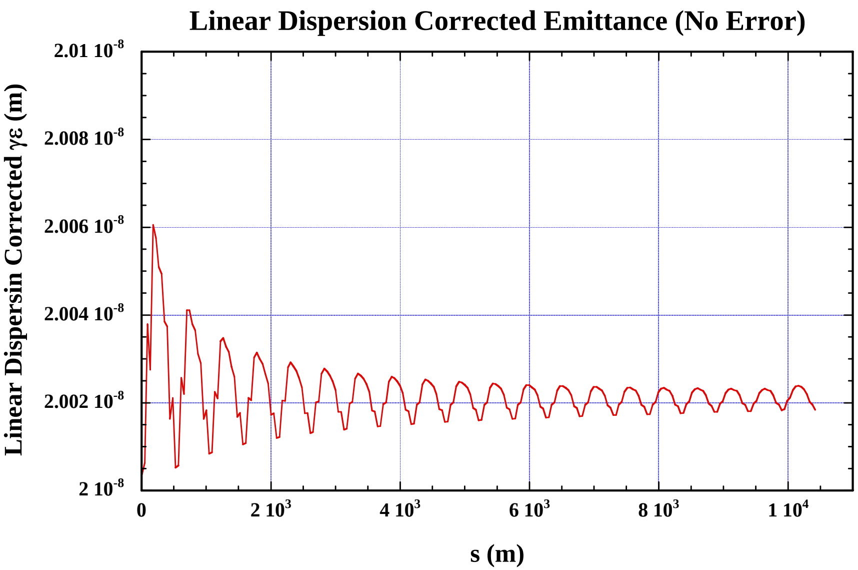
Note: Correction of Linear Dispersion -2

- In principle, correction of non-linear dispersion is possible. But practically, it will be very difficult. Only 1st order dispersion can be measured and corrected (practically).
- Even if 1st order dispersion is corrected at the end of linac, there can be large higher order dispersion remained.
- Transverse E-M fields at zero dispersion will induce linear (1st order) dispersion. And transverse, position dependent E-M fields (quad magnet) at non-zero n-th order dispersion will induce (n+1)th order dispersion.
- 1st order dispersion should be kept small everywhere in the linac to suppress higher order dispersions, then for preservation of low emittance.

Emittances in curved linac without errors



This is getting small as the relative energy spread becomes small.

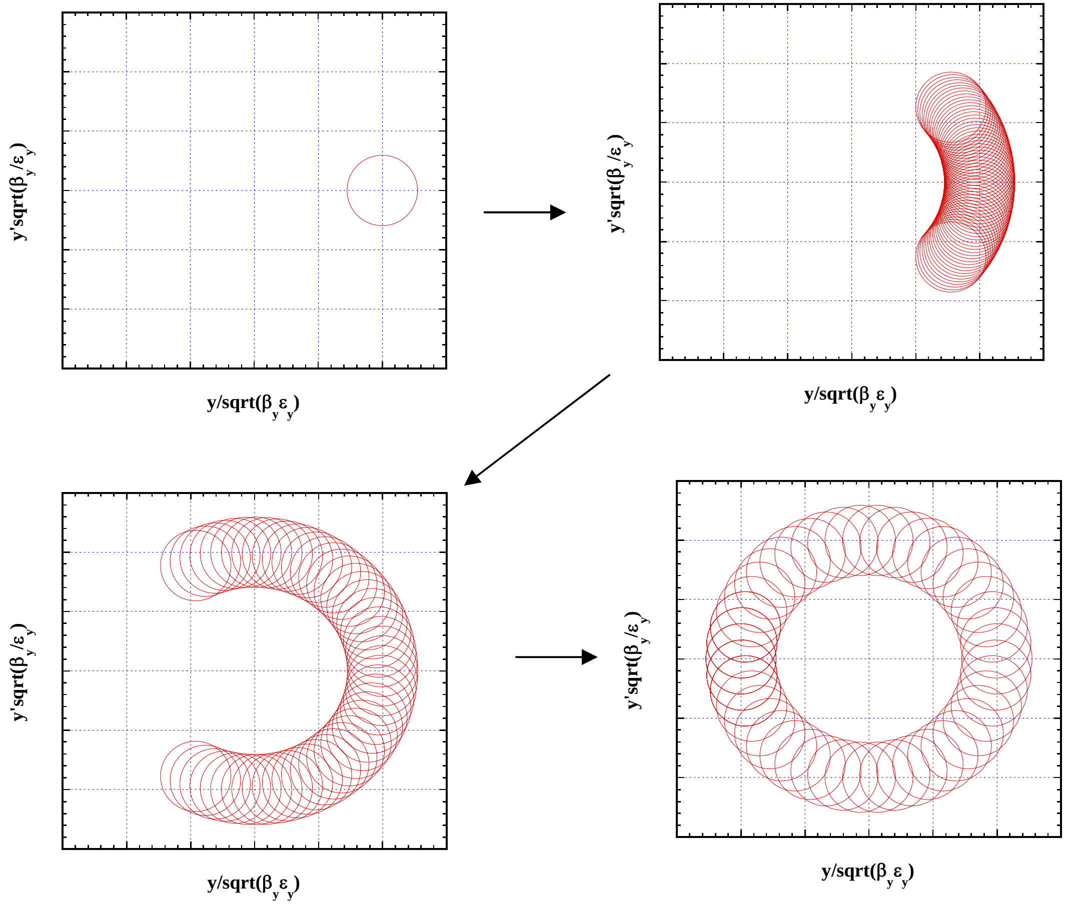


The emittace increases by 0.1% of nominal. Initial dispersion should be matched

Dispersive effect in perfect linac

"Filamentation" with injection error

Different phase advance for different energy particles.

