



Linear Colliders

Lecture 2

Subsystems I



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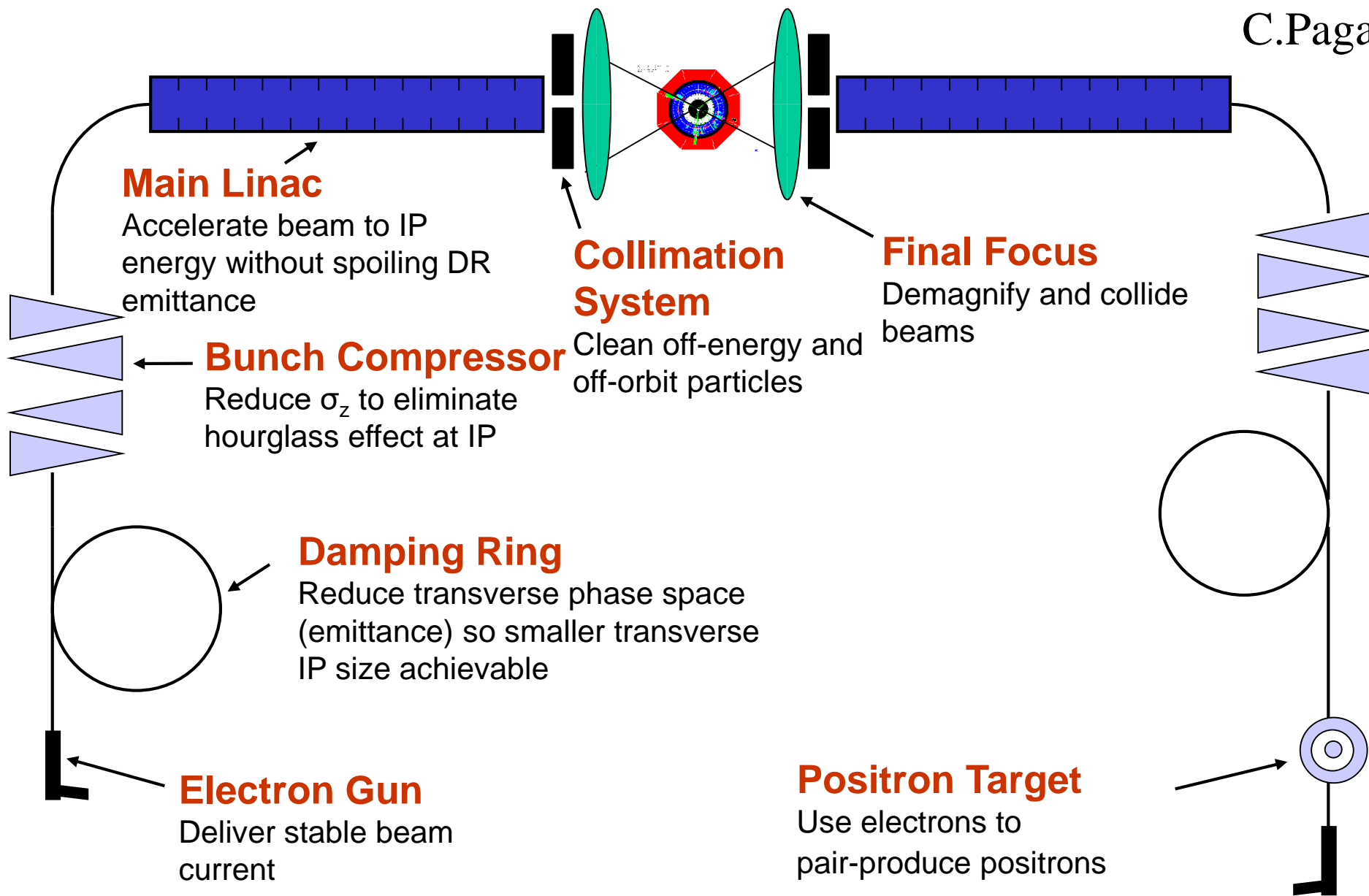
- Particle Sources
- Damping Rings
- Bunch Compressor
- Main Linac

Last lecture, we arrived at:

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D$$

- we want **high RF-beam conversion efficiency** η_{RF}
- need **high RF power** P_{RF}
- **small normalised vertical emittance** $\varepsilon_{n,y}$
- **strong focusing at IP** (small β_y and hence **small bunch length** σ_z)
- could also allow higher beamstrahlung δ_{BS} if willing to live with the consequences (Luminosity spread and background)

C.Pagani



• will see the different elements in the following...

- we need large number of bunches of (polarized) leptons

- **electron sources:**

- laser-driven DC photo injector

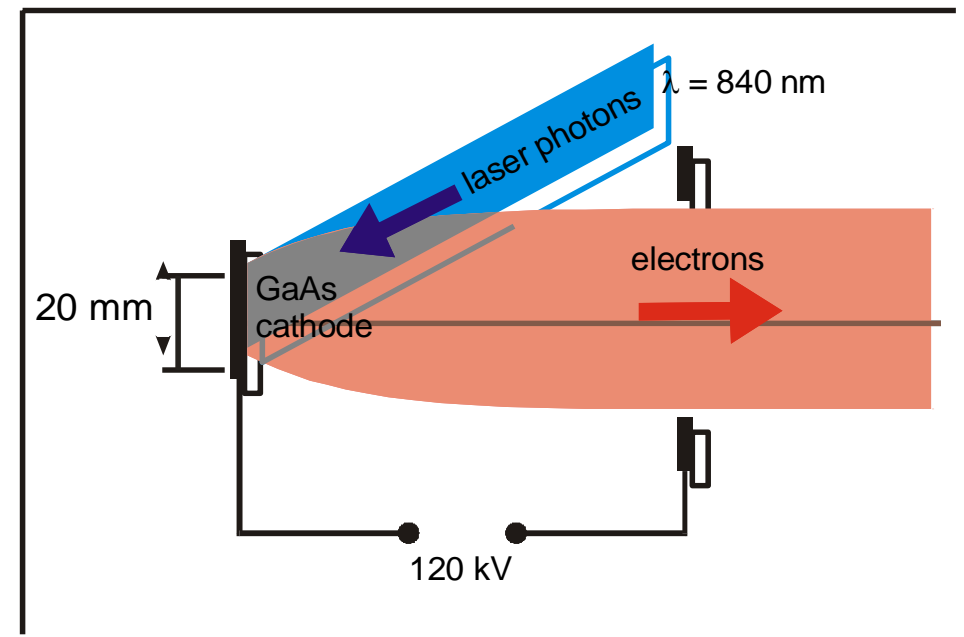
- circularly polarized photons on GaAs cathode (incompatible with RF gun)

- $\epsilon_n \sim 50 \mu\text{m rad}$
factor ~ 10 in x plane
factor ~ 500 in y plane
too large!!!

- dominated by **space charge**

- RF bunching system to generate bunch structure for the linac

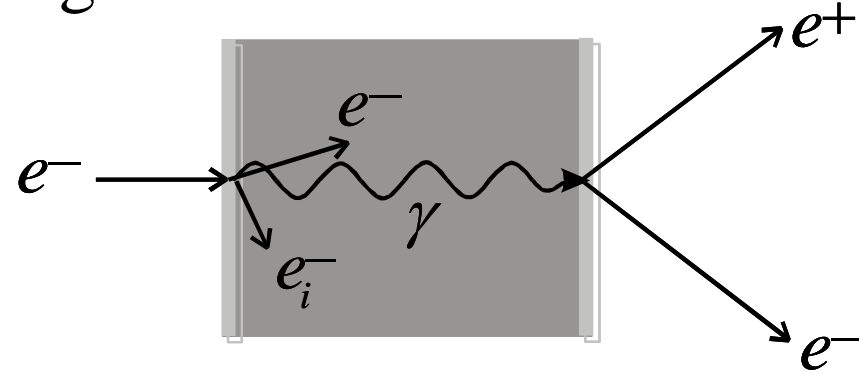
- (or laser with bunch time structure => even higher space charge)



