Linear Colliders
Lecture 2
Subsystems I

Frank Tecker – CERN

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

Reminder: Luminosity

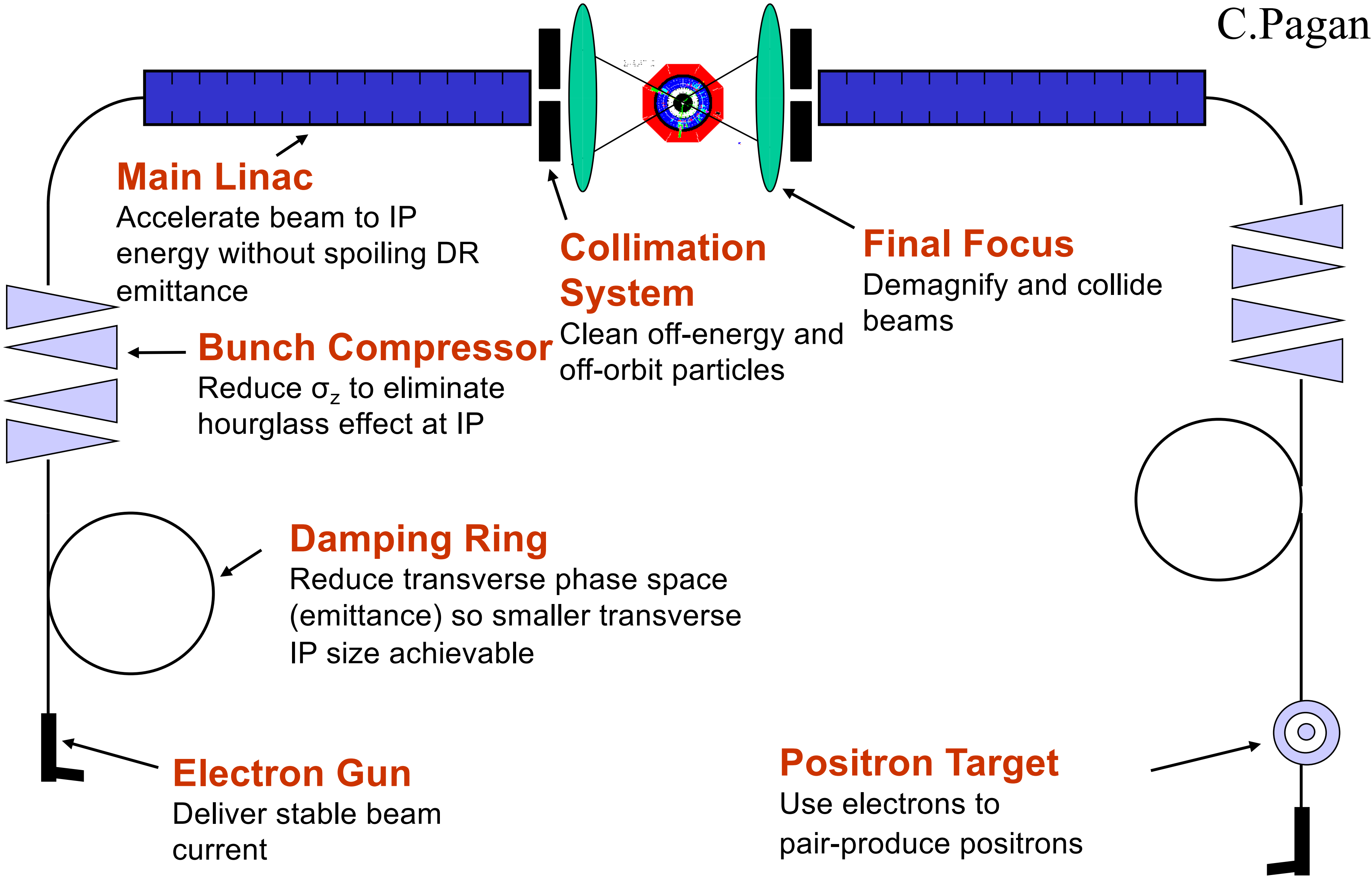
Last lecture, we arrived at:

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

- 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)

Generic Linear Collider

C.Pagani



Main Linac
Accelerate beam to IP energy without spoiling DR emittance

Collimation System
Clean off-energy and off-orbit particles

Final Focus
Demagnify and collide beams

Bunch Compressor
Reduce σ_z to eliminate hourglass effect at IP

Damping Ring
Reduce transverse phase space (emittance) so smaller transverse IP size achievable

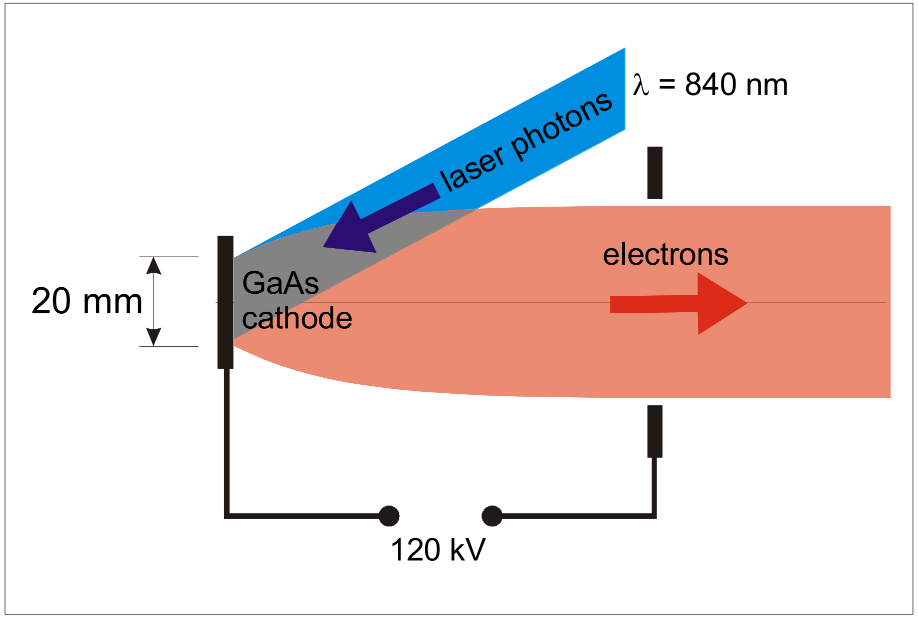
Electron Gun
Deliver stable beam current

Positron Target
Use electrons to pair-produce positrons

- will see the different elements in the following…

e+ e- sources

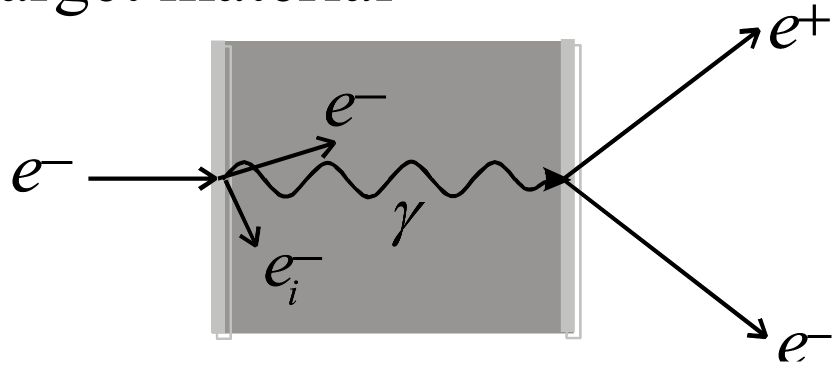
- we need large number of bunches of (polarized) leptons
- electron sources:
  - laser-driven DC photo injector
  - circularly polarized photons on GaAs cathode (incompatible with RF gun)
  - $\varepsilon_n \sim 50\ \mu\text{m rad}$
    factor ~10 in x plane
    factor ~500 in y plane
    too large!!!
  - dominated by space charge