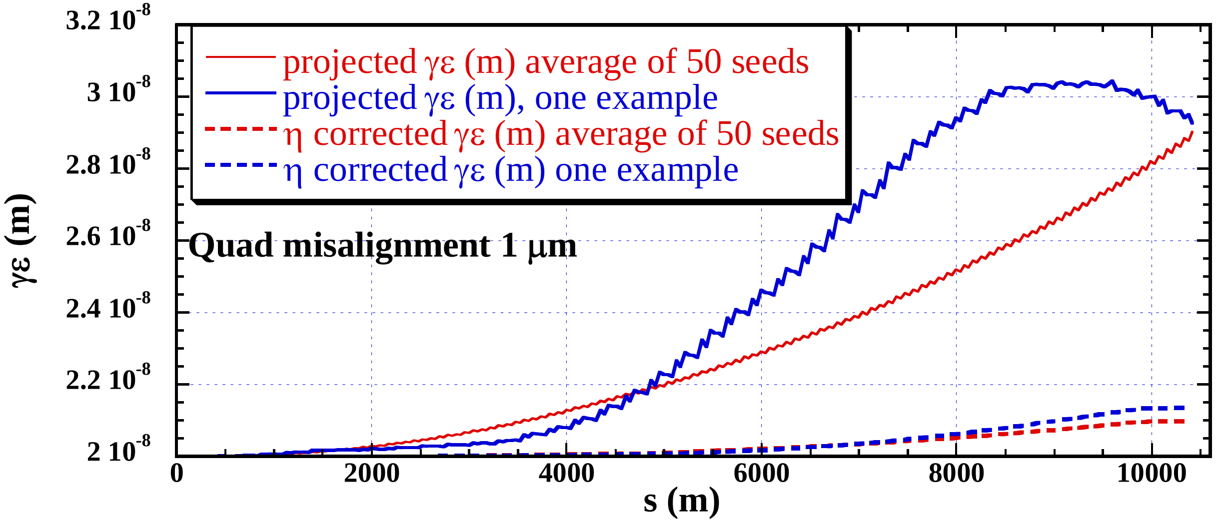


Dispersive effect from quad misalignment

- Charged particle goes through quad magnet with offset is kicked.
- The transverse momentum change is proportional to the offset.
- The angle change proportional to inverse of energy of the particle.
- Many of such angle differences induce non-linear dispersion, which cannot corrected later.

Simulation result - Emittance along linac (straight linac)

Random offset, σ 1um..

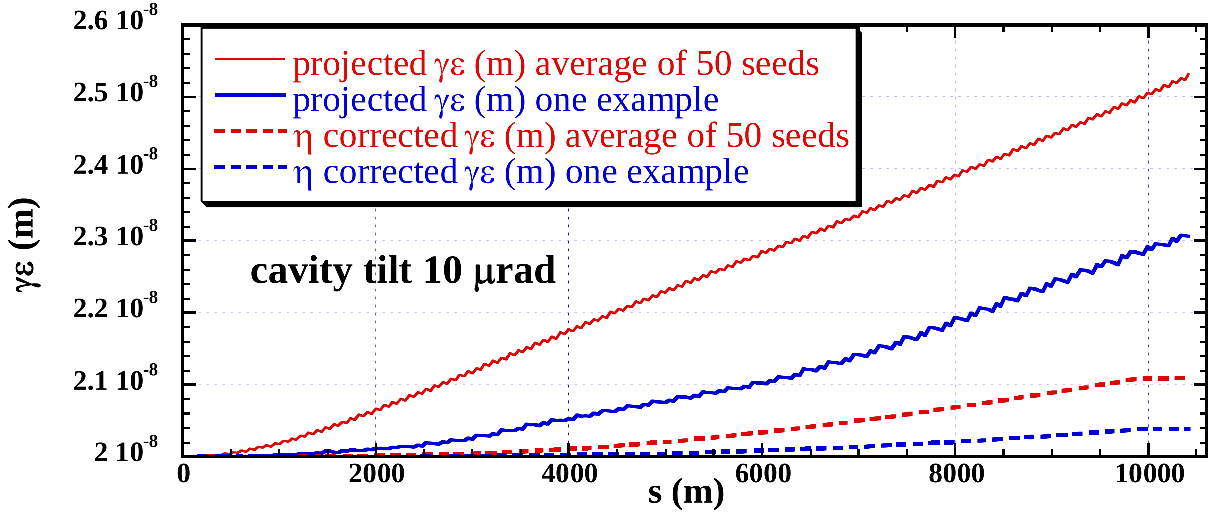


Dispersive effect of cavity tilt

- Charged particle is transversely kicked by the tilted cavity.
- The momentum change is about Vc*tilt angle / 2 (see next slide).
- The angle change proportional to inverse of energy of the particle.
- Many of such angle change differences and quad magnet fields induce non-linear dispersion, which cannot corrected later.

Simulation result - Orbit and Emittance along linac (straight linac)

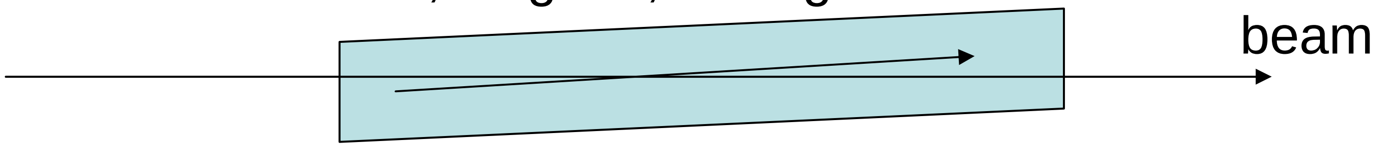
Random tilt, σ 10 μrad.