- basic mechanism: **pair production** in target material

- standard method: **'thick' target**

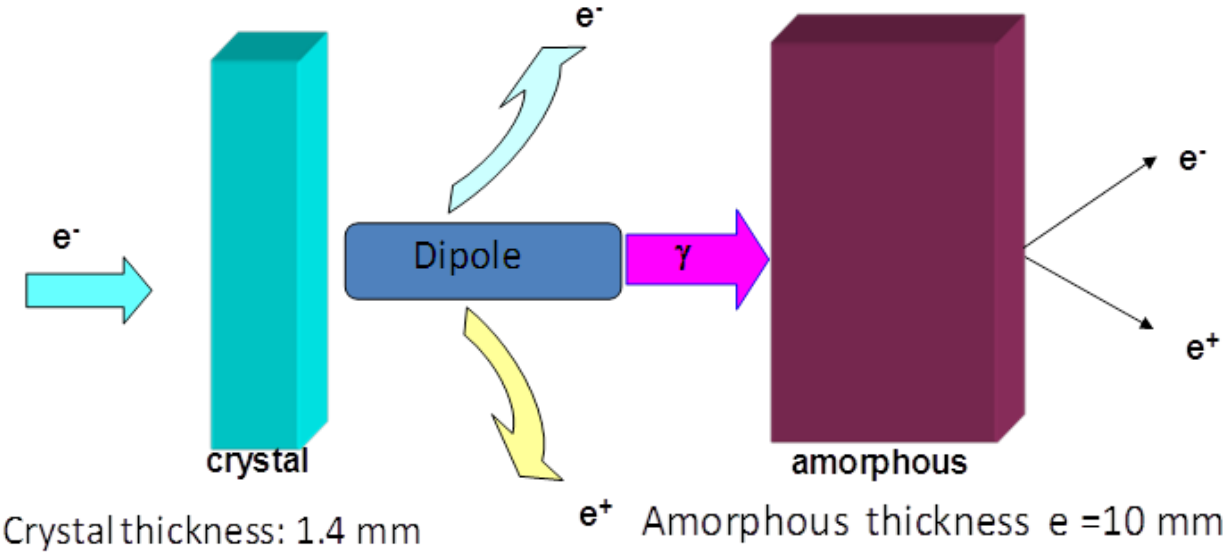
primary e- generate photons
these convert into pairs



- **Hybrid source:**

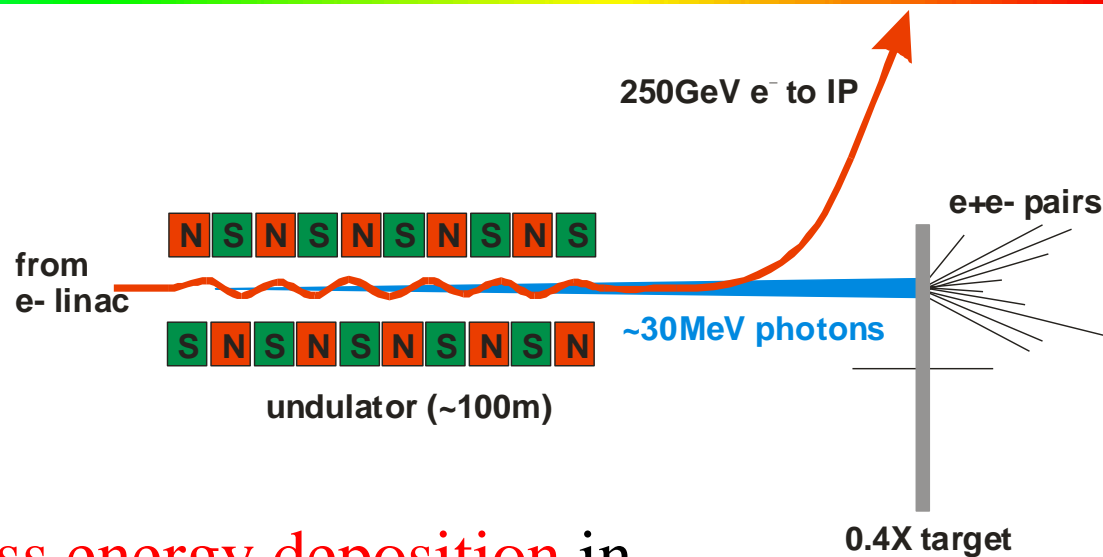
crystal +
amorphous target

- enhanced photon flux
by channeling effect



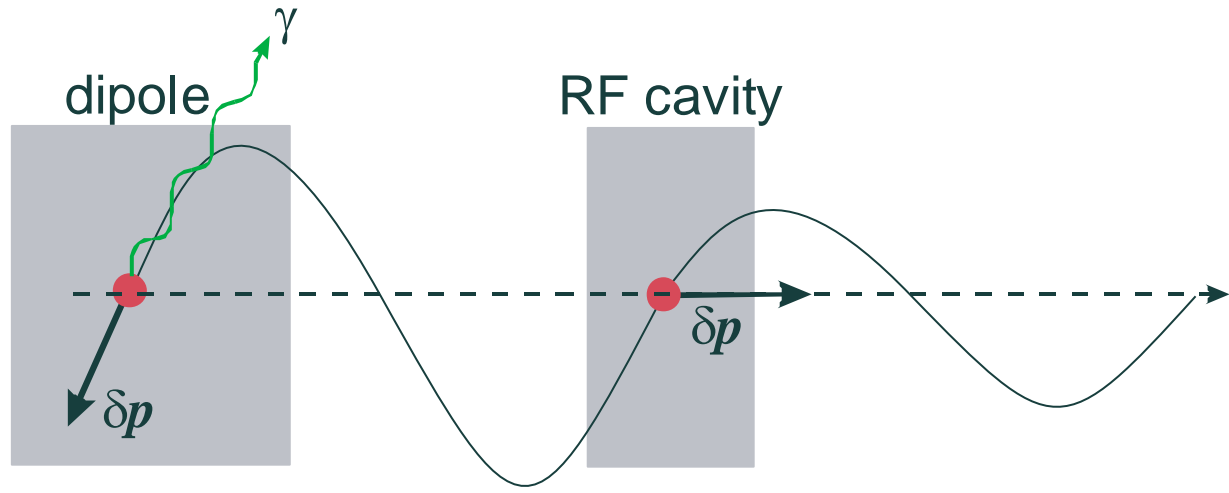
- positrons are captured in accelerating structure inside solenoid
and accelerated

- **undulator source:**
high energy e- produce photons in wiggler magnet + thin conversion target



- ~0.4 rad. length \Rightarrow much **less energy deposition** in the target (5 kW compared to 20 kW) \Rightarrow no parallel targets needed
- **smaller emittance** due to less coulomb scattering (factor ~2) but still much bigger than needed!!!
 $\epsilon_n \sim 10.000 \mu\text{m rad} !!!$
- could produce polarised e+ by helical undulator
- **but: need very high initial electron energy** $> 150 \text{ GeV} !$
 - use primary e- beam
 - consequences for the commissioning and operation

- e- and particularly e+ from the source have a **much too high ϵ**
⇒ we have to reduce the transverse bunch size
- solution: use synchrotron radiation in a **damping ring**
(remember lectures Synchrotron Radiation + damping)



- γ emission with transverse component
 - acceleration only in longitudinal direction
- } radiation damping!!!

- exponential damping to equilibrium emittance:

$$\epsilon_f = \epsilon_{eq} + (\epsilon_i - \epsilon_{eq}) e^{-2T/\tau_D}$$

initial emittance
(~0.01 m rad for e⁺)
damping time

final emittance
equilibrium emittance

- for e⁺ we need emittance reduction by few 10⁵
- ~7-8 damping times required

- damping time:

$$\tau_D = \frac{2E}{P}$$

$$P = \frac{2}{3} \frac{r_e c}{(m_0 c^2)^3} \frac{E^4}{\rho^2}$$

$$\tau_D \propto \frac{\rho^2}{E^3}$$

P - emitted radiation power

LEP: $E \sim 90$ GeV, $P \sim 15000$ GeV/s, $\tau_D \sim 12$ ms

- $\tau_D \propto \frac{\rho^2}{E^3}$ suggests high-energy for a small ring. But

- required RF power: $P_{RF} \propto \frac{E^4}{\rho^2} \times n_b N$

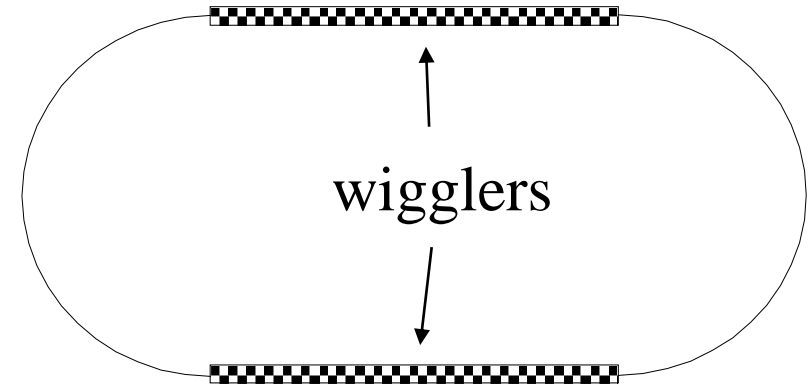
- equilibrium emittance: $\varepsilon_{n,x} \propto \frac{E^2}{\rho}$ limit E and ρ in practice

- DR example:

- Take $E \approx 2$ GeV
- $\rho \approx 50$ m
- $P_\gamma = 27$ GeV/s [28 kV/turn]
- hence $\tau_D \approx 150$ ms - we need $7-8 \tau_D$!!! \Rightarrow store time too long !!!