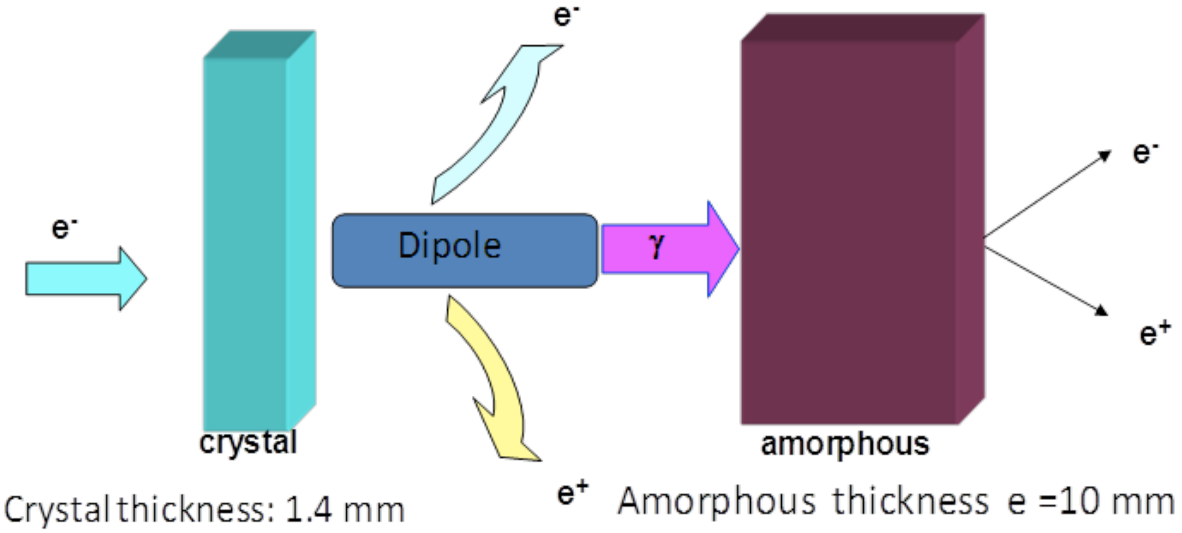
  - RF bunching system to generate bunch structure for the linac
  - (or laser with bunch time structure => even higher space charge)

e+ source

- basic mechanism: pair production in target material
- standard method: 'thick' target
  primary e- generate photons
  these convert into pairs



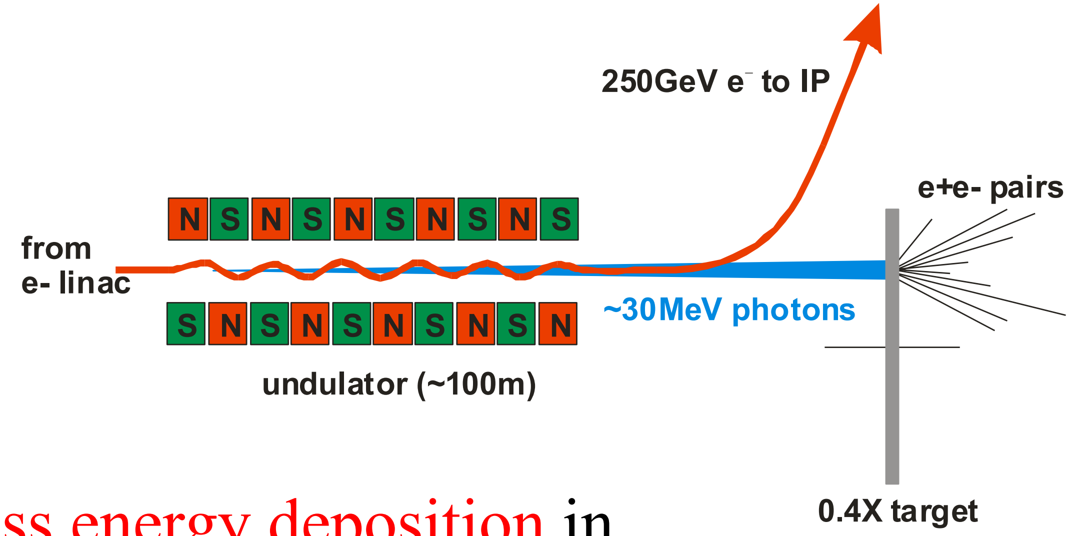
- Hybrid source:
  crystal +
  amorphous target
- enhanced photon flux
  by channeling effect



- positrons are captured in accelerating structure inside solenoid and accelerated

e+ source

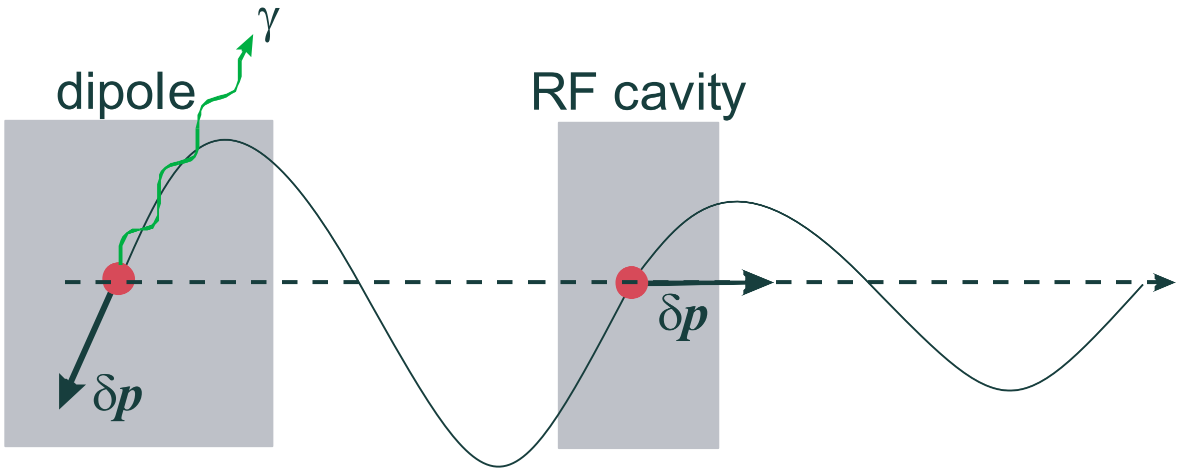
- undulator source:
  high energy e- produce photons in wiggler magnet + thin conversion target



- ~0.4 rad. length ⇒ much less energy deposition in the target (5 kW compared to 20 kW) ⇒ no parallel targets needed
- smaller emittance due to less coulomb scattering (factor ~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 GeV !
  - use primary e- beam
  - consequences for the commissioning and operation

Damping rings

- 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!!!