Note: Edge focus reduce the effect of cavity tilt

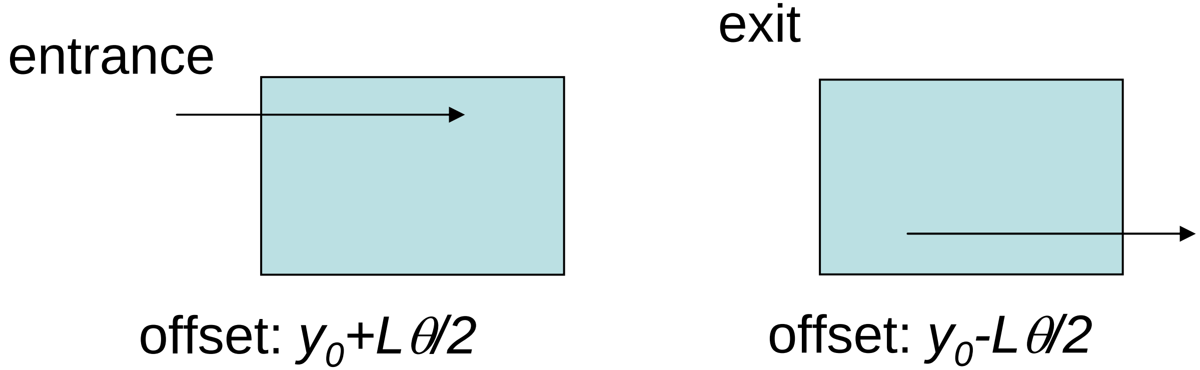
SKIP

Acc. field E, length L, tilt angle θ



Transverse kick in the cavity: $\Delta pt = \theta eEL$

Edge (de)focus [see appendix]



Transverse kick at the entrance: $\Delta pt = -eE\,(y_0+\theta\,L/2)/2$

Transverse kick at the exit: $\Delta pt = eE\,(y_0-\theta\,L/2)/2$

→Total transverse kick by the cavity: $\Delta pt = \theta eEL/2$

Static corrections (transverse motion)

Necessity of Beam based corrections

- Without corrections, required alignment accuracy to keep emittance small will be, roughly:
  - 0.1~1 um for quad offset
  - 1~10 urad for cavity tilt

  which will not be achieved.

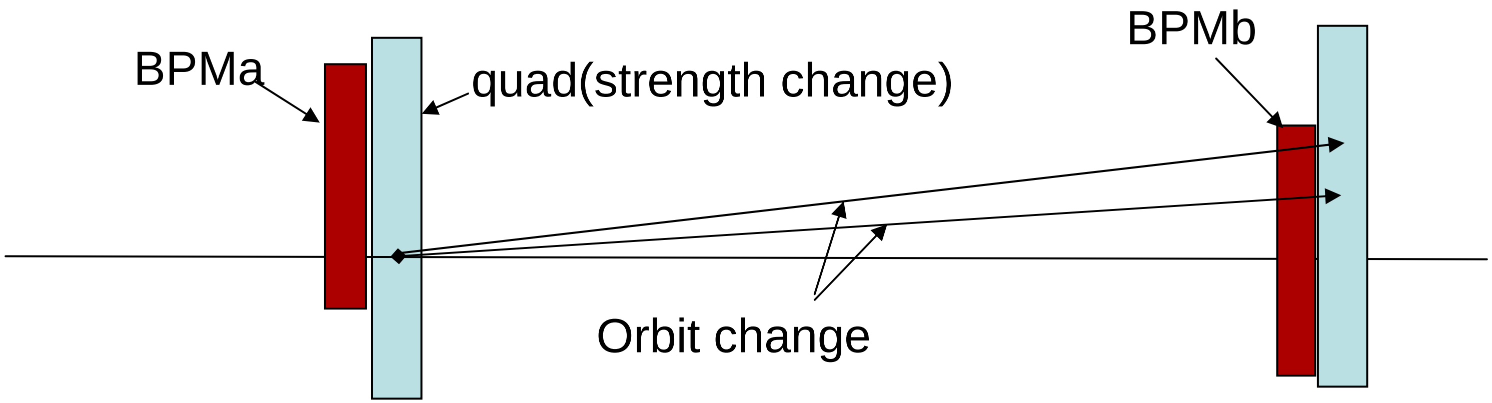
  (cavity offset ~ a few 100 um may not be serious problem.)

Beam based static corrections

- Corrections using information from beam measurement will be necessary
  - 1 to 1 correction
    - non-invasive, but will not be enough
  - Kick minimization
    - non-invasive, but cannot correct for cavity tilt. Need additional correction
  - DFS (Dispersion Free Steering)
    - invasive, seems promising
  - Ballistic Steering
    - invasive. Not yet studied if it is good or not for curved linac ?
  - etc.
- These are “Local” corrections. Beam quality is to be corrected everywhere in the linac.

Quad shunting
for finding Quad - BMP center offset

- Some correction methods need to know BPM - Quad center offset accurately. (BPM is attached to quad.)
- Quad shunting (change strength) and measuring beam will probably be the best way.
- Changing strength of <u>superconducting magnet</u> cannot be so fast. The procedure will take time. (Possible? How long?)
- The accuracy depend of BPM resolution, how much strength is changed and stability of field center (for different strengths and also long term).



$$(\mathrm{Q-BPM\ offset})_a = (\mathrm{BPM}_a \mathrm{read}) - \frac{(\mathrm{BPM}_b \mathrm{read\ change})}{(\mathrm{Q\ strength\ change})}$$