- Increase damping and P using *wiggler magnets*

- Insert **wigglers** in **straight sections** in the damping ring



- Average power radiated per electron with wiggler straight section

$$P = c \frac{\Delta E_{\text{wiggler}} + \Delta E_{\text{arcs}}}{L_{\text{wiggler}} + 2\pi\rho_{\text{arcs}}}$$

$\Delta E_{\text{wiggler}}$ energy loss in wiggler

ΔE_{arcs} energy loss in the arcs

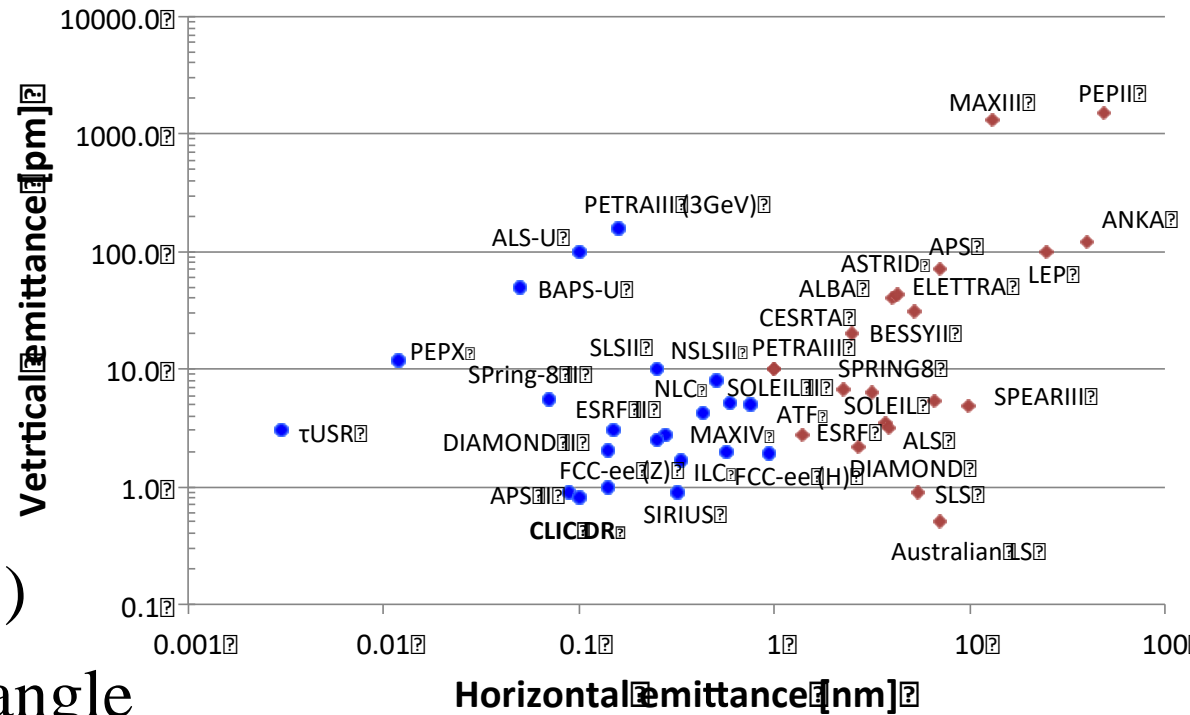
L_{wiggler} total length of wiggler

- Energy loss in wiggler:

$$\Delta E_{\text{wiggler}} \approx \frac{K_{\gamma}}{2\pi} E^2 \langle B^2 \rangle L_{\text{wiggler}} \quad \text{with } K_{\gamma} \approx 8 \cdot 10^{-6} \text{ GeV}^{-1} \text{ Tesla}^{-2} \text{ m}^{-1}$$

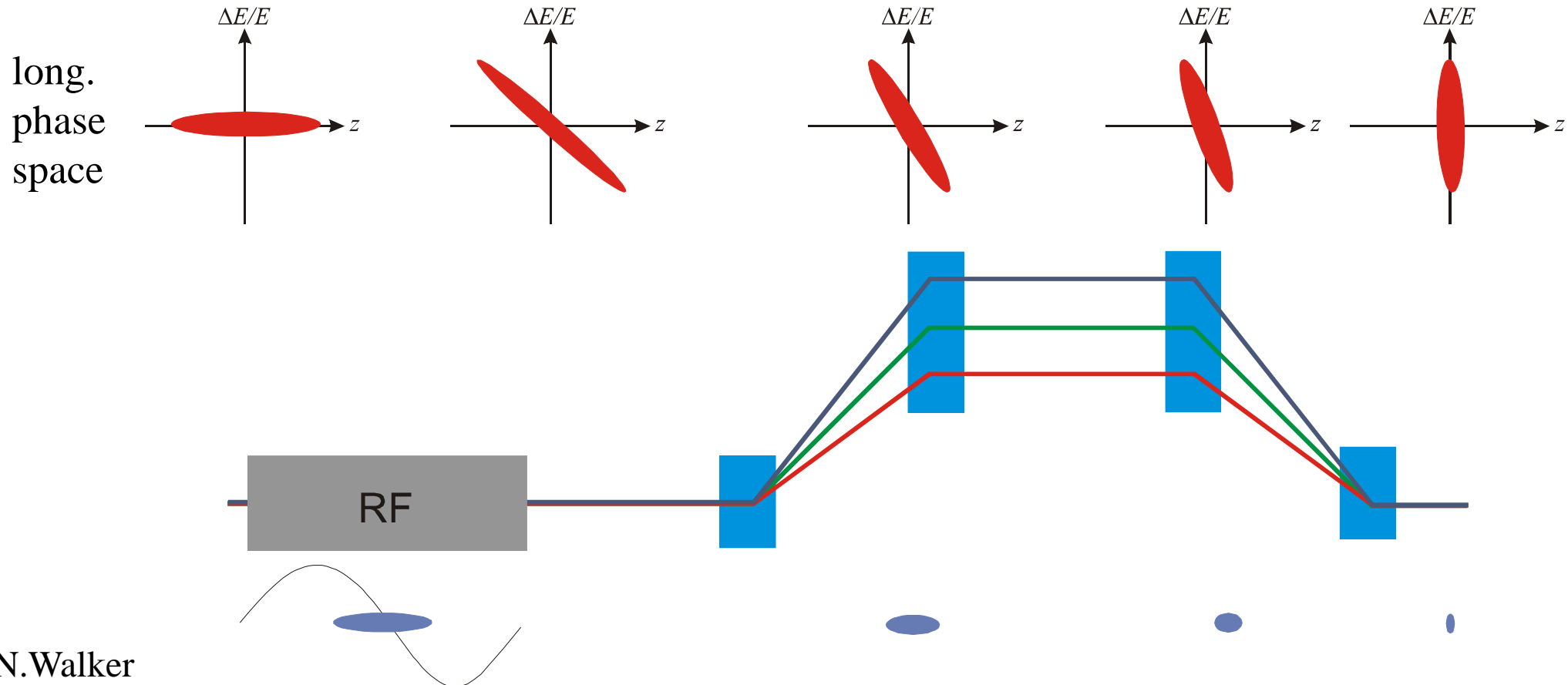
$\langle B^2 \rangle$ is the field square averaged over the wiggler length

- Horizontal emittance ϵ_x defined by lattice
- theoretical vertical emittance limited by
 - space charge
 - intra-beam scattering (IBS)
 - photon emission opening angle



- DR emittance in the range of existing/planned light sources
- In practice, ϵ_y limited by magnet alignment errors [cross plane coupling by tilted magnets]
- typical vertical alignment tolerance: $\Delta y \approx 30 \mu\text{m}$
 ⇒ requires beam-based alignment techniques!

