



# Linear Colliders

## Lecture 2

### Subsystems I



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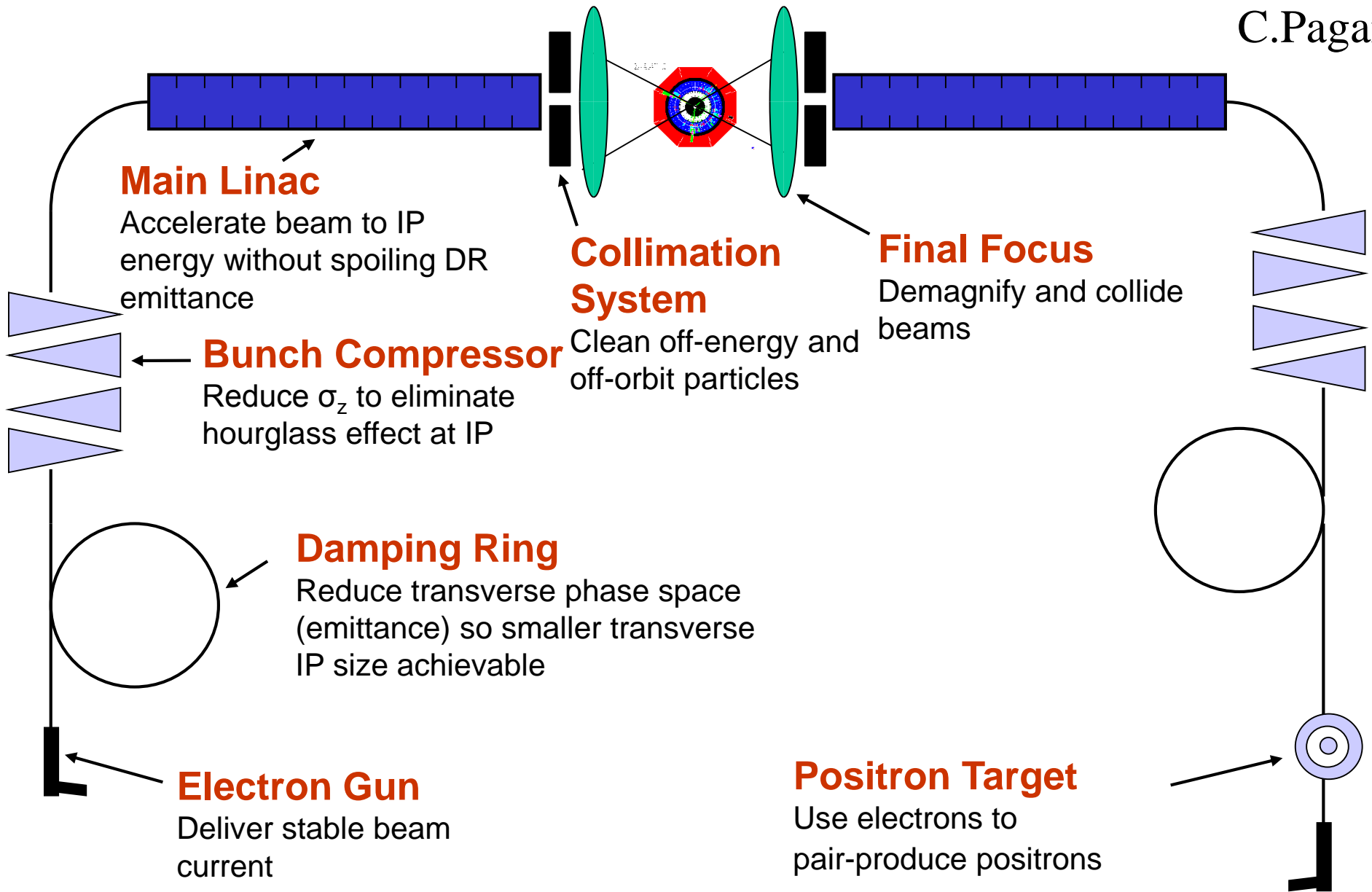
- Particle Sources
- Damping Rings
- Bunch Compressor
- Main Linac

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**  $\eta_{RF}$
- need **high RF power**  $P_{RF}$
- **small normalised vertical emittance**  $\varepsilon_{n,y}$
- **strong focusing at IP** (small  $\beta_y$  and hence **small bunch length**  $\sigma_z$ )
- could also allow higher beamstrahlung  $\delta_{BS}$  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

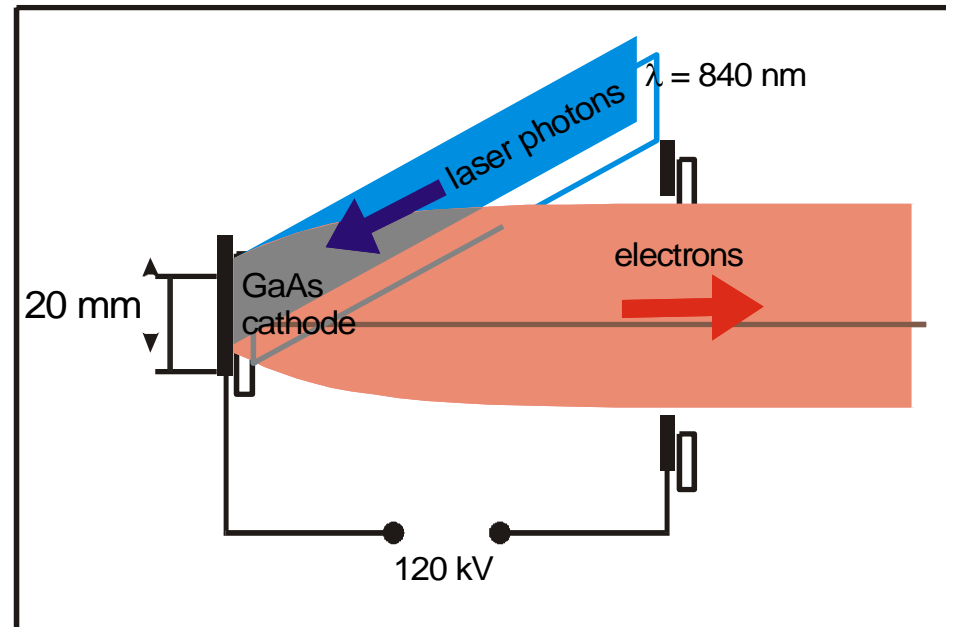
- circularly polarized photons on GaAs cathode (incompatible with RF gun)

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

- dominated by **space charge**

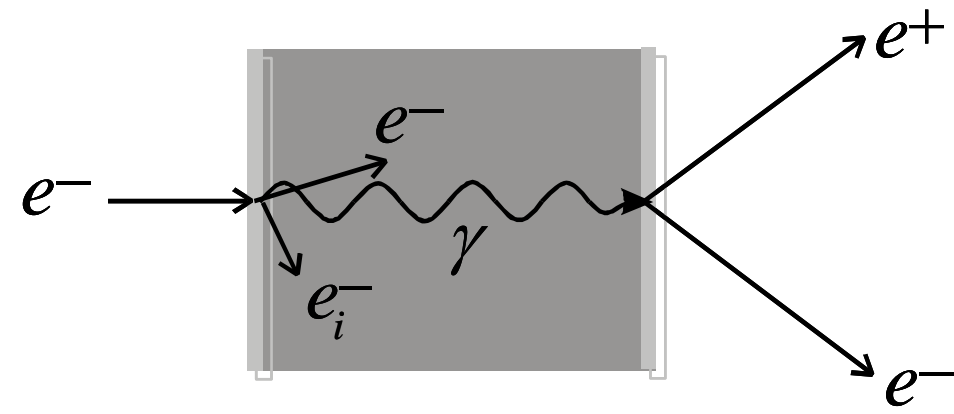
- RF bunching system to generate bunch structure for the linac