Damping rings

- exponential damping to equilibrium emittance:

initial emittance
(~0.01 m rad for e⁺)

$$\varepsilon_f = \varepsilon_{eq} + (\varepsilon_i - \varepsilon_{eq})\, e^{-2T/\tau_D}$$

final emittance

equilibrium emittance

damping time

- for e+ we need emittance reduction by few 10^5
- ~7-8 damping times required
- damping time:

$$\tau_D = \frac{2E}{P} \qquad P = \frac{2}{3}\frac{r_e c}{(m_o c^2)^3}\frac{E^4}{\rho^2} \qquad \boxed{\tau_D \propto \frac{\rho^2}{E^3}}$$

P - emitted radiation power

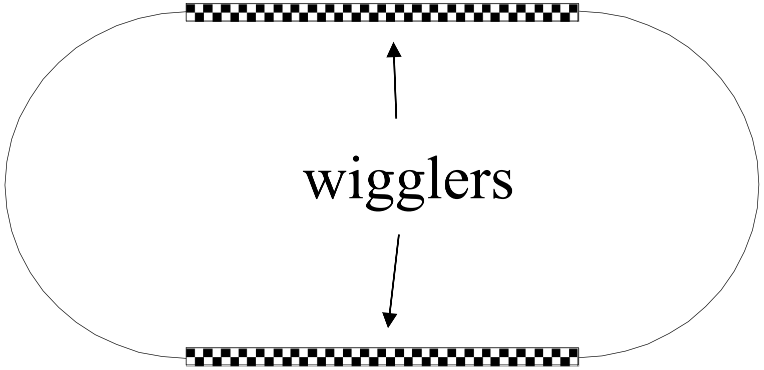
LEP: E ~ 90 GeV, P ~ 15000 GeV/s, τ_D ~ 12 ms

Damping rings

- $\tau_D \propto \frac{\rho^2}{E^3}$ 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 τ_D !!! ⇒ store time too long !!!
- Increase damping and P using *wiggler magnets*

Damping Wigglers

- 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

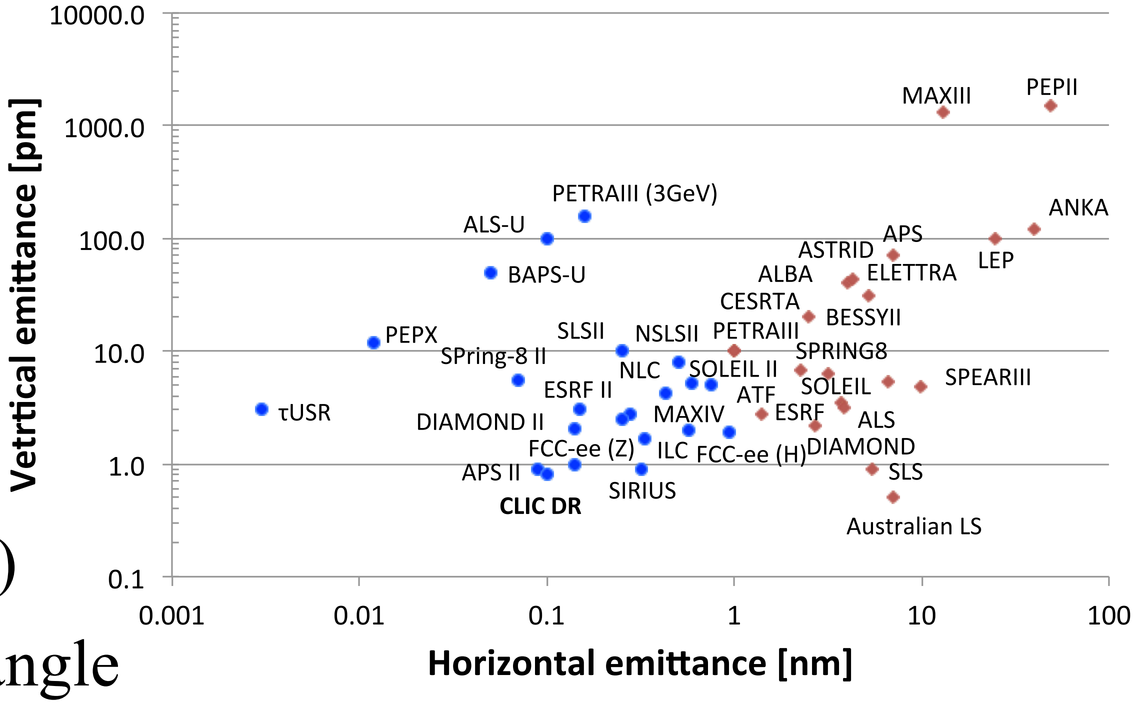
- Energy loss in wiggler:

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

$<B^2>$ is the field square averaged over the wiggler length

Damping ring: emittance limits

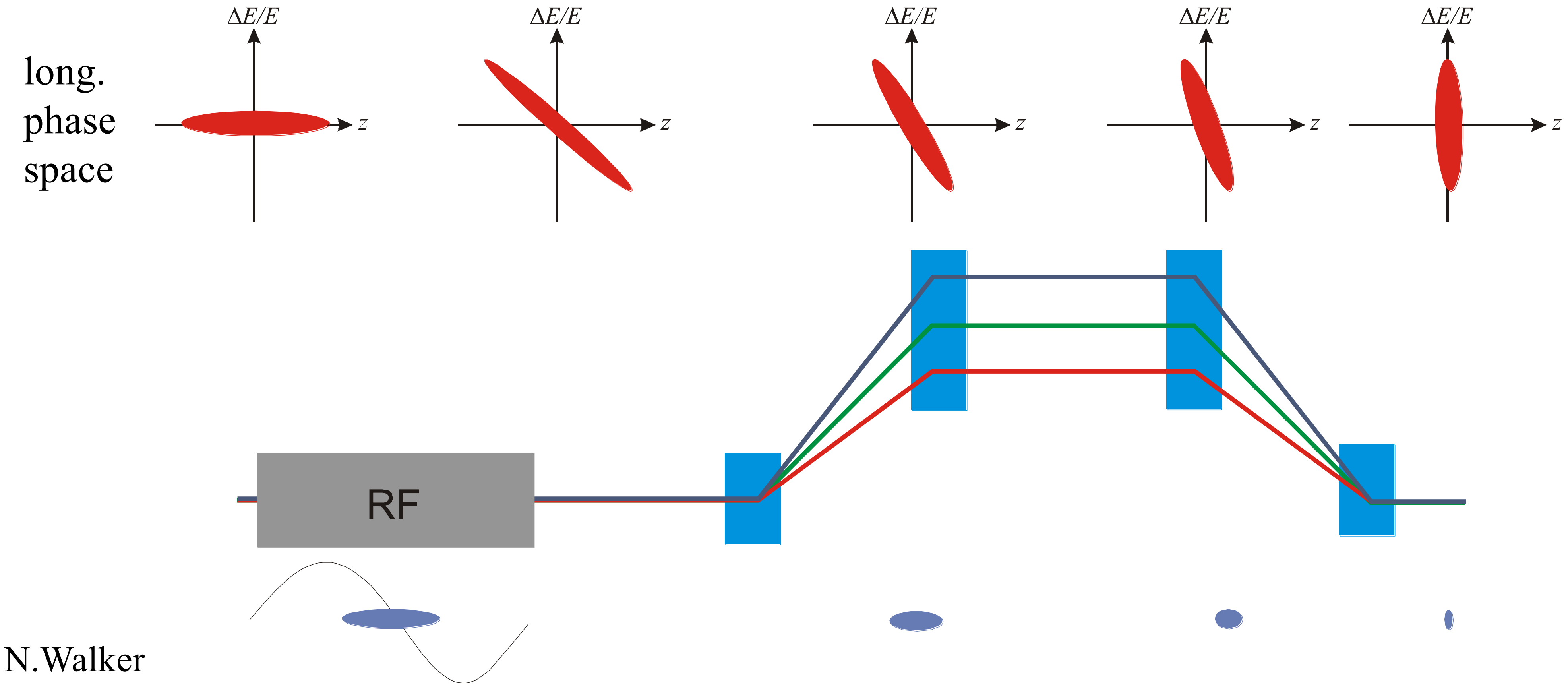
- Horizontal emittance ε_x defined by lattice
- theoretical vertical emittance limited by
  - space charge
  - intra-beam scattering (IBS)
  - photon emission opening angle