- bunch length from damping ring: \sim few mm
- required at IP: \sim few 100 μm or shorter
- solution: introduce energy/time correlation with chicane:



initial (uncorrelated) momentum spread:
 initial bunch length
 compression ratio
 beam energy
 RF induced (correlated) momentum spread:
 RF voltage
 RF wavelength
 longitudinal dispersion (transfer matrix element):

δ_u
 $\sigma_{z,0}$
 $F_c = \sigma_{z,0} / \sigma_z$
 E
 $\begin{matrix} TM \\ c \end{matrix}$
 V_{RF}
 $\lambda_{RF} = 2\pi / k_{RF}$
 R_{56}

conservation of longitudinal emittance ($\sigma_z \delta = \text{const.}$):

$$F_c = \frac{\sqrt{\delta_c^2 + \delta_u^2}}{\delta_u} \Leftrightarrow \delta_c = \delta_u \sqrt{F_c^2 - 1}$$

fixed by DR

RF cavity $\delta_c \approx \frac{k_{RF} V_{RF} \sigma_{z,0}}{E} \Leftrightarrow V_{RF} = \frac{E \delta_c}{k_{RF} \sigma_{z,0}} = \frac{E}{k_{RF}} \left(\frac{\delta_u}{\sigma_{z,0}} \right) \sqrt{F_c^2 - 1}$

compress at low energy

- chicane (dispersive section) linear part

$$z_1 \approx z_0 + R_{56} \delta$$

- Minimum bunch length for upright ellipse
 \Rightarrow correlation $\langle z\delta \rangle = 0$



$$\langle z\delta \rangle_f = \langle z\delta \rangle_i + R_{56} \delta^2 = 0$$

- Initial correlation

$$\langle z\delta \rangle_i = \frac{k_{RF} V_{RF}}{E} \sigma_{z,0}^2 = \delta_c \sigma_{z,0}$$



- With $\delta^2 = \delta_u^2 + \delta_c^2$ we get

$$R_{56} = -\frac{\delta_c \sigma_{z,0}}{\delta_c^2 + \delta_u^2}$$

- For high compression ratio ($\delta_c \gg \delta_u$)

$$R_{56} \approx -\frac{\sigma_{z,0}}{\delta_c}$$

$$S_{z,0} = 2 \text{ mm}$$

$$d'_u = 0.1\%$$

$$S_z = 100 \text{ mm} \supset F_c = 20$$

$$f_{RF} = 3 \text{ GHz} \supset k_{RF} = 62.8 \text{ m}^{-1}$$

$$E = 2 \text{ GeV}$$

$$\delta = 2\%$$

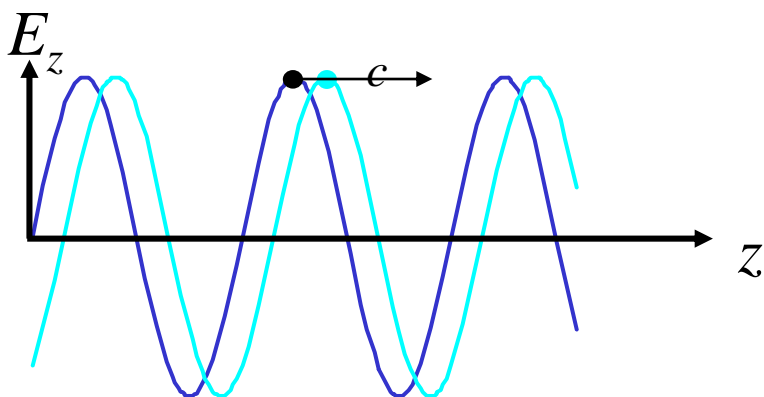
$$V_{RF} = 318 \text{ MV}$$

$$R_{56} = 0.1 \text{ m}$$

- Remark: we get a **large energy spread** after compression
- \Rightarrow large chromatic effects in the linac
- Consider a two stage compression with acceleration in between to reduce relative energy spread along the line

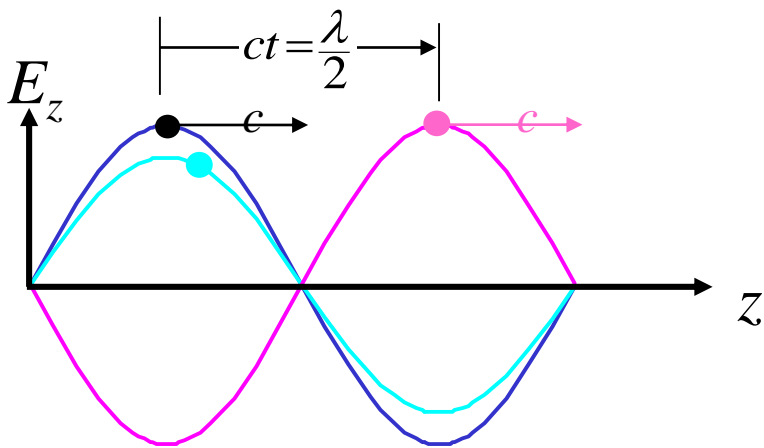
- Now we got small, short bunches we **"only"** have to accelerate them to collision energy

- Accelerating cavities:**



travelling wave structure:
 need *phase velocity* = c
 (*disk-loaded structure*)

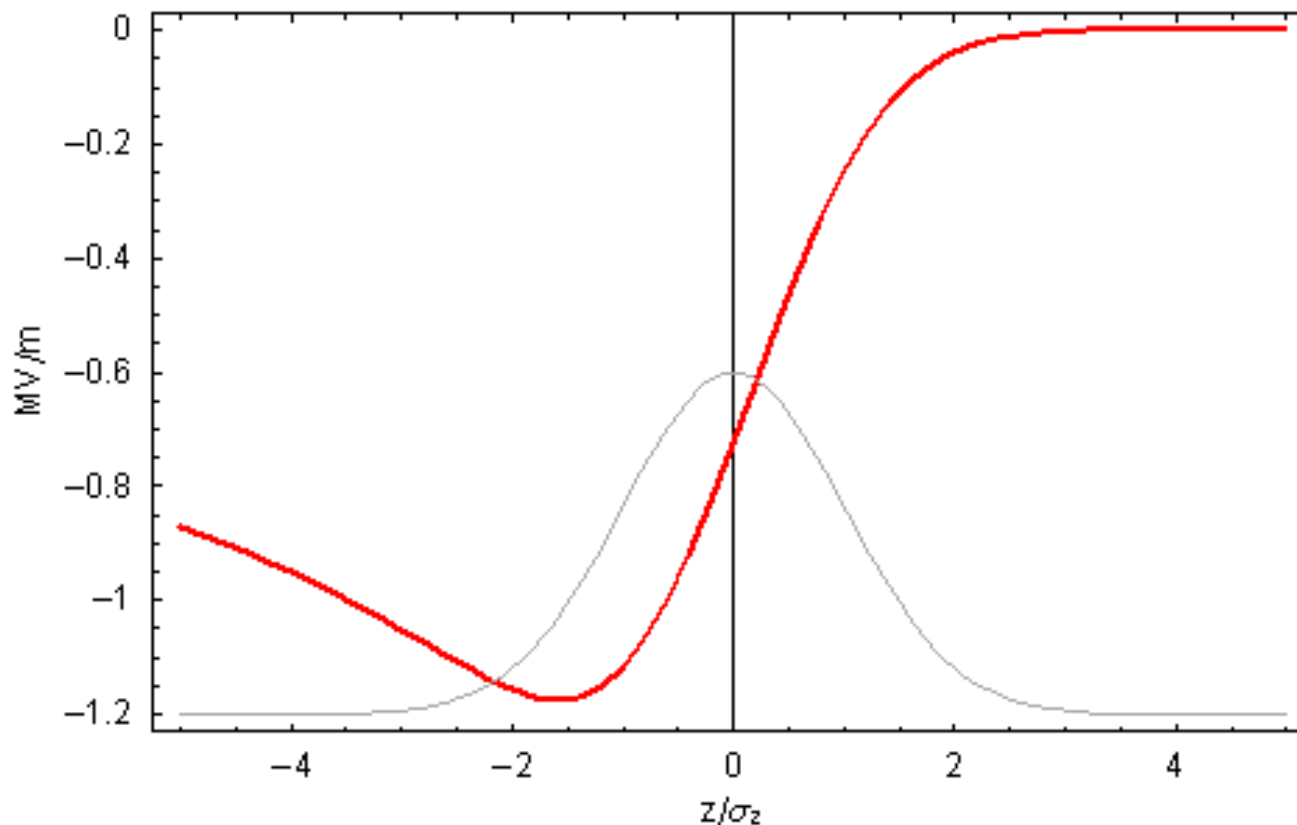
bunch sees constant field:
 $E_z = E_0 \cos(\varphi)$