- or laser with bunch time structure ( $\Rightarrow$  even higher space charge)

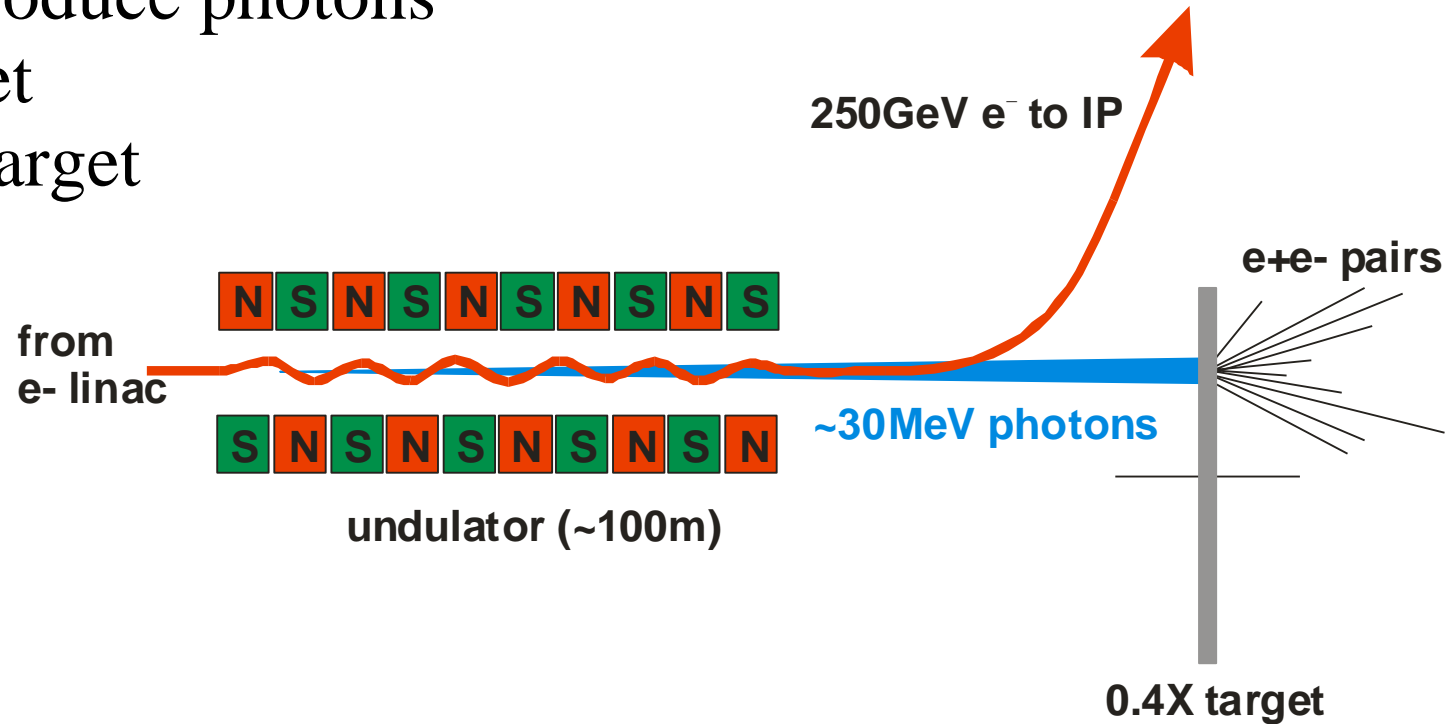


- basic mechanism: **pair production** in target material

- standard method: **'thick' target**  
primary e- generate photons  
these converts into pairs



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



- **undulator source:**

- ~0.4 rad. length  $\Rightarrow$  much **less energy deposition** in the target (5 kW compared to 20 kW)  $\Rightarrow$  no parallel targets

- **smaller emittance** due to less coulomb scattering (factor  $\sim 2$ ) but still much bigger than needed!!!

$$\varepsilon_n \sim 10.000 \mu\text{m rad} !!!$$

- could produce polarised e+ by helical undulator

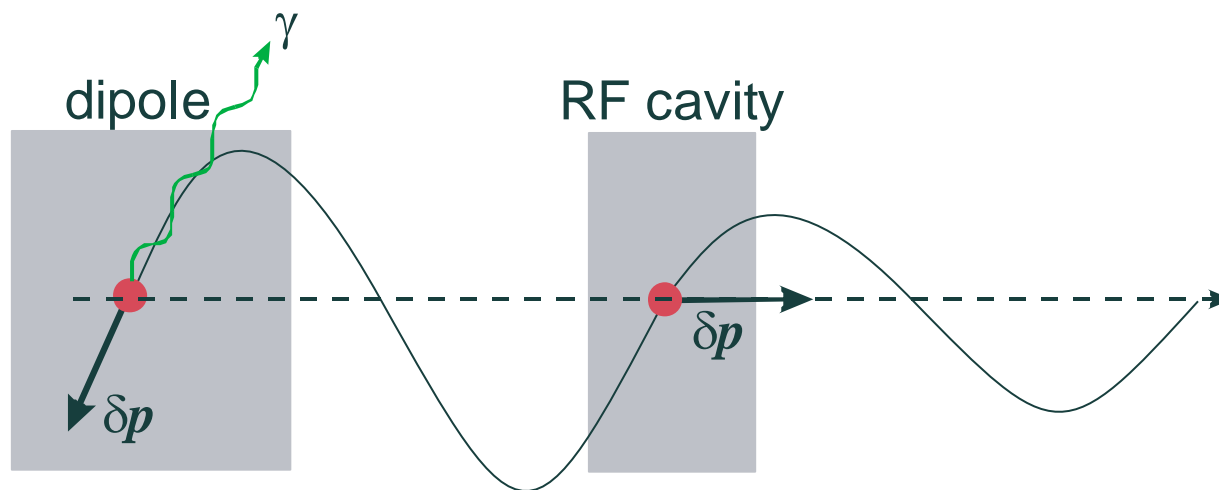
- **but:** need **very high initial electron energy**  $> 150 \text{ GeV}$  !