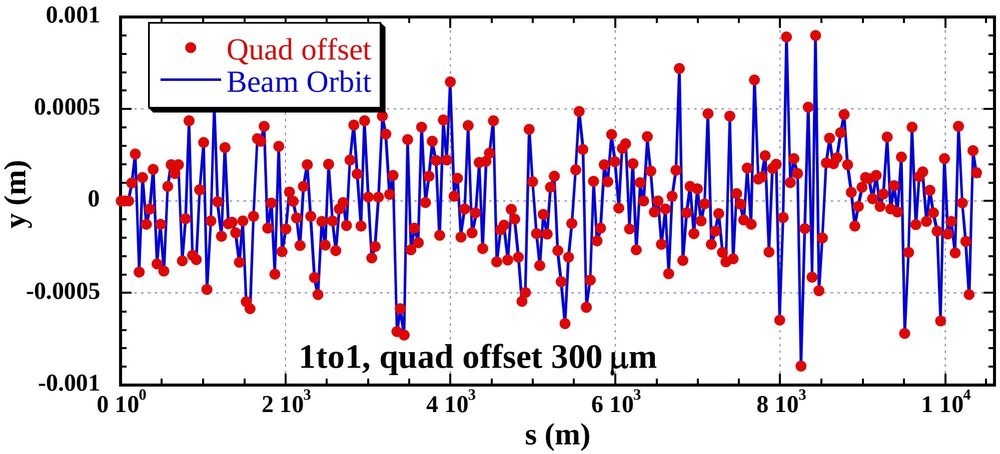
One to one correction

Make BPM readings zero, or designed readings

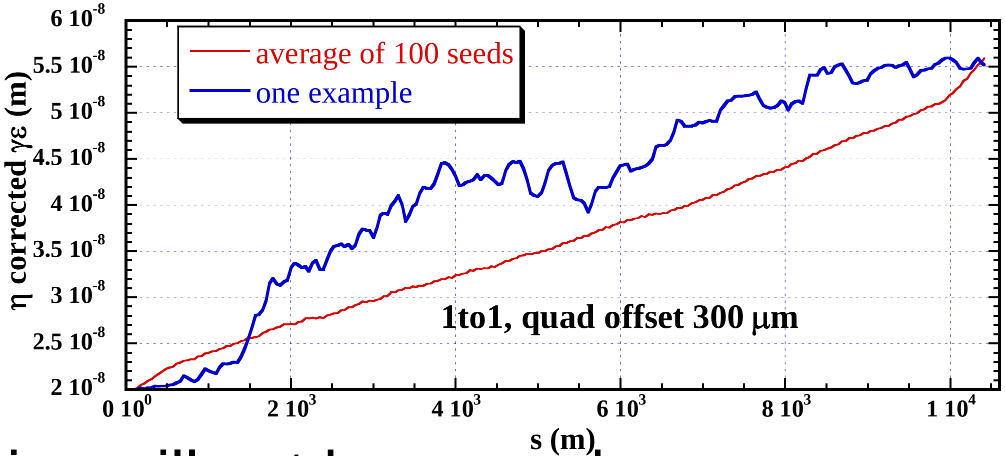
Simulation result:

Quad random offset σ 300 μm, no other errors

Example of quad offset and beam orbit



Emittance along linac



One to one correction will not be enough.

SKIP

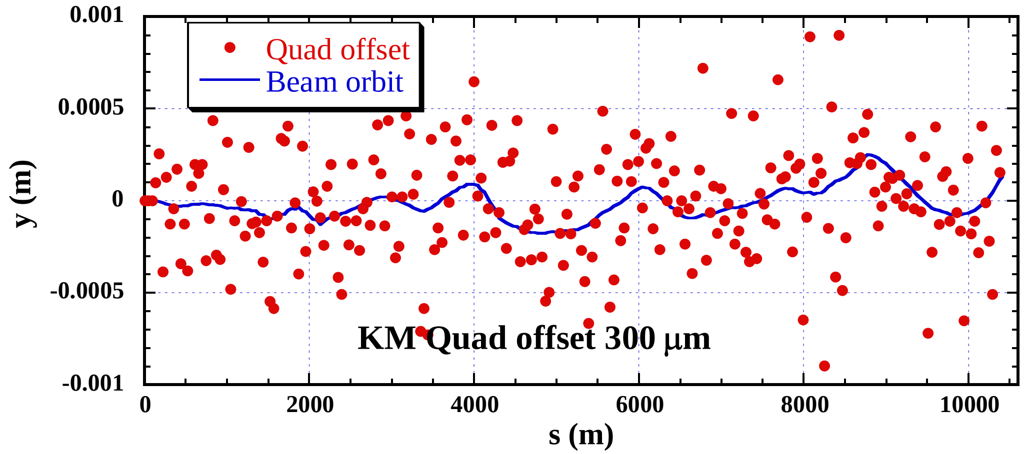
Kick Minimization (KM)

- Basically:
  - Steer beam to minimize kick angle at every quadrupole-dipole magnet pair. Or minimize deviation from designed kick angle. (Requiring Quad and dipole magnets are attached or very close each other.)
  - See appendix for a little more details
- Can be non-invasive correction
  - may be used as a “dynamic correction” for relatively slow quad motions.
- Accurate information of Quad - BPM offset is important.
- Can correct quad misalignment but not effective for cavity tilt.

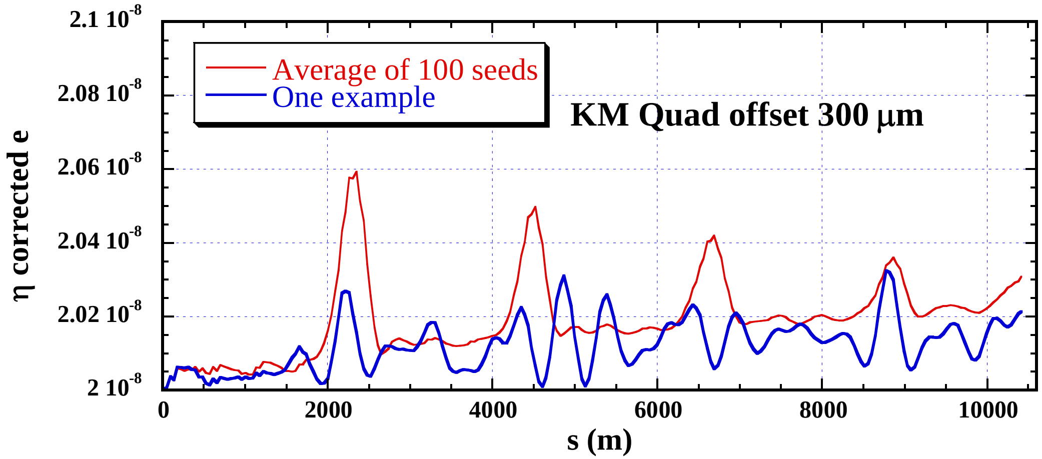
KM, example of simulation result

SKIP

Simulation result:
Quad random offset σ 300 μm, no other errors
Example of quad offset and beam orbit