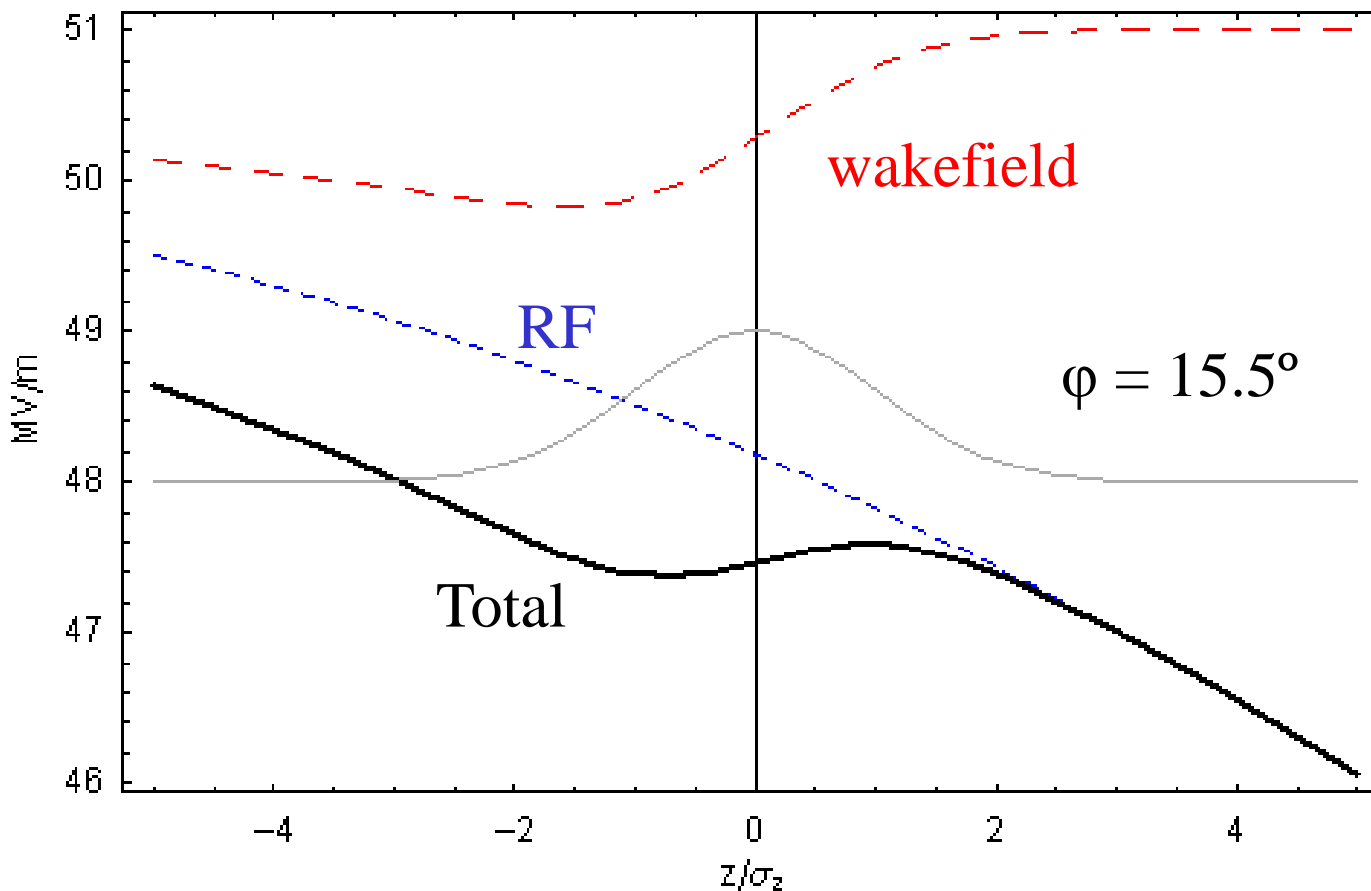
standing wave cavity:

bunch sees field:
 $E_z = E_0 \sin(\omega t + \varphi) \sin(kz)$
 $= E_0 \sin(kz + \varphi) \sin(kz)$

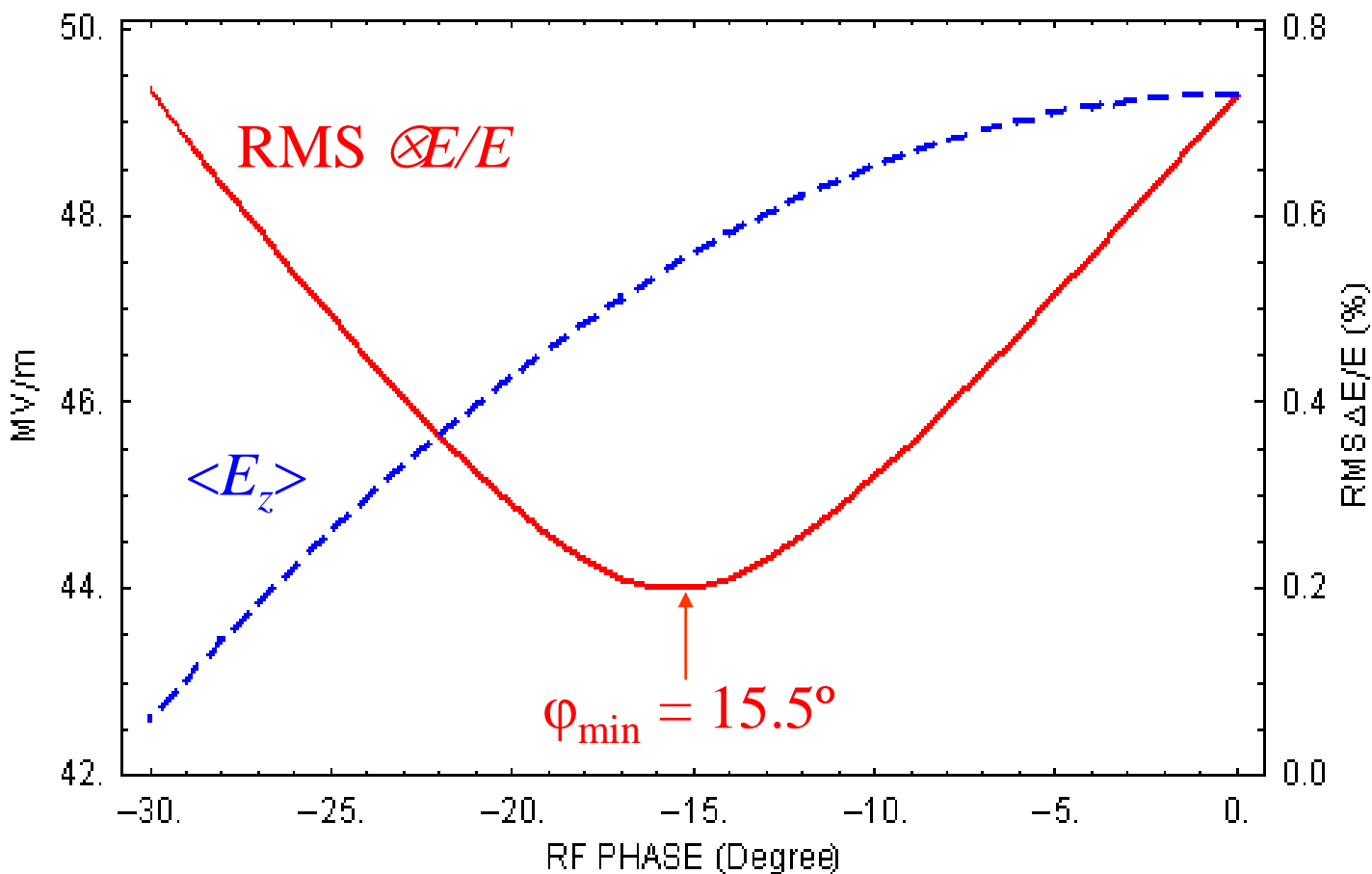
- Beam absorbs RF power \Rightarrow **decreasing RF field** in cavities
- **Single bunch** beam loading: longitudinal wake field
- Particles within a bunch see a decreasing field
 \Rightarrow energy gain different **within** a bunch



- Run **off crest** and use RF curvature to compensate single bunch beam-loading
- **Reduces the effective gradient**