- could use primary e- beam

- consequences for the commissioning and operation

- positrons are captured in accelerating structure inside solenoid and accelerated

- e- and particularly e+ from the source have a **much too high  $\varepsilon$**   
 $\Rightarrow$  we have to reduce the bunch size
- solution: use synchrotron radiation in a **damping ring**  
 (remember lecture Synchr. Rad II)



- $\gamma$  emission with transverse component
  - acceleration only in longitudinal direction
- } radiation damping!!!

initial emittance  
(~0.01 m rad for e<sup>+</sup>)

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

final emittance
equilibrium emittance
damping time

- for e<sup>+</sup> we need emittance **reduction** by **few 10<sup>5</sup>**
- ~7-8 damping times required
- damping time:

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

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

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

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:  $\mathcal{E}_{n,x} \propto \frac{E^2}{\rho}$  limit  $E$  and  $\rho$  in practice

- DR example:

- Take  $E \approx 2$  GeV

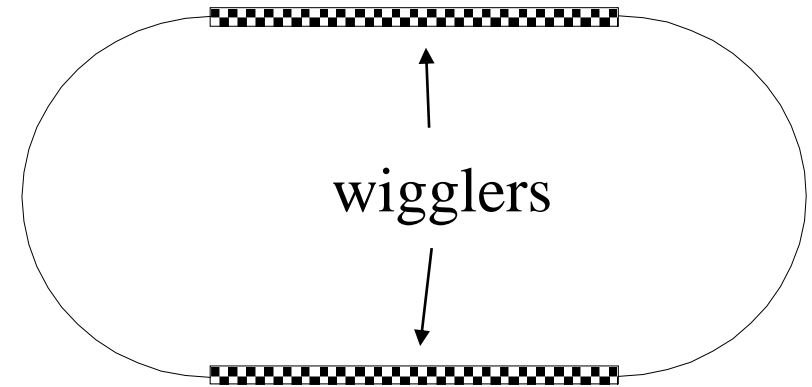
- $\rho \approx 50$  m

- $P_\gamma = 27$  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

$\Delta E_{\text{arcs}}$  energy loss in the arcs

$L_{\text{wiggler}}$  total length of wiggler

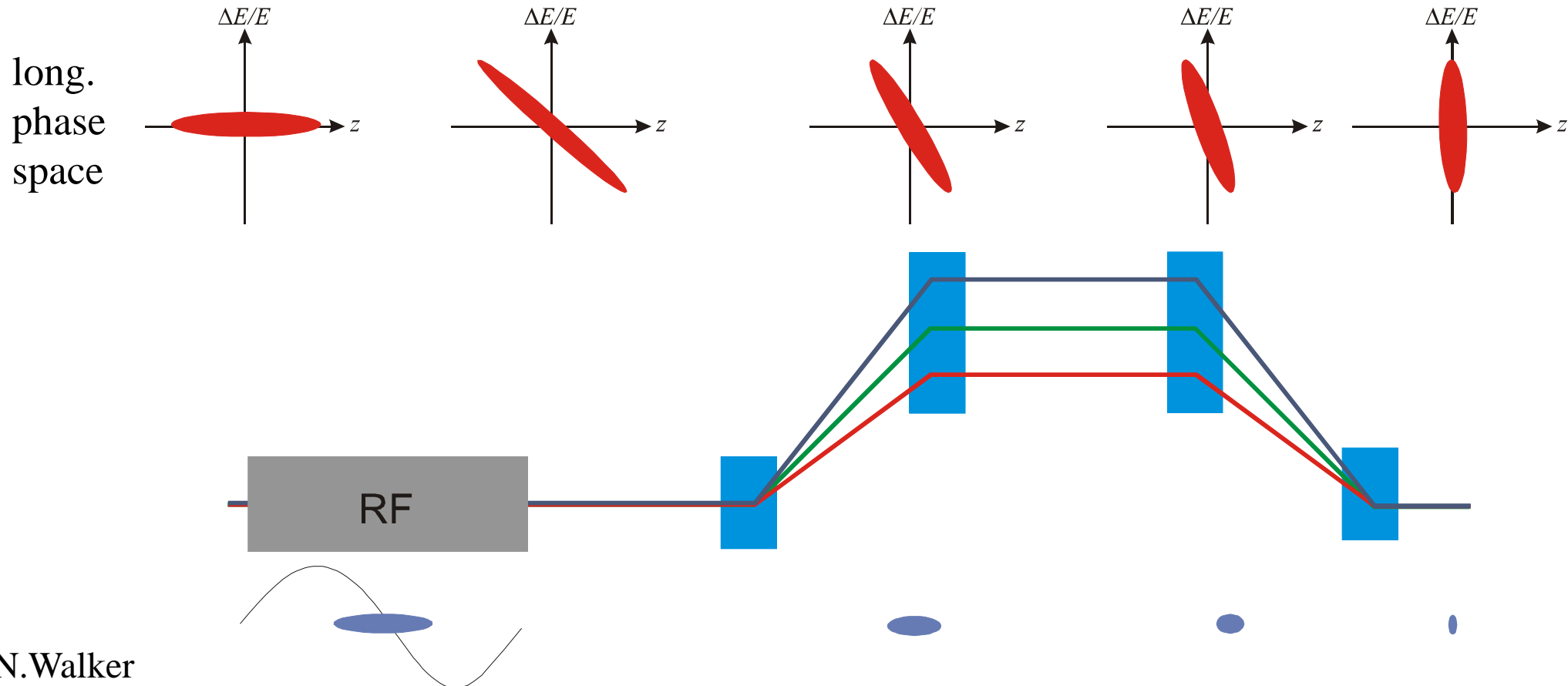
- Energy loss in wiggler:

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

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

- Horizontal emittance  $\varepsilon_x$  defined by lattice
- theoretical vertical emittance limited by
  - space charge
  - intra-beam scattering (IBS)
  - photon emission opening angle
- In practice,  $\varepsilon_y$  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  $\mu\text{m}$  or shorter
- solution: introduce energy/time correlation with chicane:



initial (uncorrelated) momentum spread:

$\delta_u$

initial bunch length

$\sigma_{z,0}$

compression ratio

$F_c = \sigma_{z,0} / \sigma_z$

beam energy

$E$

RF induced (correlated) momentum spread:

$\delta_c^{TM}$

RF voltage

$V_{RF}$

RF wavelength

$\lambda_{RF} = 2\pi / k_{RF}$

longitudinal dispersion (transfer matrix element):

$R_{56}$

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

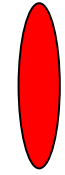
RF cavity

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

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 ( $\delta_c \gg \delta_u$ )

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

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

$$d'_u = 0.1\%$$

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

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

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

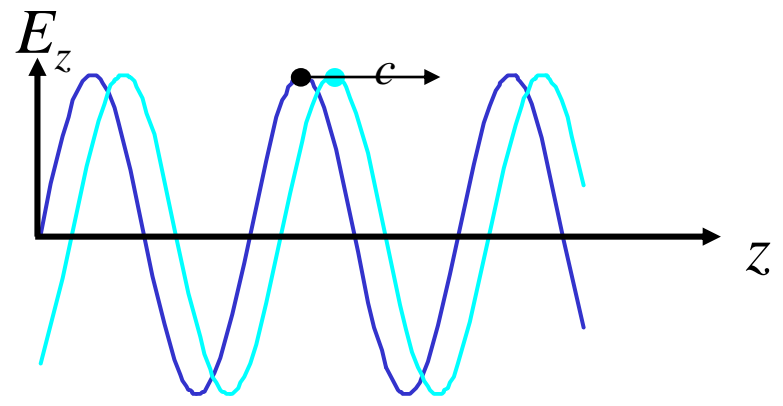
$$\delta = 2\%$$

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

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

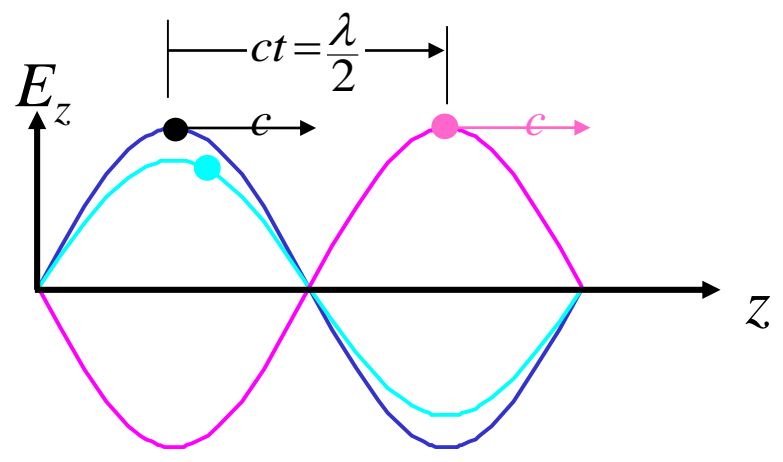
- Remark: we get a **large energy spread** after compression
- $\Rightarrow$  large chromatic effects in the linac
- Consider a two stage compression with acceleration in between to reduce relative energy spread along the line