- 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 compression

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



N.Walker

The linear bunch compressor

initial (uncorrelated) momentum spread:	δ_u
initial bunch length	$\sigma_{z,0}$
compression ratio	$F_c = \sigma_{z,0} / \sigma_z$
beam energy	E
RF induced (correlated) momentum spread:	δ_c
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

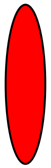
RF cavity

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

compress at low energy

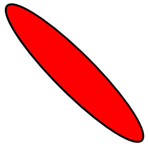
The linear bunch compressor

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

- For high compression ratio ($\delta_c \gg \delta_u$) $R_{56} \approx -\dfrac{\sigma_{z,0}}{\delta_c}$

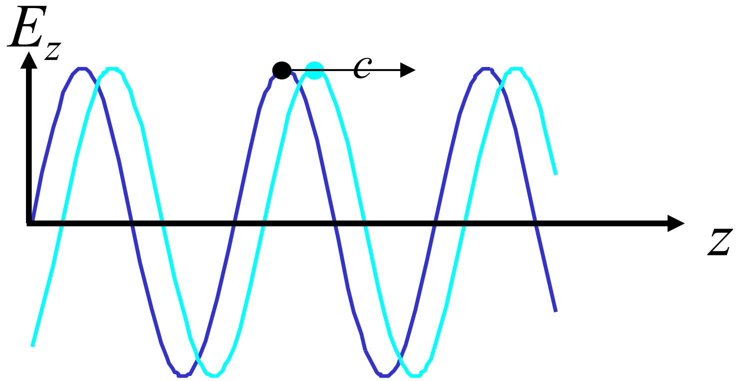
Bunch compressor - Example

$$\left.\begin{aligned} \sigma_{z,0} &= 2\,\mathrm{mm} \\ \delta_{\mathrm{u}} &= 0.1\% \\ \sigma_z &= 100\,\mu\mathrm{m} \Rightarrow F_c = 20 \\ f_{RF} &= 3\,\mathrm{GHz} \;\Rightarrow k_{RF} = 62.8\,\mathrm{m}^{-1} \\ E &= 2\,\mathrm{GeV} \end{aligned}\right\} \quad \begin{aligned} \delta &= 2\% \\ V_{RF} &= 318\,\mathrm{MV} \\ R_{56} &= 0.1\,\mathrm{m} \end{aligned}$$

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

The Main Linac

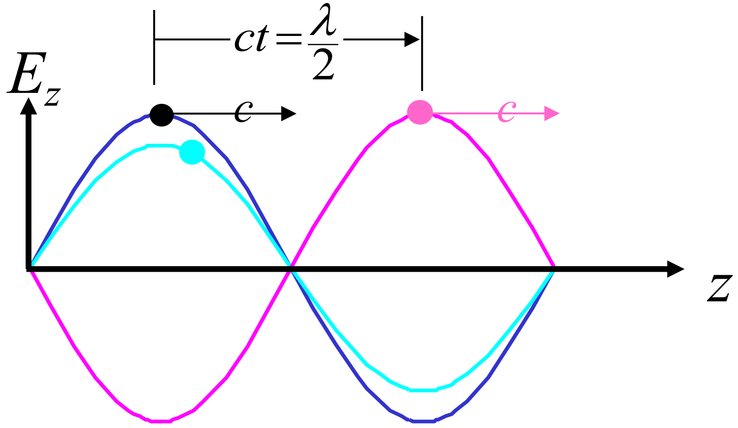
- Now we got small, short bunches
  we **"only"** have to accelerate them to collision energy
- Accelerating cavities:



<u>travelling wave structure</u>:

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

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



<u>standing wave cavity</u>:

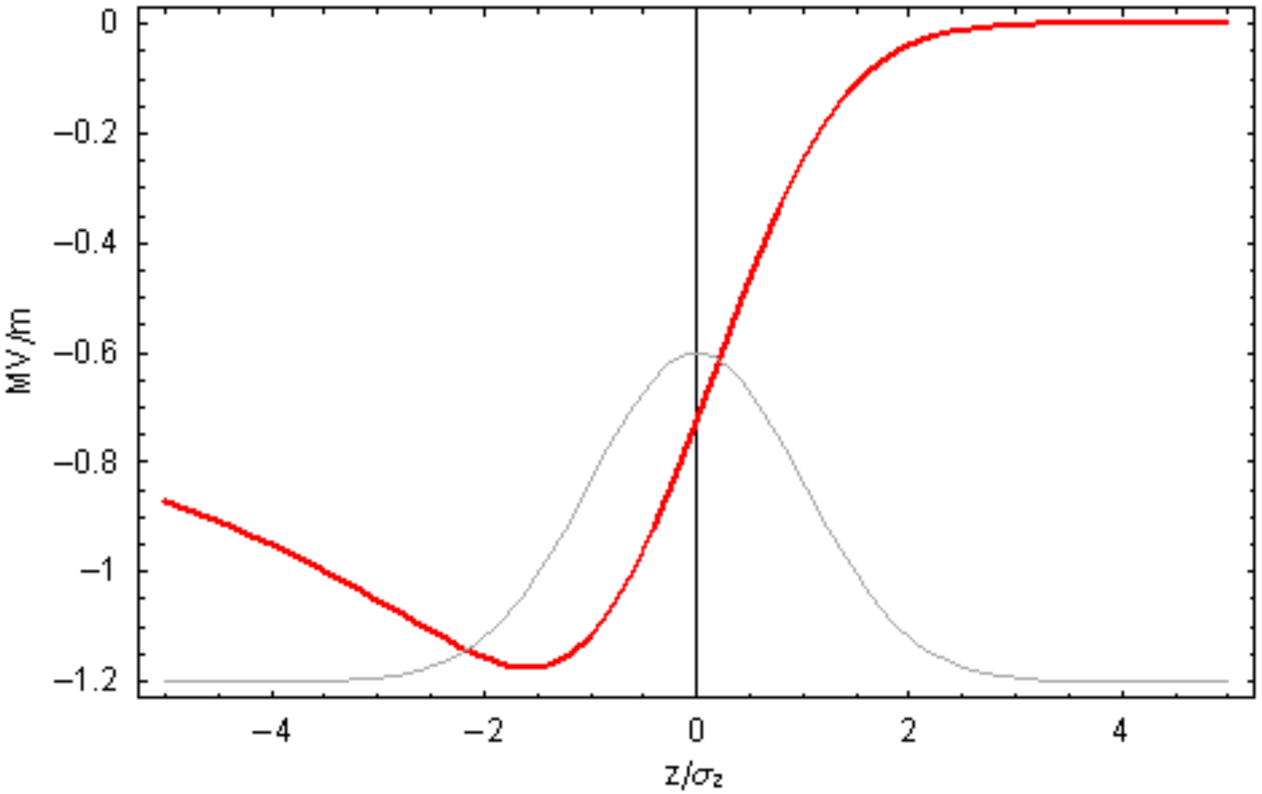
bunch sees field:

$$E_z = E_0 \sin(\omega t + \varphi)\sin(kz)$$

$$= E_0 \sin(kz + \varphi)\sin(kz)$$

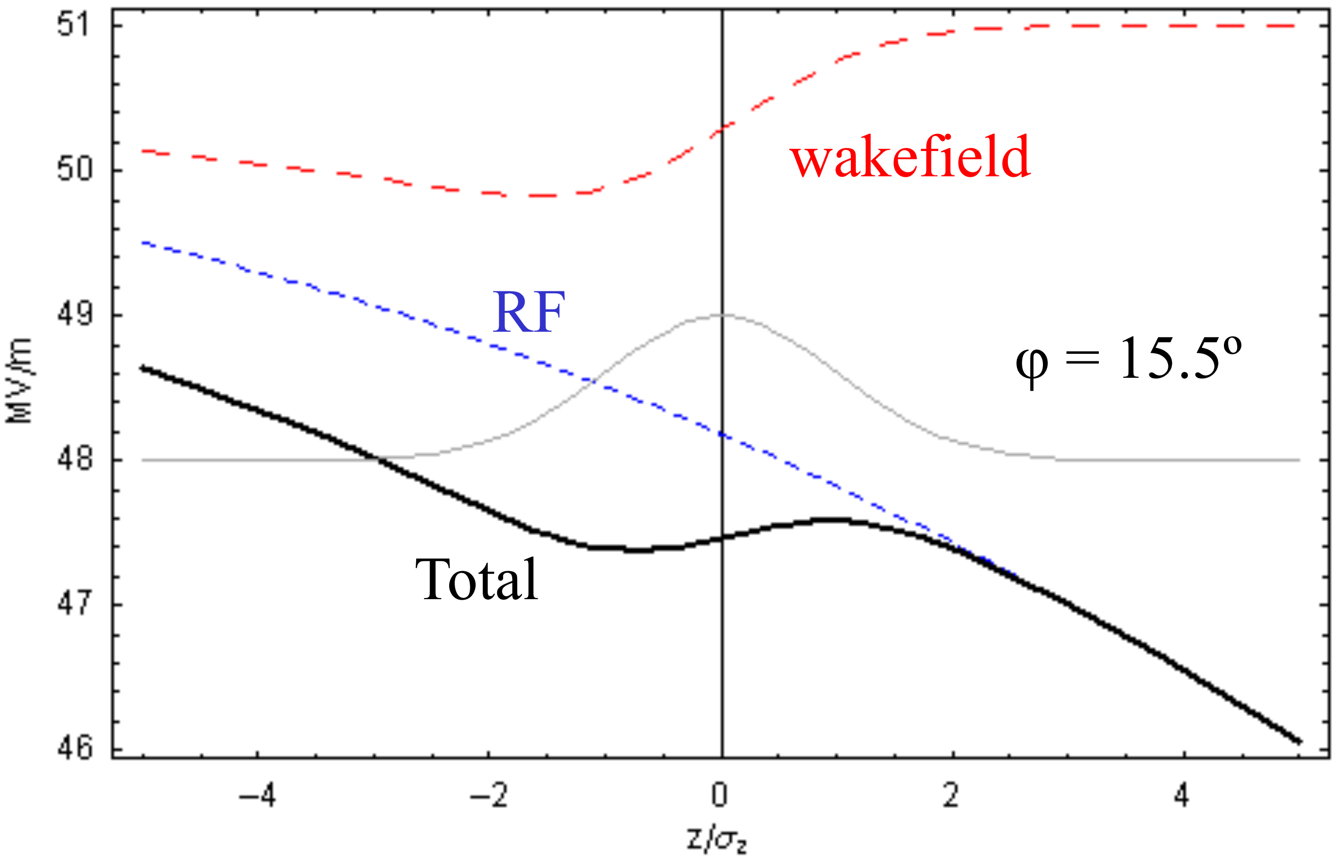
Single bunch effects: longitudinal

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



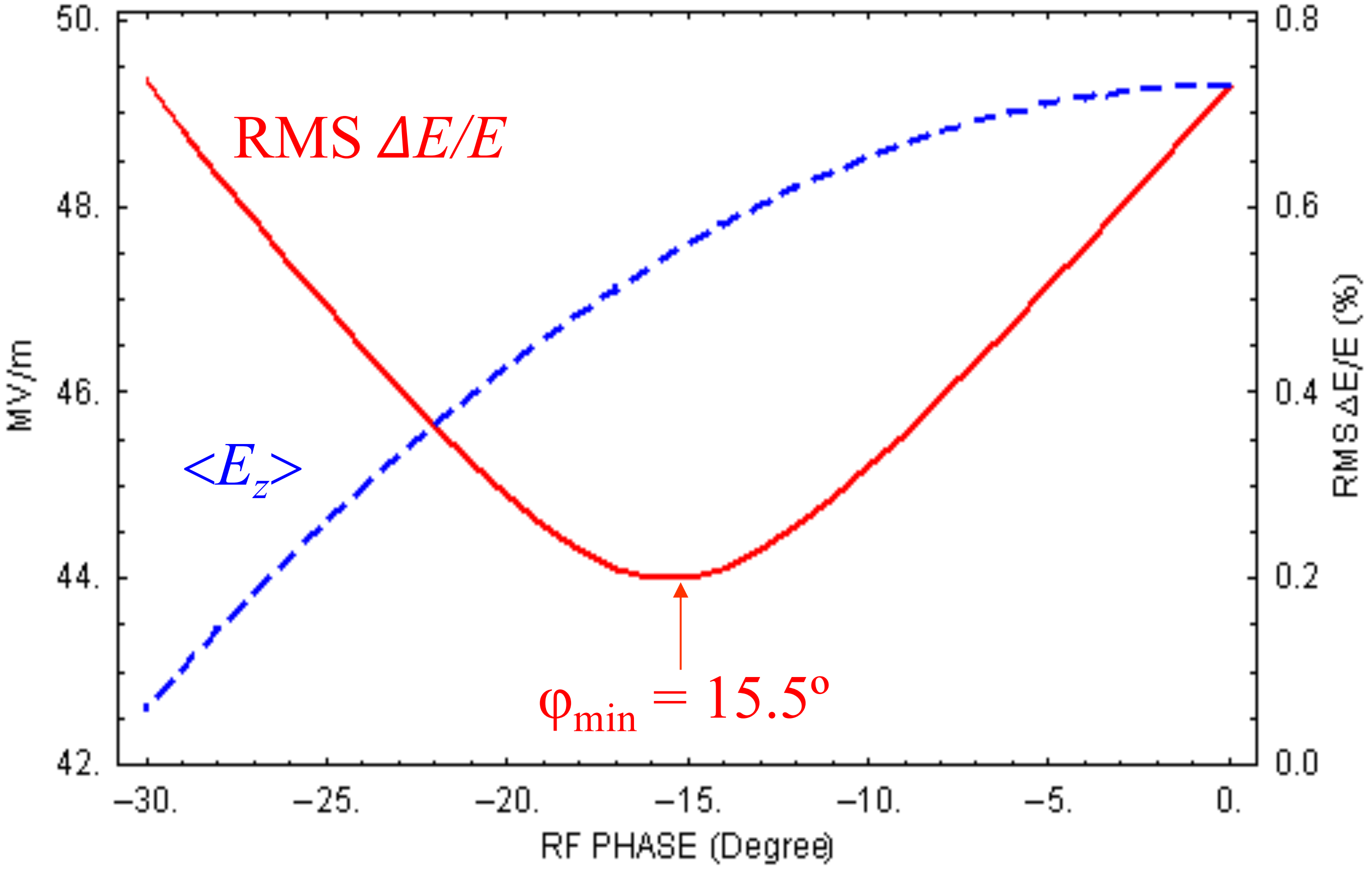
Beam-loading compensation

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



Beam-loading compensation

- Minimize momentum spread



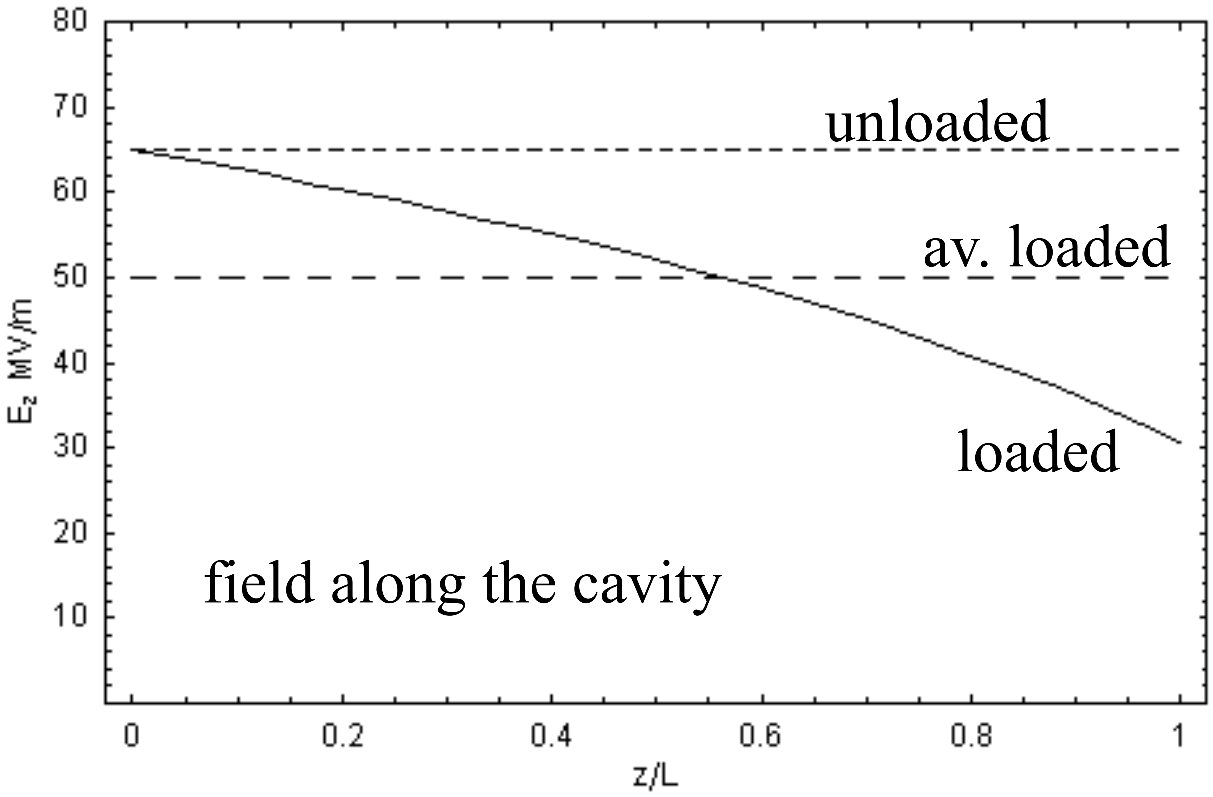
TW Cavity: Beam Loading

- 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 impedence