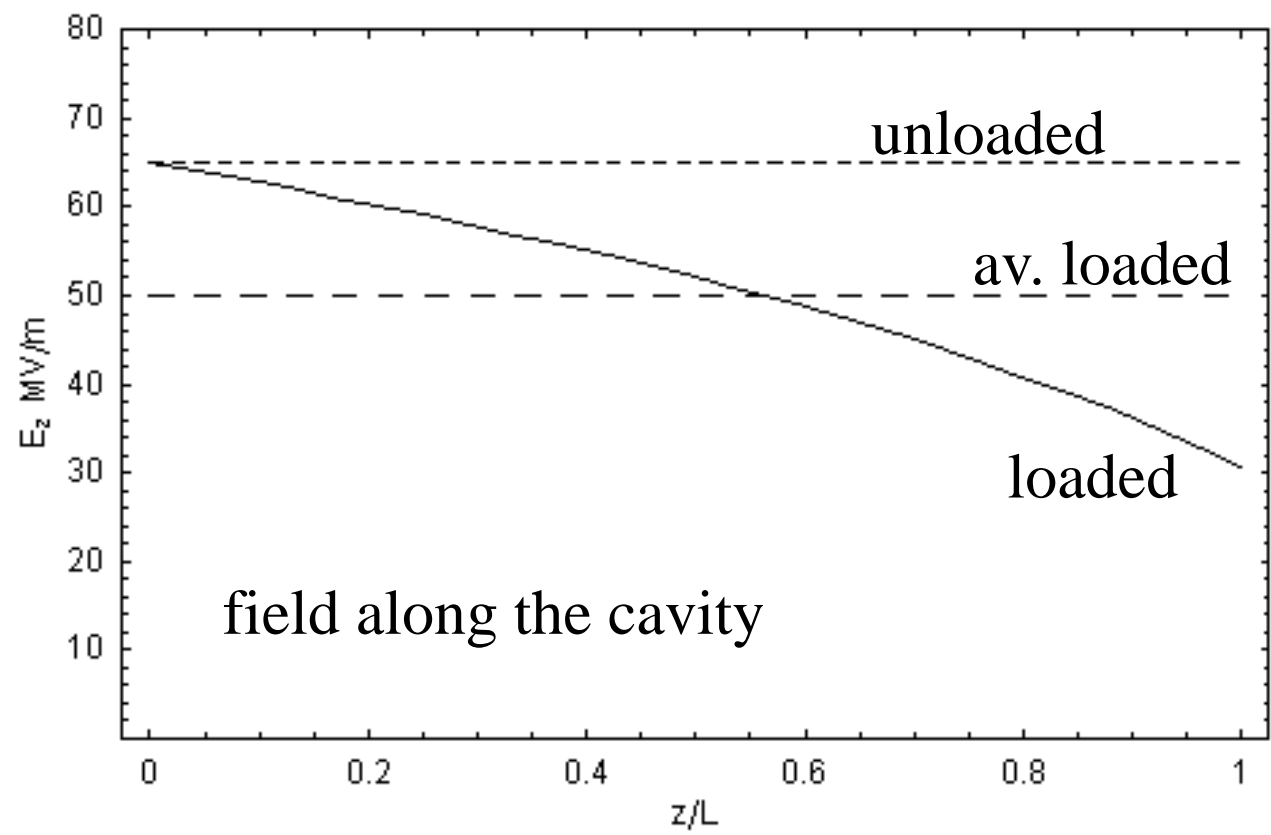
- Minimize momentum spread



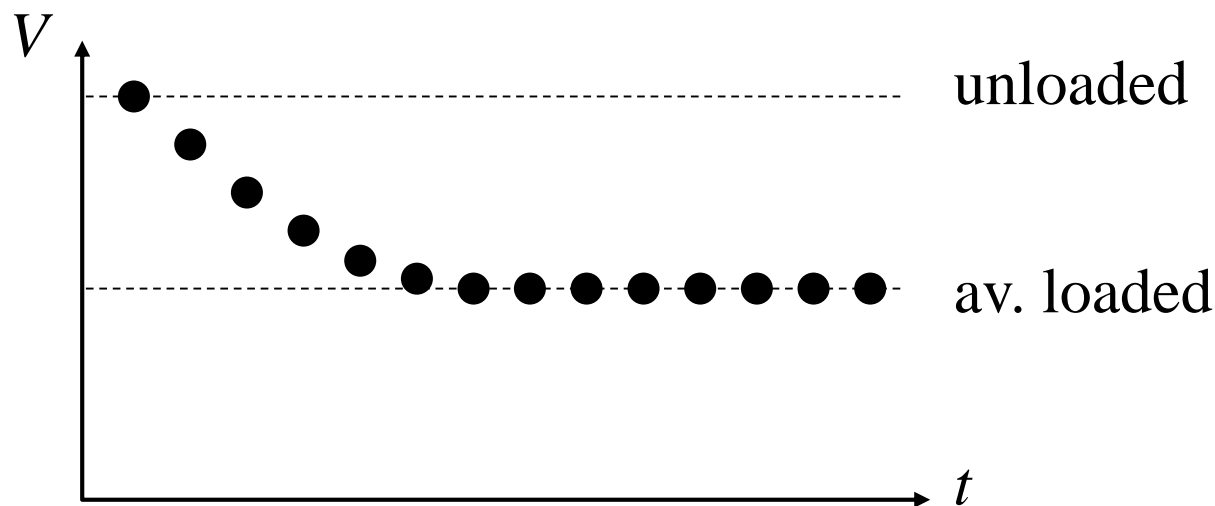
- Beam absorbs RF power
 ⇒ gradient reduced **along** TW cavity for steady state

$$\frac{dP}{dz} = -\frac{E_z^2}{r_s} - I_b E_z$$

r_s shunt impedance
 I_b peak beam current



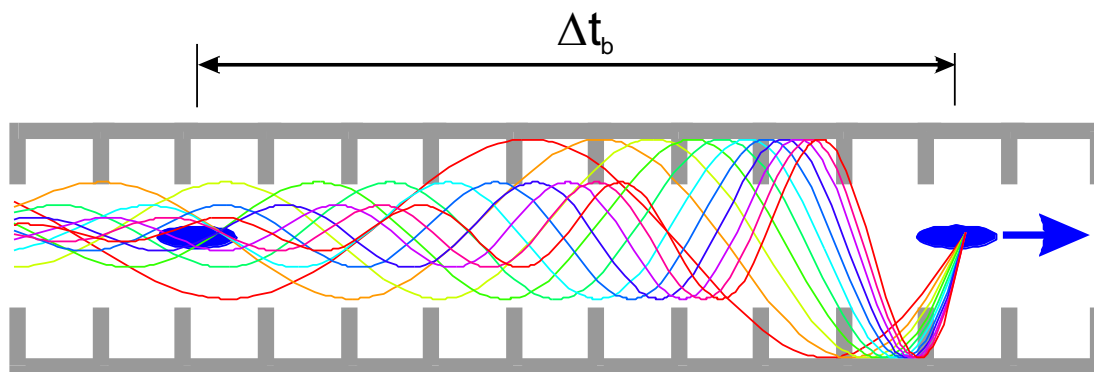
- **Transient beam loading (multi bunch effect):**
 - first bunches see the full unloaded field, energy gain different
 - In the LC design, long bunch trains achieve steady state quickly, and previous results very good approximation.
 - However, transient over first bunches needs to be compensated
 - ‘Delayed filling’ of the structure



- With **superconducting** standing wave (SW) cavities:
- Little losses to cavity walls
- You can have afford **long RF pulse** with
 - Many bunches
 - Large time between the bunches
- RF feed-back to compensate beam-loading before the next bunch arrives

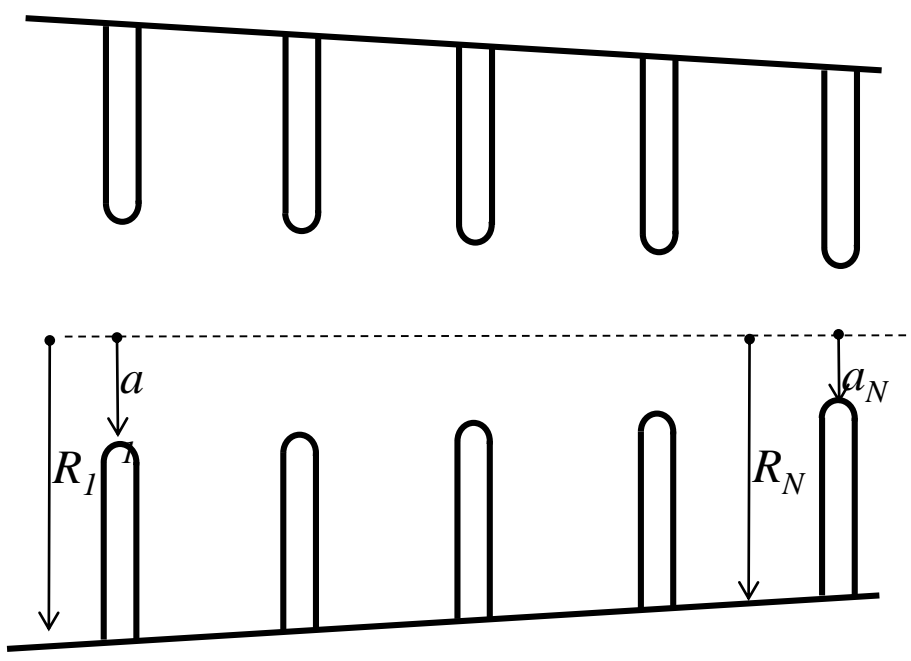
=> long bunch trains in SC linear collider design