- 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:  
 $E_z = E_0 \cos(\varphi)$

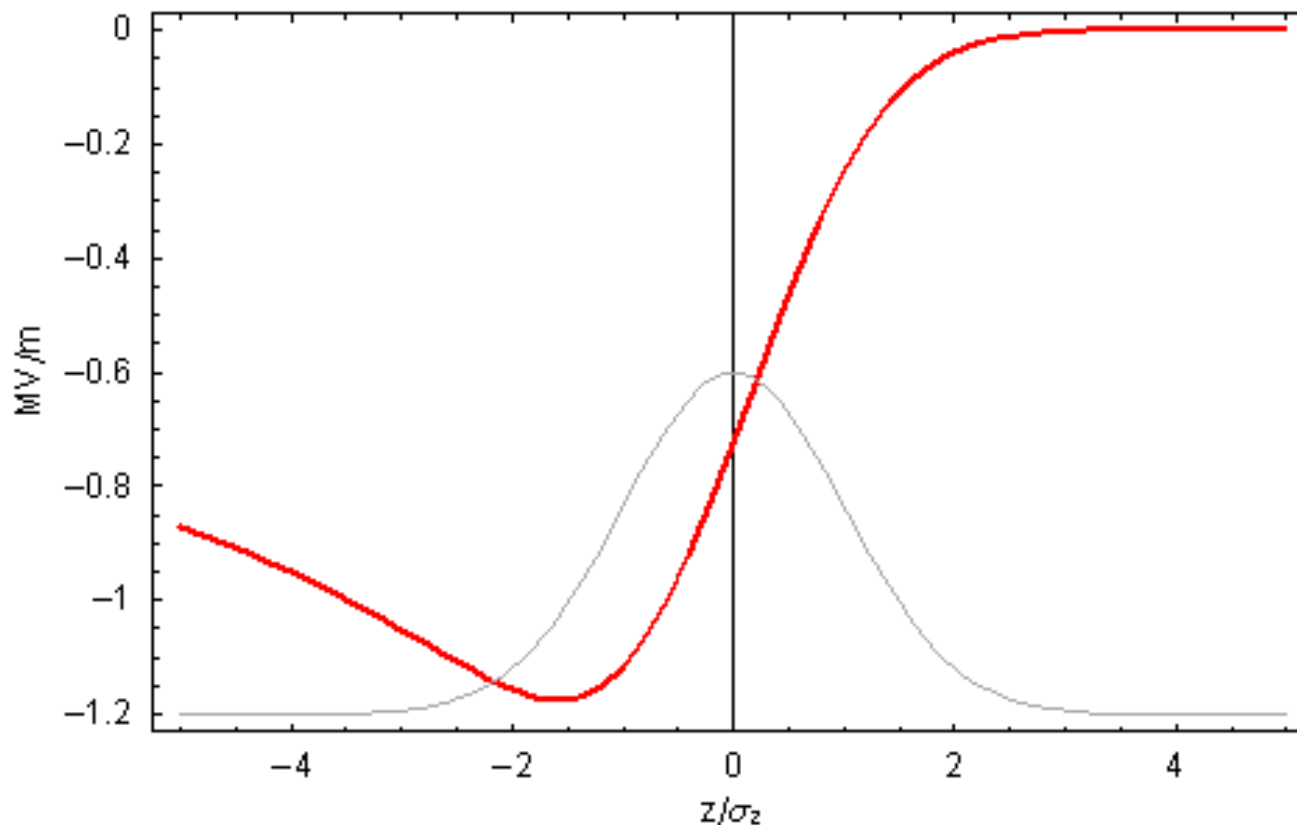


standing wave cavity:

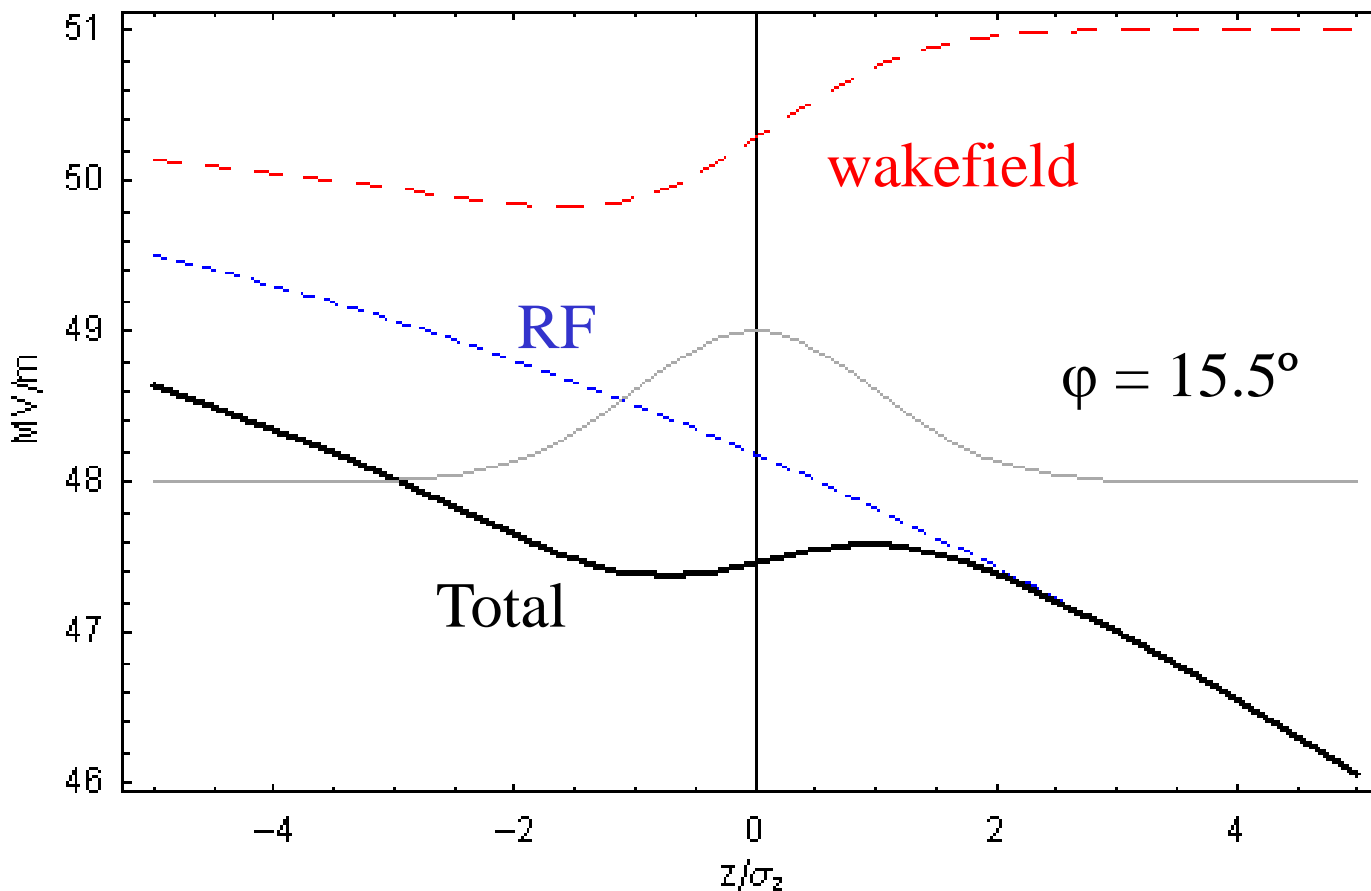
bunch sees field:  
 $E_z = E_0 \sin(\omega t + \varphi) \sin(kz)$   
 $= E_0 \sin(kz + \varphi) \sin(kz)$