Emittance along linac

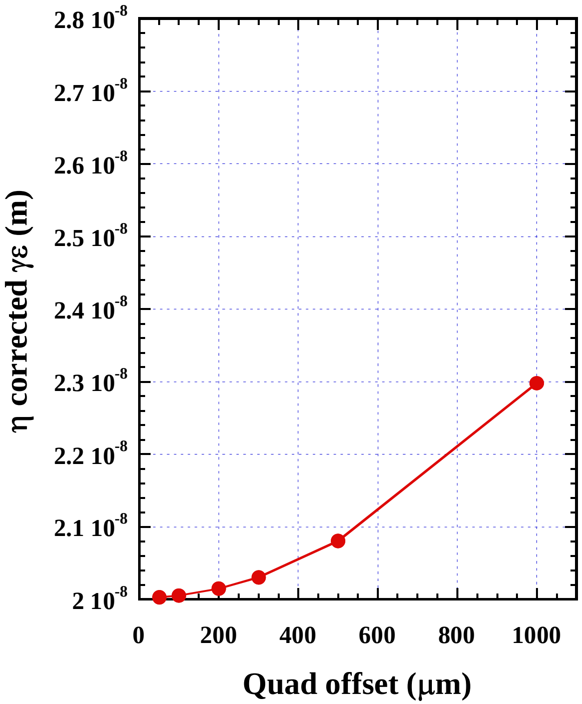


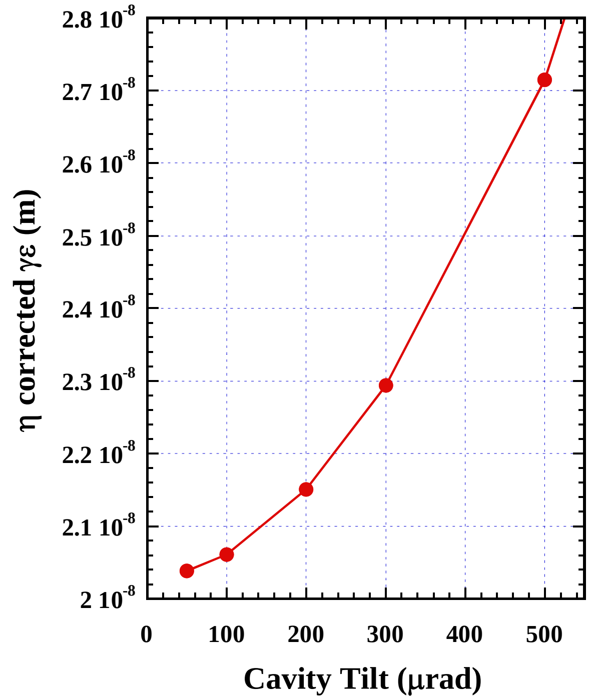
KM, example of simulation result - 2

SKIP

Sensitivity to errors.

Emittance at the end of linac. Average of 100 random seeds.



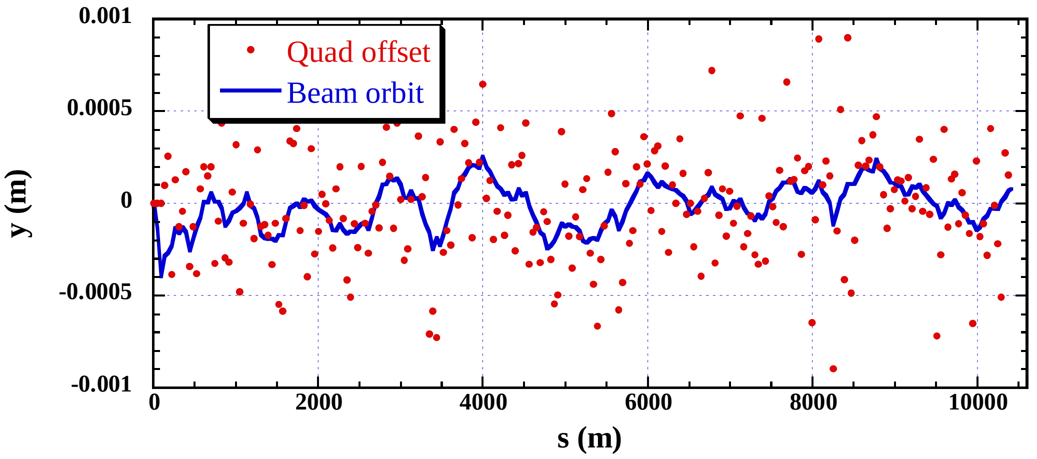


DFS (Dispersion Free Steering)