- Linac must **preserve** the **small beam sizes**, in **particular in y**
- Possible sources for emittance dilutions are:
 - Dispersive errors: ($\Delta E \rightarrow y$)
 - Transverse wakefields: ($z \rightarrow y$)
 - Betatron coupling: ($x, p_x \rightarrow y$)
 - Jitter: ($t \rightarrow y$)
- All can **increase projection** of the beam size at the IP
- Projection determines luminosity

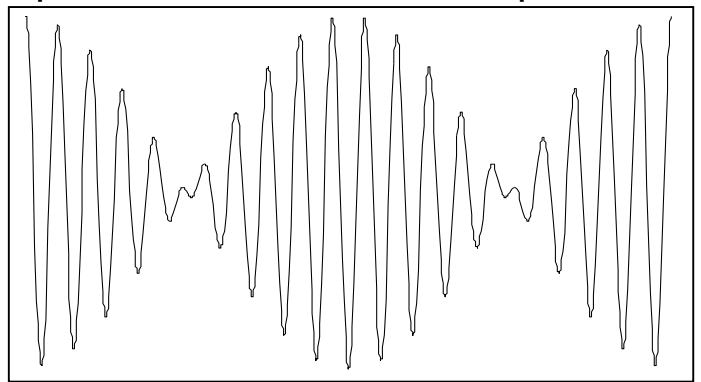


- Bunches induce field in the cavities
- Later bunches are perturbed by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!

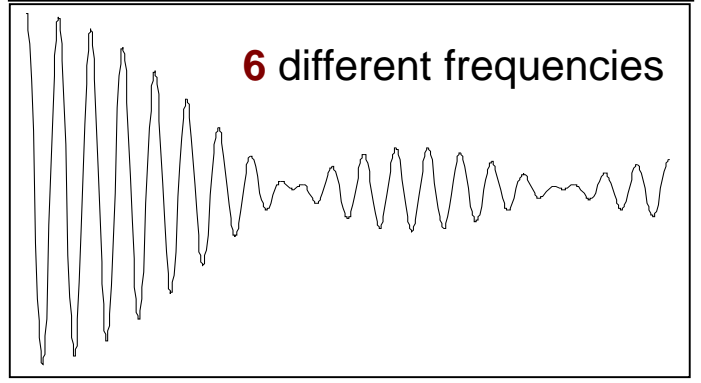
- Effect depends on a/λ (a iris aperture) and structure design details
- transverse wakefields roughly scale as $W_{\perp} \propto f^3$
- less important for lower frequency:
Super-Conducting (SW) cavities suffer less from wakefields
- Long-range minimised by structure design
- Dipole mode detuning



Long range wake of a dipole mode spread over **2** different frequencies

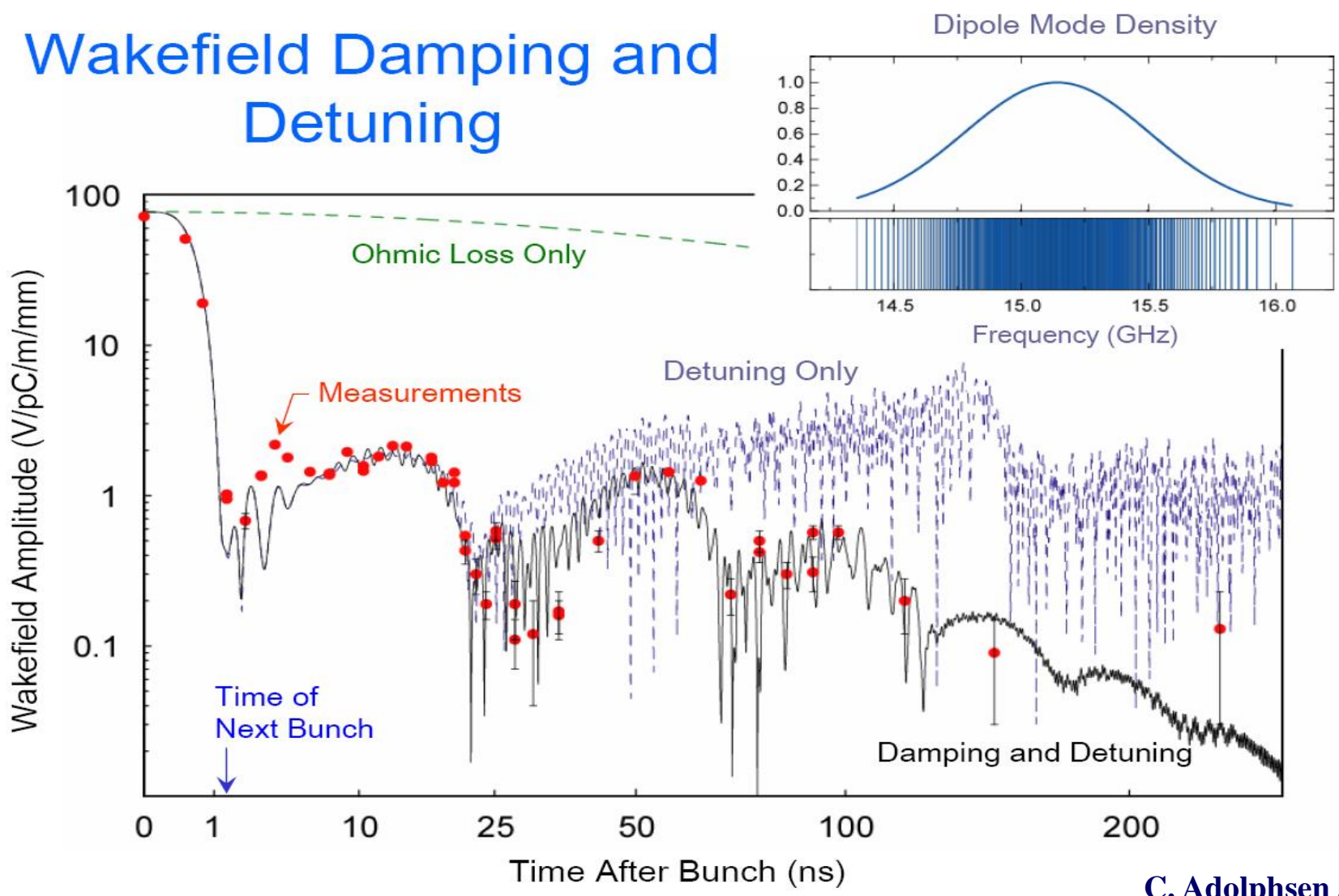


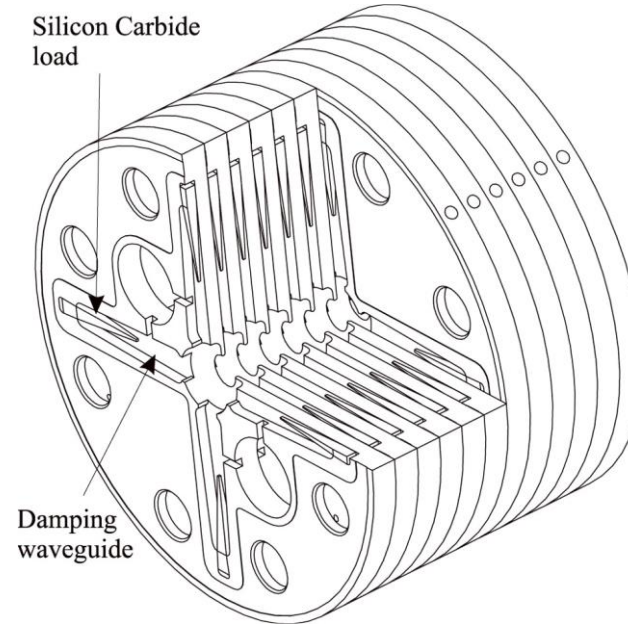
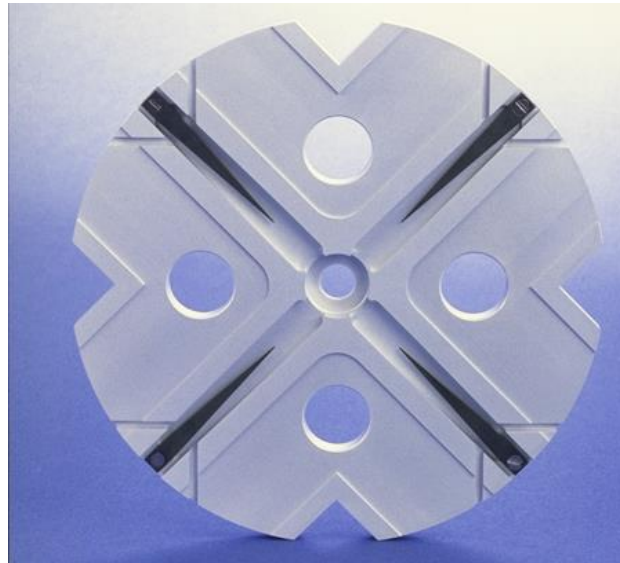
6 different frequencies