I_b peak beam current



TW Cavity: Beam loading

- 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

SW cavity: multi-bunch BL

- 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

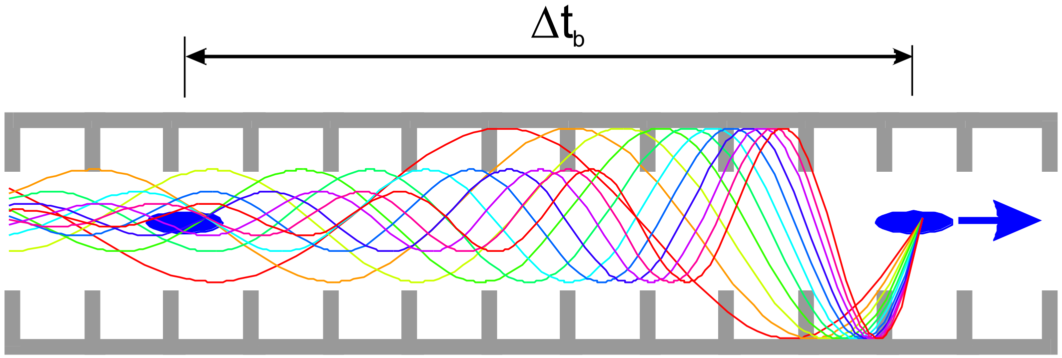
=> long bunch trains in SC linear collider design

Linac: emittance dilution

- 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: ($x, px \rightarrow y$)
  - Jitter: ($t \rightarrow y$)

- All can increase projection of the beam size at the IP
- Projection determines luminosity