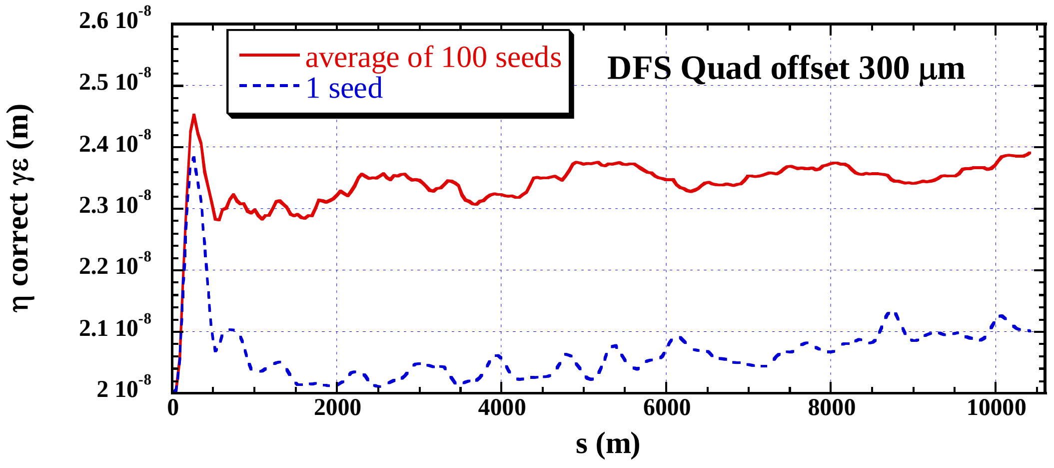
- Basically:
  - Change beam energy and measure beam orbit.
  - Steer beam to minimize orbit difference. Or, minimize deviation from designed orbit difference in the case of the curved linac.
  - See appendix for an example of algorithms (not necessarily the best one)
    - Results seem to depend on some details of algorithms. (?)
- Need to change accelerating voltage to change beam energy. ~ 10%
  - How accurately it can be, practically???
- BPM resolution is important but information of Quad - BPM offset is not so important.
  - Because “difference of orbit” is looked at.

DFS, example of simulation result

Simulation result:
Quad random offset σ 300 μm, no other errors
Example of quad offset and beam orbit



Emittance along linac

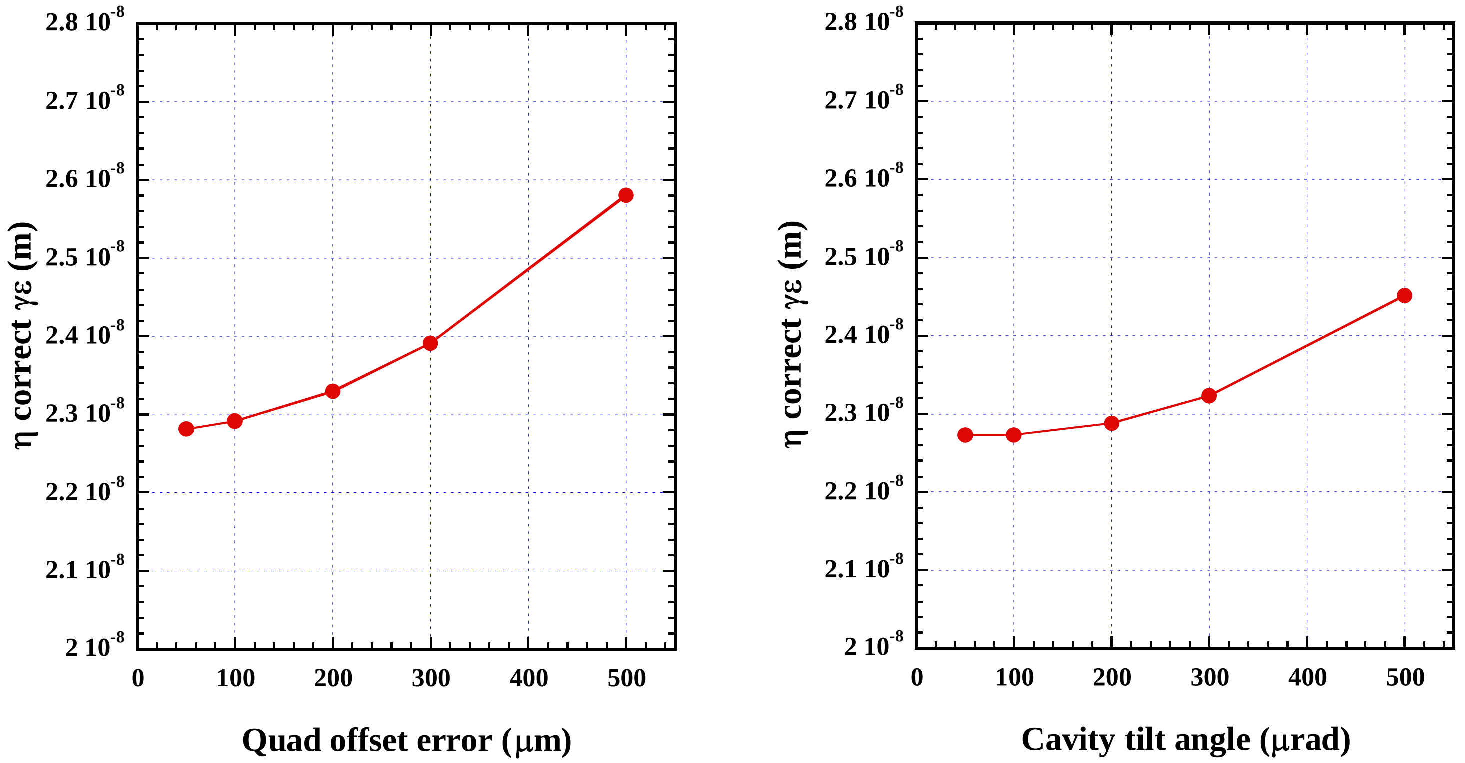


This particular algorithm may not be optimum.
Do not quote these figures.

DFS, example of simulation result - 2

Sensitivity to errors.

Emittance at the end of linac. Average of 100 random seeds.