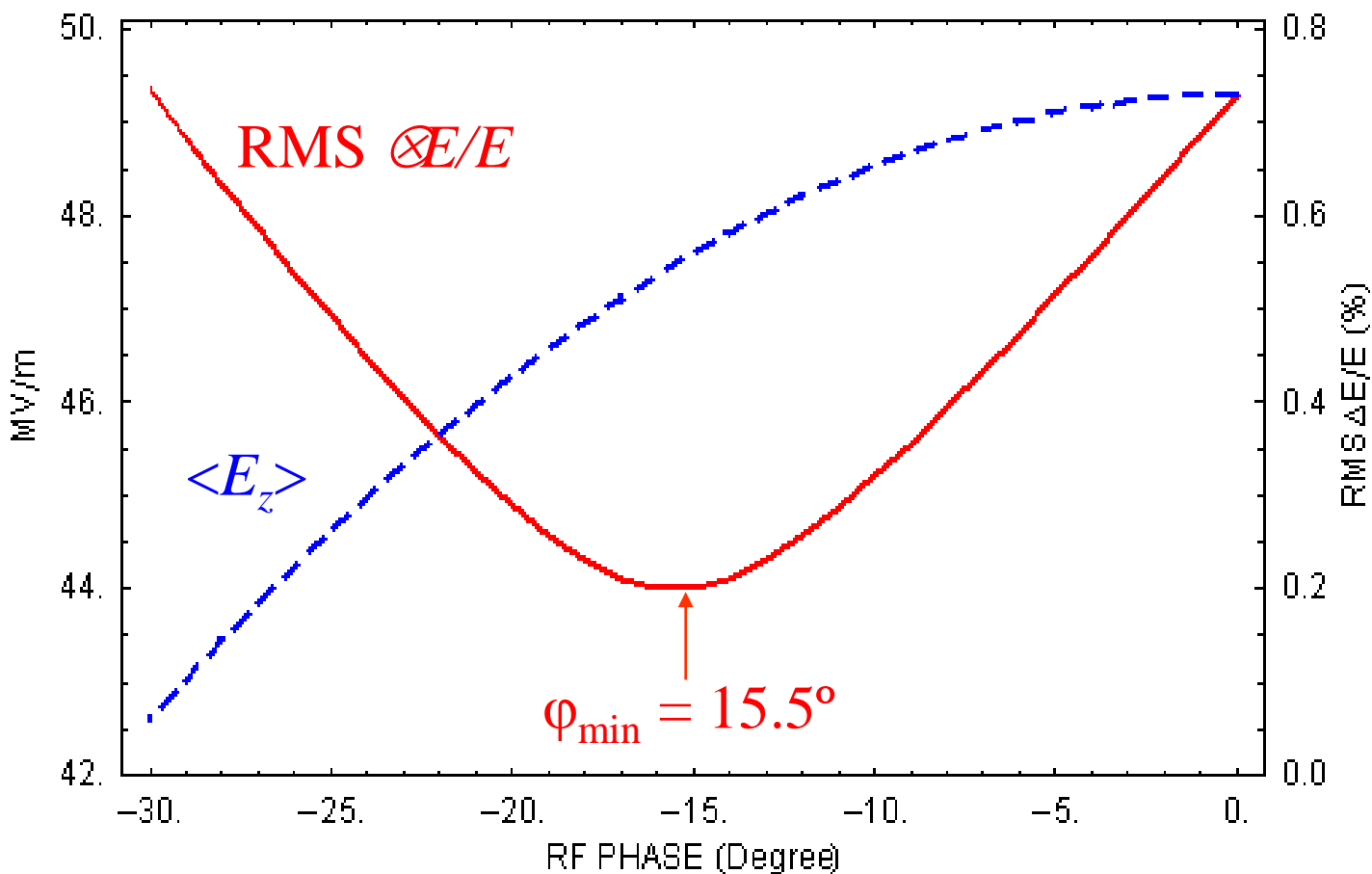
- Beam absorbs RF power  $\Rightarrow$  **decreasing RF field** in cavities
- **Single bunch** beam loading: longitudinal wake field
- Particles within a bunch see a decreasing field  
 $\Rightarrow$  energy gain different **within** a bunch