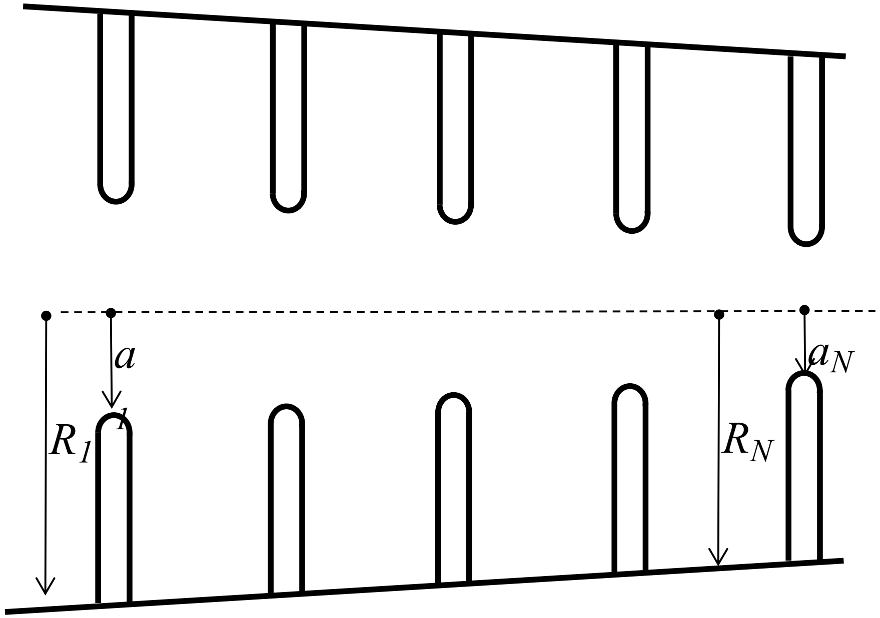
Linac: transverse wakefields



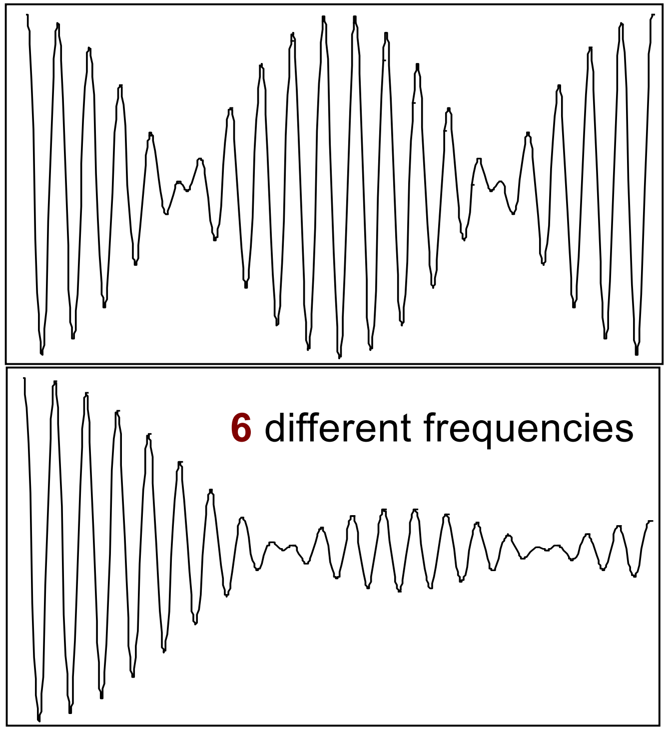
- Bunches induce field in the cavities
- Later bunches are perturbed by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!