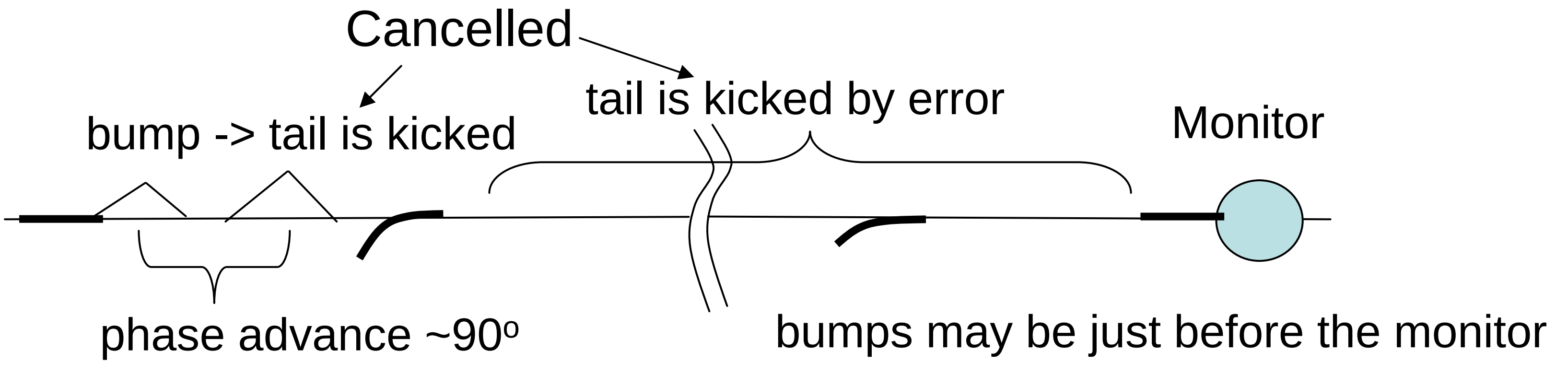
This particular algorithm may
not be optimum.
Do not quote these figures.

“Global” corrections

- In addition to “Local” corrections.
- Scan knobs, measuring beam at the end of the linac or certain linac section, and finding the best setting of the knobs.
- For ILC, we are considering:
  - Knobs: Orbit bumps
  - Measurement: emittance or beam size
  - Correct dispersive effect: “Dispersion bumps”
  - Correct wakefield effect: “Wakefield bumps”

Dispersion Bumps and Wakefield Bumps

- Energy-dependent kick (dispersion) or/and z-dependent kick (wakefield) in the section is to be compensated by the bumps.
  - Possible (in principle) by two bumps, phase advance 90 deg. apart.
  - The length of the section should not be so long. Induced dispersion or z-x/y correlation (by wakefield) should be corrected before significant filamentation.



Dynamic corrections (Feedback)

Dynamic errors

- Mechanical motion
  - Motion induced by the machine itself (motors for cooling, bobbles in pipes, etc.)
  - Cultural noise (nearby traffic, etc.)
  - Ground motion (slow movement, earth quake)

- Strength
  - Field strength of magnets
  - Accelerating field, amplitude and phase

- EM field from outside
  - no problem for high energy beam (?)

Typical speed of fluctuations and corrections for transverse motion

Speed (Hz)	Possible source	Effective correction	For
$>10^6$	DR kickers, what else ?	Feed forward (in turnaround)	Position
$1 \sim 10^6$	Machine, cultural noise, Power supply, ground motion	Intra pulse feedback at IP	Position
0.001 ~ 1	Temperature change, ground motion,	Simple orbit feedback (in BDS and Linac)	Position
? ~ 0.01	What else?	More sophisticated orbit FB(, e.g. KM, If necessary).	Emittance
0 ~ 0.0001?		“static” corrections	Emittance

Note on Dynamic correction in ILC Main Linac - 1

Some simulations studies were, (and are being), performed. But,

Studies have not well matured for ILC and there is no commonly agreed scheme, but probably:

1. Orbit correction at several locations.
2. Energy feed back. One or two locations / linac (?)
3. One-to-one orbit correction (using all or most correctors and BPM, slower than1)
4. Some non-invasive corrections, if necessary.

Need to be careful from Machine protection point of view.

IF feedbacks change machine parameter too much, the beam may hit some part of machine.

Note on Dynamic correction in ILC Main Linac - 2

Dynamic errors (component position movement, field strength fluctuations) during "static" tuning can be problem.

- "Static" tuning will take time (many minutes or an hour or ?)
- "Static" tuning assumes (requires) stability of the machine during beam measurements and corrections.

This effect is not expected to be so serious (?), but has not been well studied.

LAST SLIDE

Status of ILC-ML beam dynamics study

- “Static” simulations have been well performed.
- “Dynamic” simulations are less developed.
- Integrated studies from Damping Ring to IP. More simulations will be needed though some studies have been done.

I (we?) expect the design performance will be achieved with reasonable tolerances of errors.

Still, a lot of things to do for confirmation of the expected performance.