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



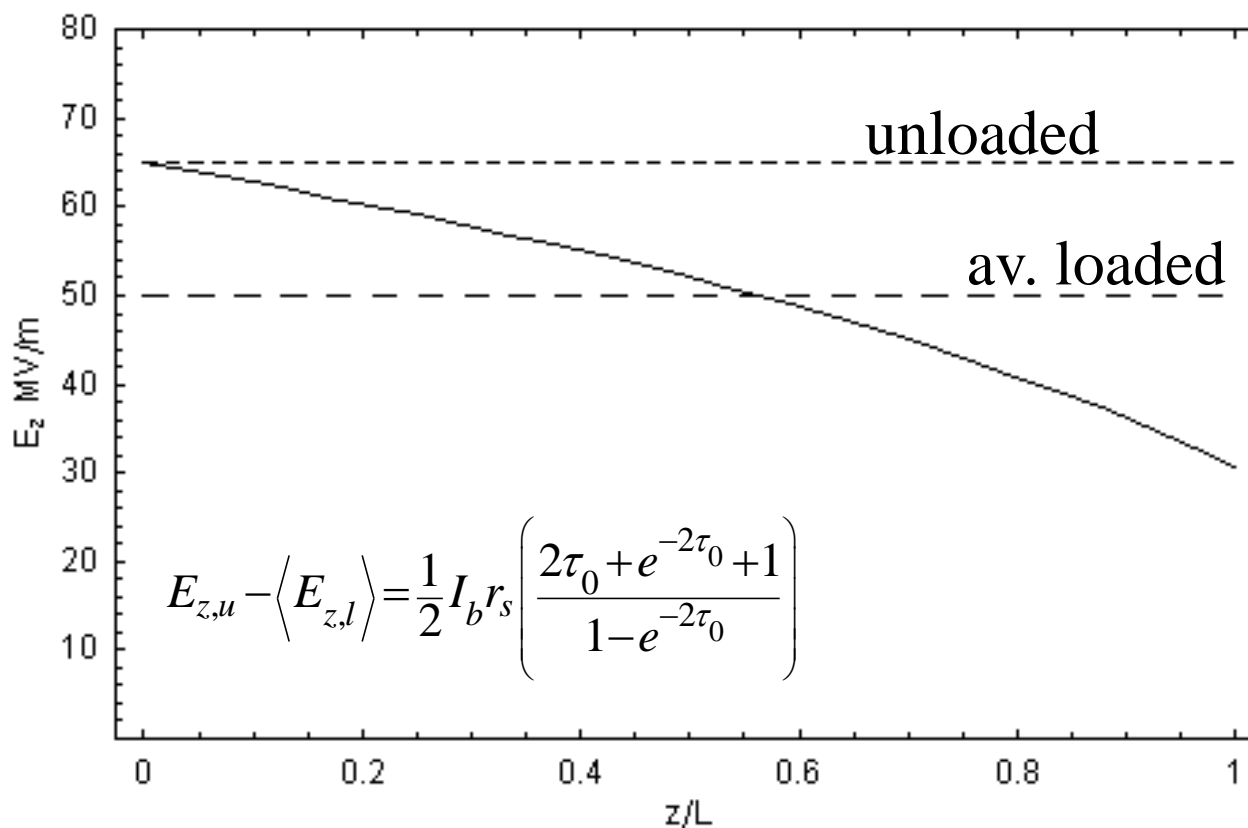
- Minimize momentum spread



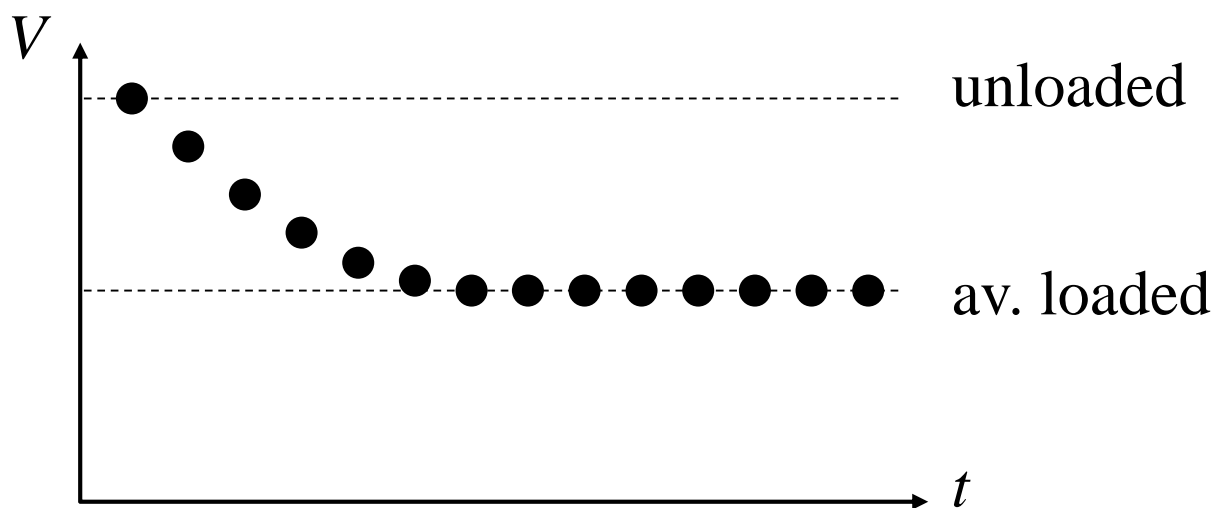
- Beam absorbs RF power  
 $\Rightarrow$  gradient reduced **along** TW cavity for steady state

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

$r_s$  shunt impedance  
 $I_b$  peak beam current

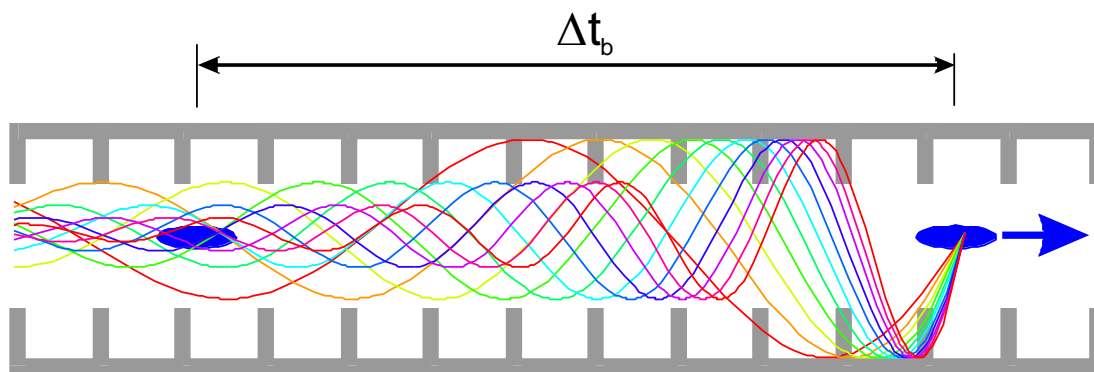


- **Transient beam loading (multi bunch effect):**
  - first bunches see the full unloaded field, energy gain different
  - for all LC designs, long bunch trains achieve steady state quickly, and previous results very good approximation.
  - However, transient over first bunches needs to be compensated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

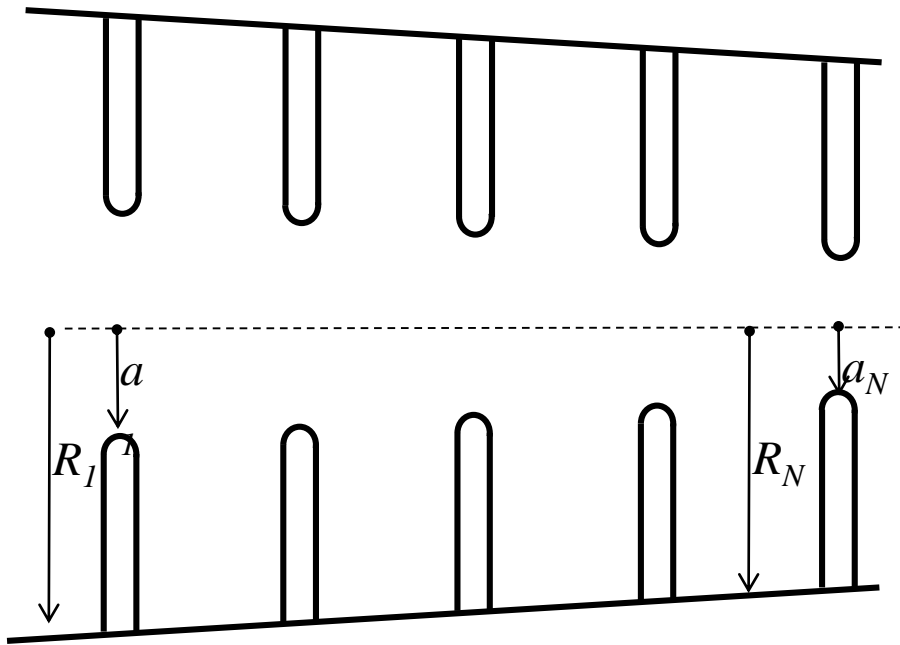
- Linac must **preserve** the **small beam sizes**, in **particular in y**
- Possible sources for emittance dilutions are:
  - Dispersive errors: ( $\Delta E \rightarrow y$ )
  - Transverse wakefields: ( $z \rightarrow y$ )
  - Betatron coupling: ( $x, p_x \rightarrow y$ )
  - Jitter: ( $t \rightarrow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