Transverse wakefields

- 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

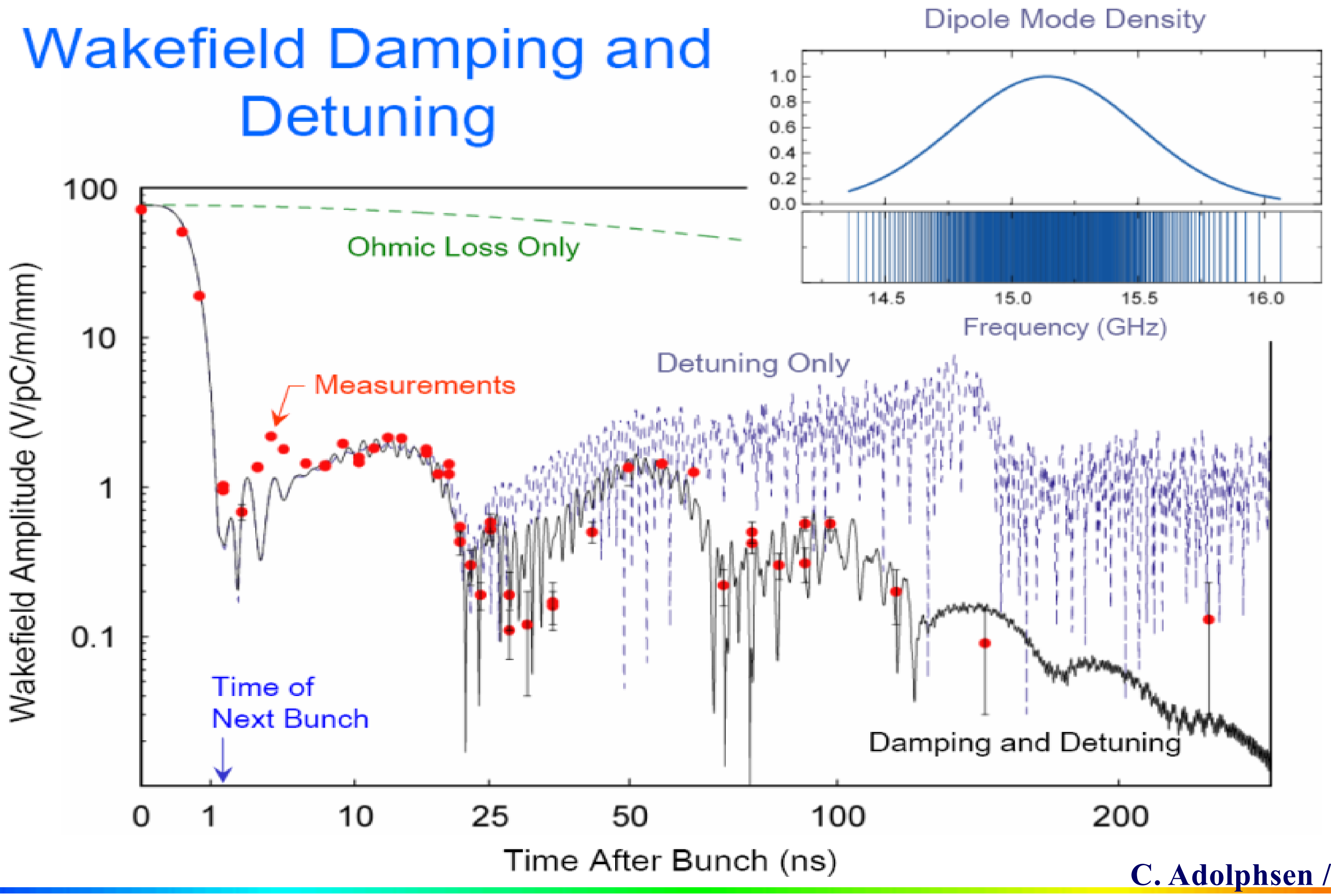


Long range wake of a dipole mode spread over **2** different frequencies



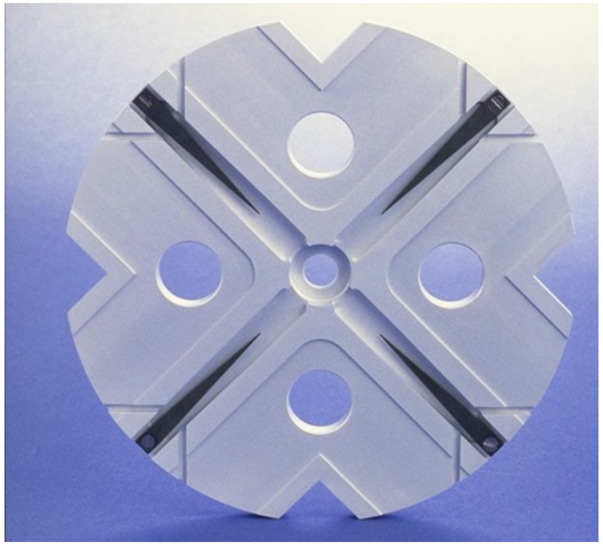
Damping and detuning

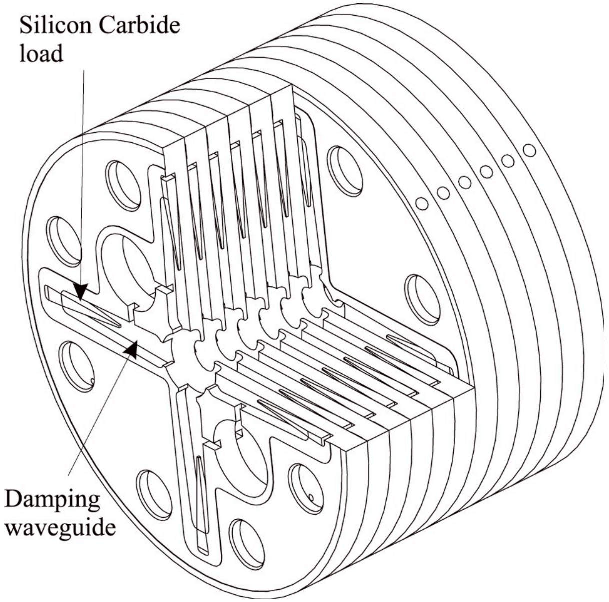
- Slight random detuning between cells makes HOMs decohere quickly
- Will recohere later: need to be damped (HOM dampers)



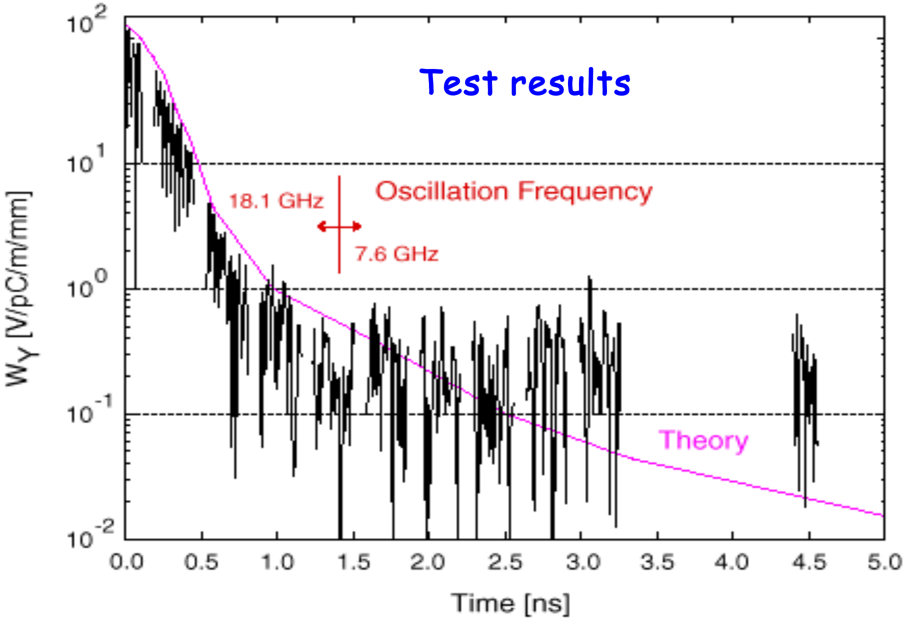
C. Adolphsen / SLAC

HOM damping



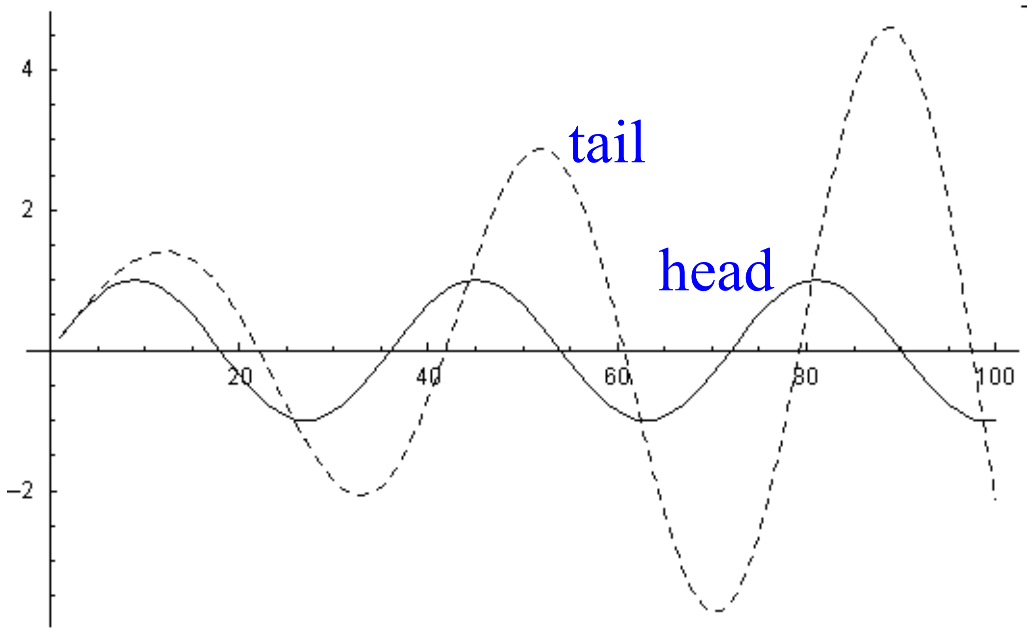


- Each cell damped by 4 radial WG
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped



Single bunch wakefields

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



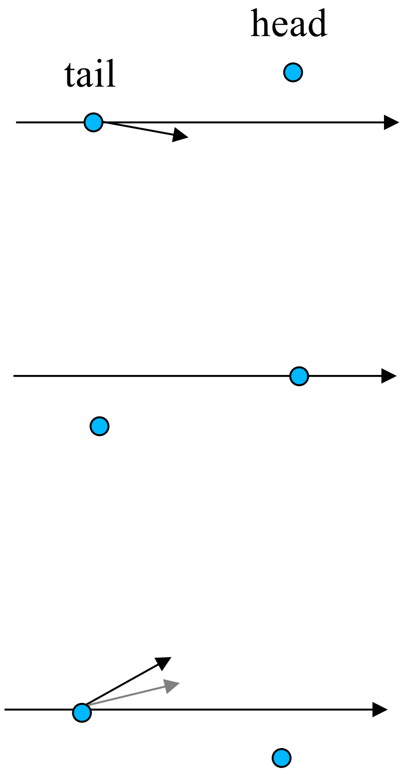
Tail particle
Equation of motion:

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

Driven Oscillator !!

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

Two particle model



- 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 $\approx\beta\theta$
- $\pi/2$ in phase further (π in total):
  - -x displacement, tail kicked by $-\theta$
  - but initial kick has changed sign
- => kicks add coherently
- => tail amplitude grows along the linac

BNS damping

- 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:

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

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

Random misalignments

- BNS damping does not cure random cavity misalignment
- Emittance growth:

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

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 Δε, it scales as

$$\delta Y_{RMS} \propto \frac{1}{N W_\perp}\sqrt{\frac{G}{\beta}} \propto \frac{1}{N f^3}\sqrt{\frac{G}{\beta}}$$

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