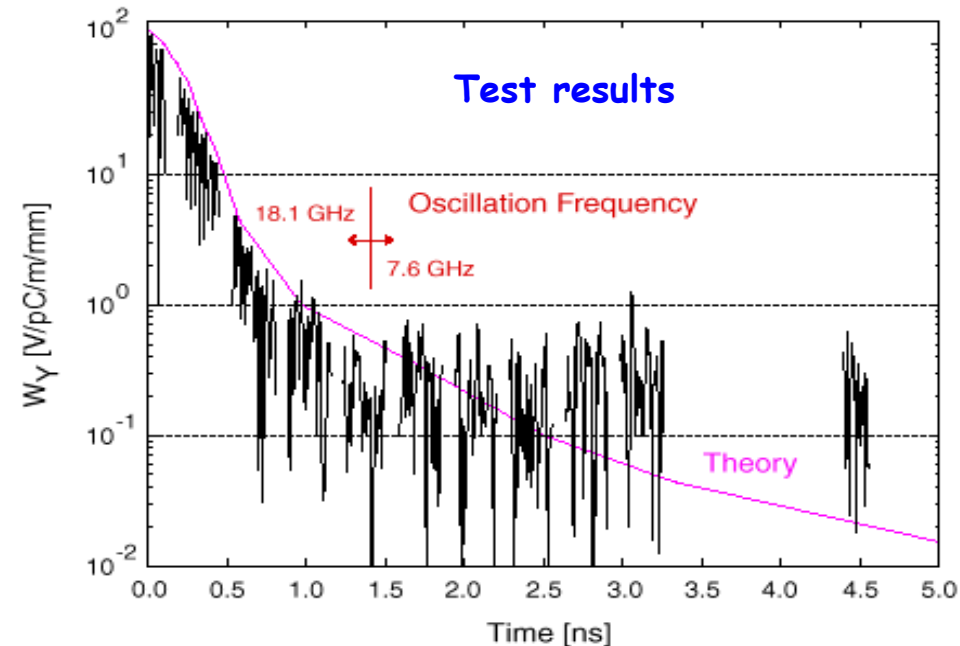
- Slight random detuning between cells makes HOMs decohere quickly
- Will re-cohere later: need to be damped (HOM dampers)

Wakefield Damping and Detuning

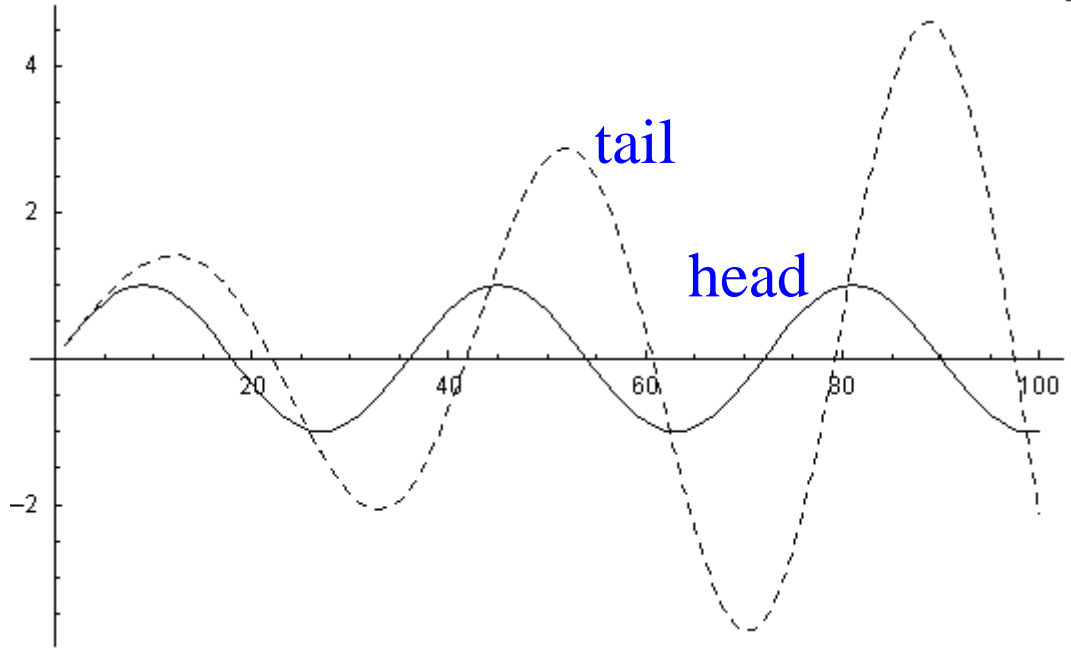




- Each cell damped by 4 radial WG
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped



- Head particle wakefields deflect tail particles
- Particle perform coherent betatron oscillations
- => head **resonantly** drives the tail



Tail particle
Equation of motion:

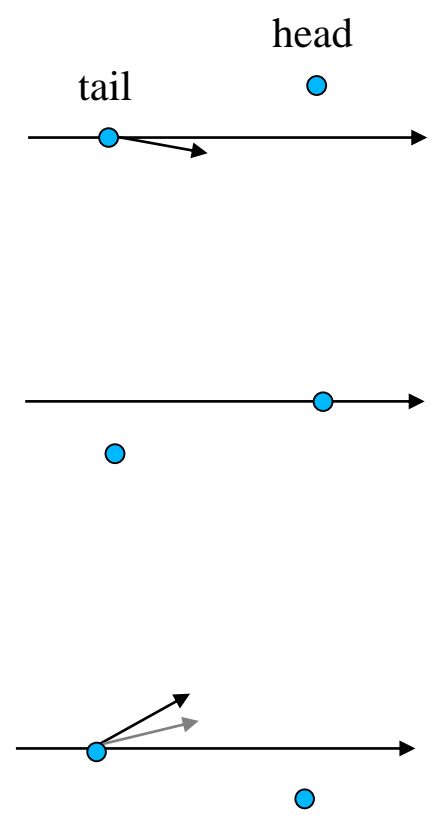
$$\frac{d^2 y_t}{ds^2} + k_1 y_t = f(W_{\perp}) y_h$$

Driven Oscillator !!

More explicit:

$$\frac{d^2 y(z)}{ds^2} + (1 - \delta) K_1 y(z) = \frac{N r_0}{\gamma} \int_z^{\infty} dz' \rho(z') y(z') W_{\perp}(z' - z)$$

- 2 particles: charge $Q/2$ each, $2\sigma_z$ apart
- Bunch at max. displacement x :
 - tail receives kick θ from head
- $\pi/2$ in betatron phase downstream:
 - tail displacement $\approx \beta\theta$
- π in phase further (π in total):
 - $-x$ displacement, tail kicked by $-\theta$
 - but initial kick has changed sign
- \Rightarrow **kicks add coherently**
- \Rightarrow **tail amplitude grows** along the linac



- Counteract effective defocusing of tail by wakefield by **increased focusing** (Balakin, Novokhatski, and Smirnov)
- Done by **decreasing tail energy** with respect to head
- By longitudinally correlated energy spread (less off-crest than longitudinal wakefield compensation)
- Transverse wakefields balanced by lattice chromaticity
- 2 particle model:

$$\Delta E = \frac{1}{8} \frac{W_{\perp} (2\sigma_z) Q L_{cell}^2}{\sin^2(\pi q_{\beta})}$$

q_{β} fractional β tune advance per cell

L_{cell} FODO cell length
- W_{\perp} non linear
- **Good compensation achievable** at the price of larger energy spread

- BNS damping does not cure random cavity misalignment

- **Emittance growth:**
$$\Delta\varepsilon \approx \delta Y_{RMS}^2 \left[\pi\varepsilon_0 N r_e W_{\perp} (2\sigma_z) \right]^2 \frac{L_{acc} \bar{\beta}_i}{2\alpha G} \left[\left(\frac{E_f}{E_i} \right)^{\alpha} - 1 \right]$$

L_{acc} structure length

$\bar{\beta}_i$ initial average beta function

α scaling of the focusing lattice (~ 0.5)

G accelerating gradient

$E_{i,f}$ initial and final energy

- For given $\Delta\varepsilon$, it scales as
$$\delta Y_{RMS} \propto \frac{1}{NW_{\perp}} \sqrt{\frac{G}{\beta}} \propto \frac{1}{Nf^3} \sqrt{\frac{G}{\beta}}$$

- Higher frequency requires better structure alignment δY_{rms}
- Partially compensated by: higher G , lower β , lower N