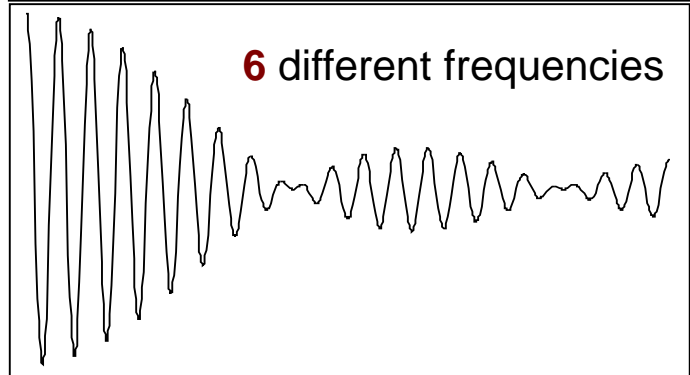
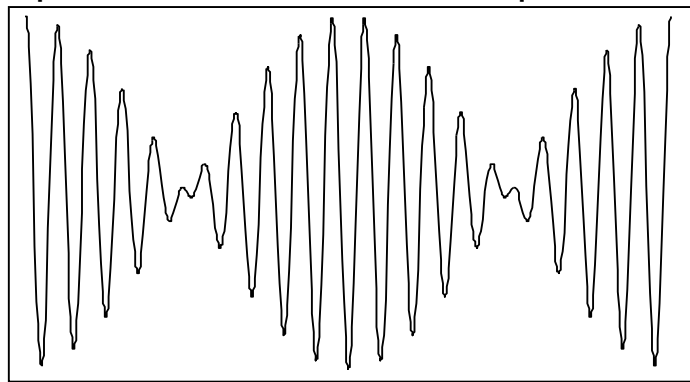
- Bunches induce field in the cavities
- Later bunches are perturbed by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!



- Effect depends on  $a/\lambda$  ( $a$  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

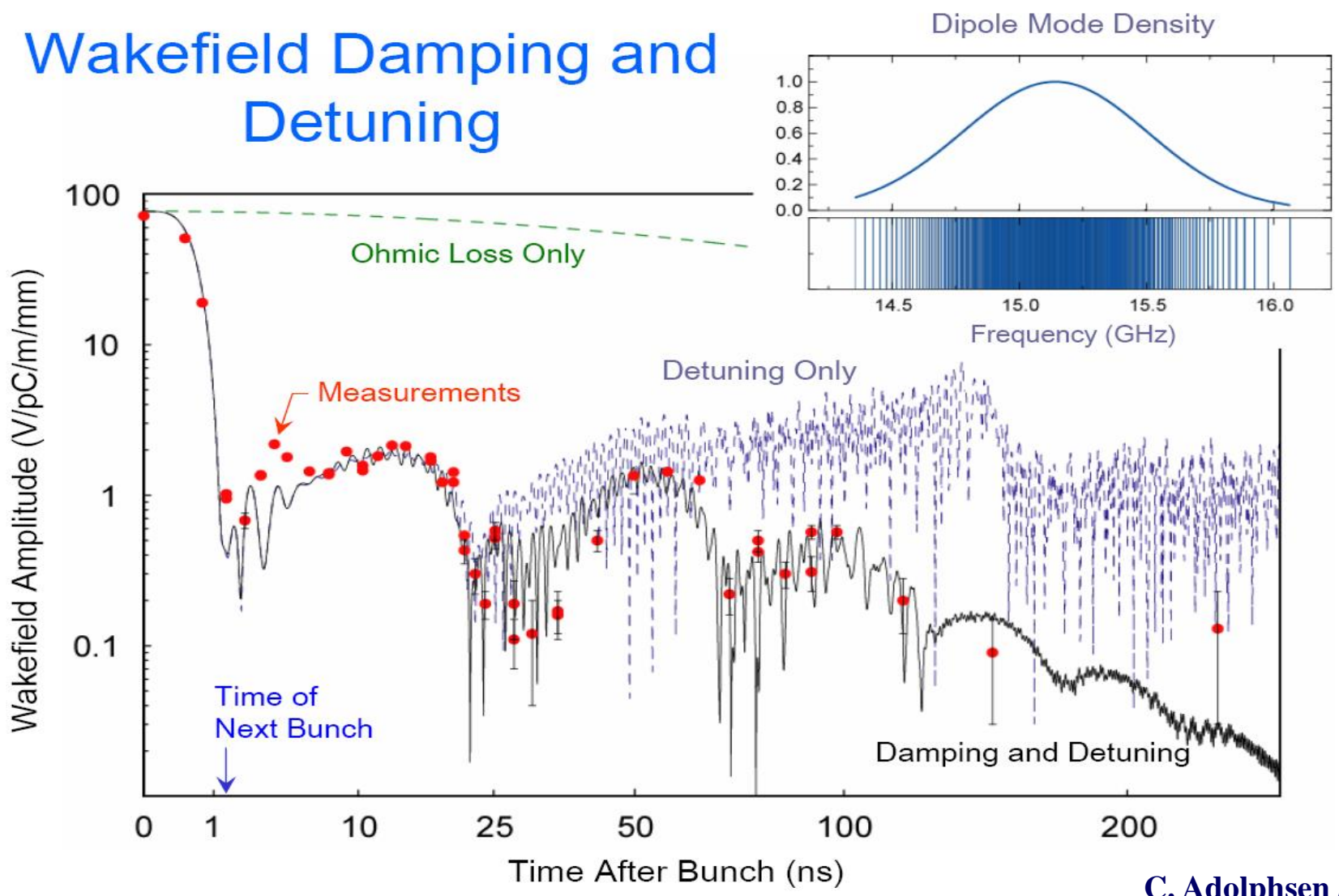


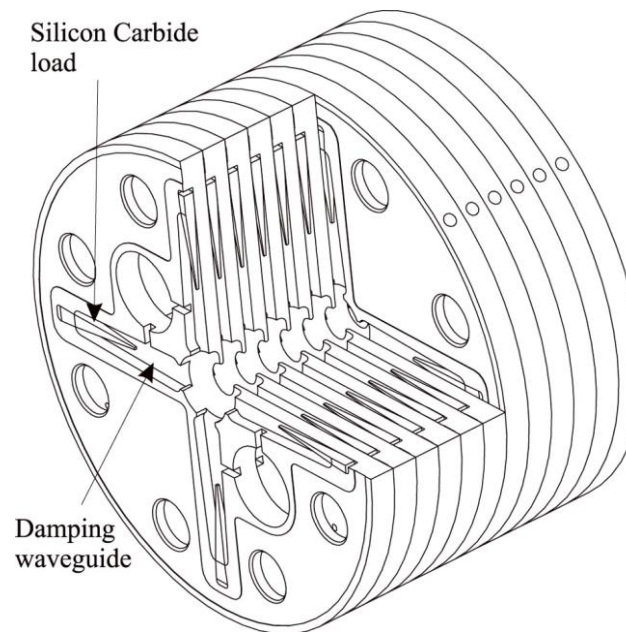
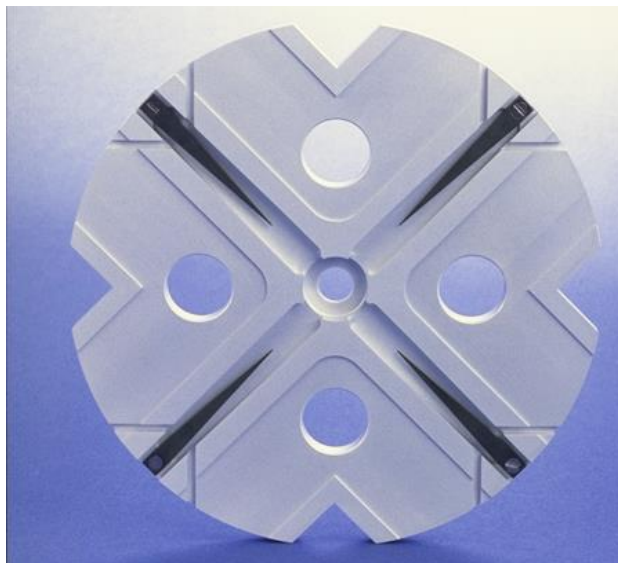
Long range wake of a dipole mode spread over **2** different frequencies