Appendix - 1

Definition of

Projected emittance and
Linear Dispersion Corrected emittance

Projected emittance

$$\equiv \sqrt{(<y^2>-<y>^2)(<y'^2>-<y'>^2)-(<yy'>-<y><y'>)^2}$$

Linear Dispersion Corrected emittance

$$\equiv \sqrt{(<(y-\eta\delta)^2>-<y-\eta\delta>^2)(<(y'-\eta'\delta)^2>-<y'-\eta'\delta>^2)-(<(y-\eta\delta)(y'-\eta'\delta)>-<y-\eta\delta><y'-\eta'\delta>)^2}$$

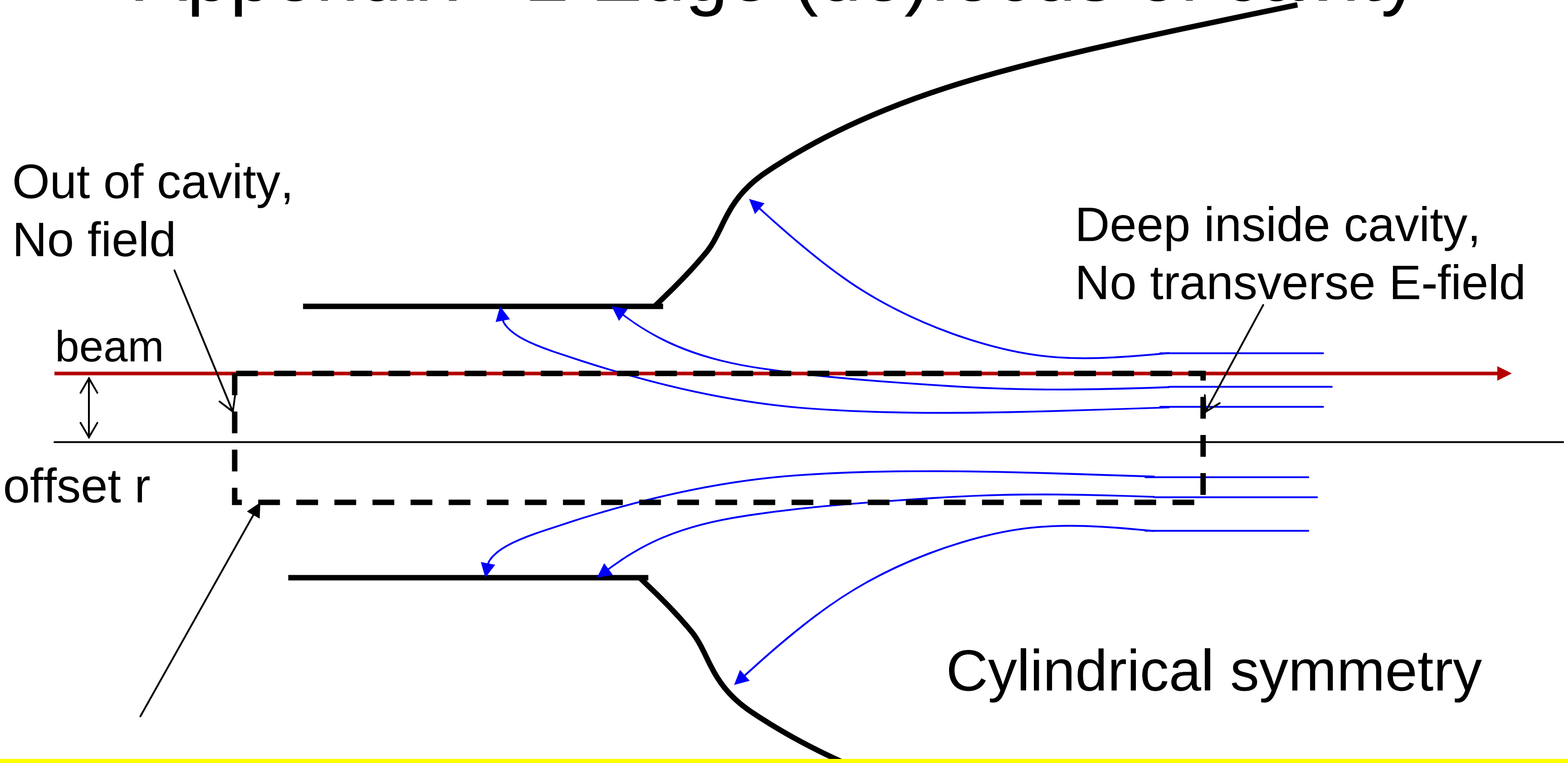
y: Vertical offset, y': Verticale angle

δ: Relative energy deviation

$\eta \equiv (<y\delta>-<y><\delta>)/(<\delta^2>-<\delta>^2)$, $\eta' \equiv (<y'\delta>-<y'><\delta>)/(<\delta^2>-<\delta>^2)$

$<>$: Average over all macro - particles

Appendix - 2 Edge (de)focus of cavity



Apply Gauss' Law to the cylinder, radius=r.
Then, relation between integrated transverse force,
felt by the beam, and accelerating field strength will be given.

Appendix- 3, Example of KM Algorithm

Every quad should have a BPM and a dipole corrector attached.
Divide linac into sections, and in each section, from upstream to down stream,
Minimize additional offset and additional kick” at quads.

$$\text{Minimize} \ \ r\sum_i y_i^2 + \sum_i \left(\theta_i - k_i y_i\right)^2,$$

θ_i : Additional kick angle (additional to designed kick) of steering at i - th quad

y_i : Offset from designed orbit at i - th quad

k_i : K - value of the i - th quad

r : Weight ratio. $= 10^{-3}$

Appendix- 4, Example of DFS Algorithm

One-to-one orbit correction (BPM reading zeroed)

Divide linac into sections, and in each section:

(1) Measure orbit with nominal beam energy. ($y_{0,i}$ at i-th BPM)

(2) Reduce initial beam energy and accelerating gradient from the linac entrance to the end of previous section by a common factor δ (e.g. 10% or δ= -0.1).

(3) Measure orbit. ($y_{\delta,i}$ at i-th BPM)

(4) Set dipole correctors in the section to minimize

$$w\Sigma(y_{\delta,i} - y_{0,i} - \Delta y_{cal,i})^2 + \Sigma(y_{0,i} - y_{cal,i})^2$$

($\Delta y_{cal,i}$ is the calculated orbit difference, $y_{cal,I}$ the calculated orbit, without errors, at I-th BPM. w is the weight factor, e.g. w=5000.).

(5) Iterate from (1) to (4).

(6) Go to next section.