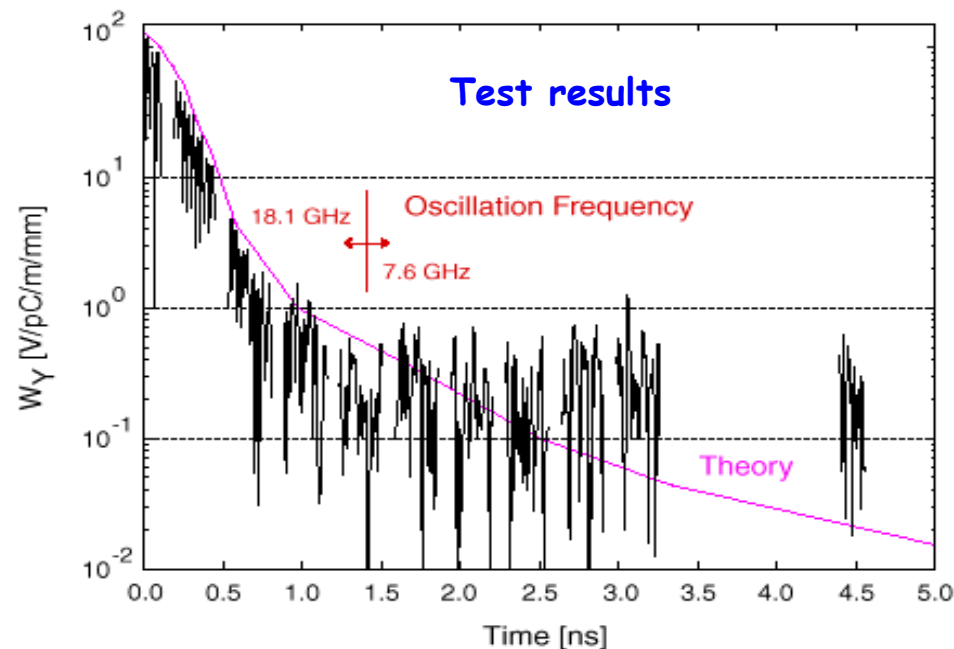
- Slight random detuning between cells makes HOMs decohere quickly
- Will re-cohere later: need to be damped (HOM dampers)

## Wakefield Damping and Detuning

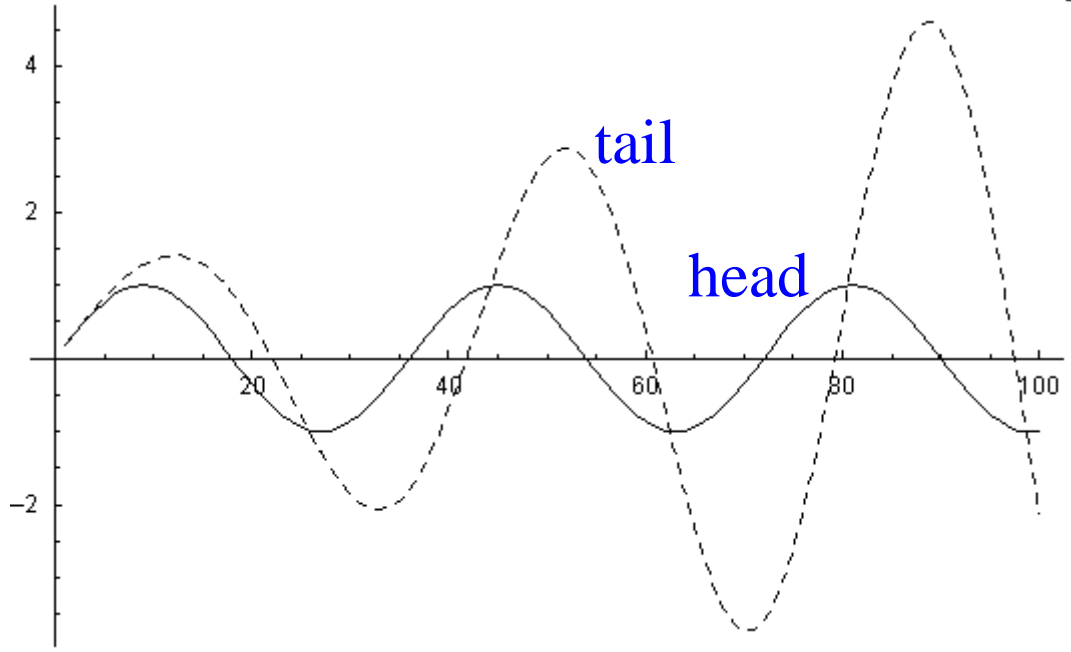




- Each cell damped by 4 radial WG
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped



- 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:

$$\frac{d^2 y(z)}{ds^2} + (1 - \delta) K_1 y(z) = \frac{Nr_0}{\gamma} \int_z^{\infty} dz' \rho(z') y(z') W_{\perp}(z' - z)$$

- 2 particles: charge  $Q/2$  each,  $2\sigma_z$  apart

- Bunch at max. displacement  $x$ :

- tail receives kick  $\theta$  from head

- $\pi/2$  in betatron phase downstream:

- tail displacement  $\approx \beta \theta$

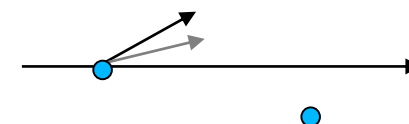
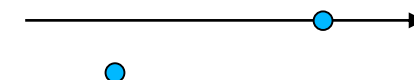
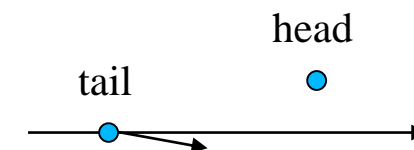
- $\pi$  in phase further ( $\pi$  in total):

- -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 (off-crest)
- Wakefields balanced by lattice chromaticity
- 2 particle model: 
$$\Delta E = \frac{1}{8} \frac{W_{\perp} (2\sigma_z) Q L_{cell}^2}{\sin^2(\pi q_{\beta})}$$
  - $q_{\beta}$  fractional  $\beta$  tune advance per cell
  - $L_{cell}$  FODO cell length
- $W_{\perp}$  non linear
- **Good compensation achievable** at the price of
  - lower energy gain by off-crest running
  - 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

$\alpha$  scaling of the focusing lattice ( $\sim 0.5$ )

$G$  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  $\delta Y_{rms}$

- Partially compensated by: higher  $G$ , lower  $\beta$ , lower  $N$