Linear Colliders
Lecture 2
Subsystems I

Frank Tecker – CERN

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

Reminder: Luminosity

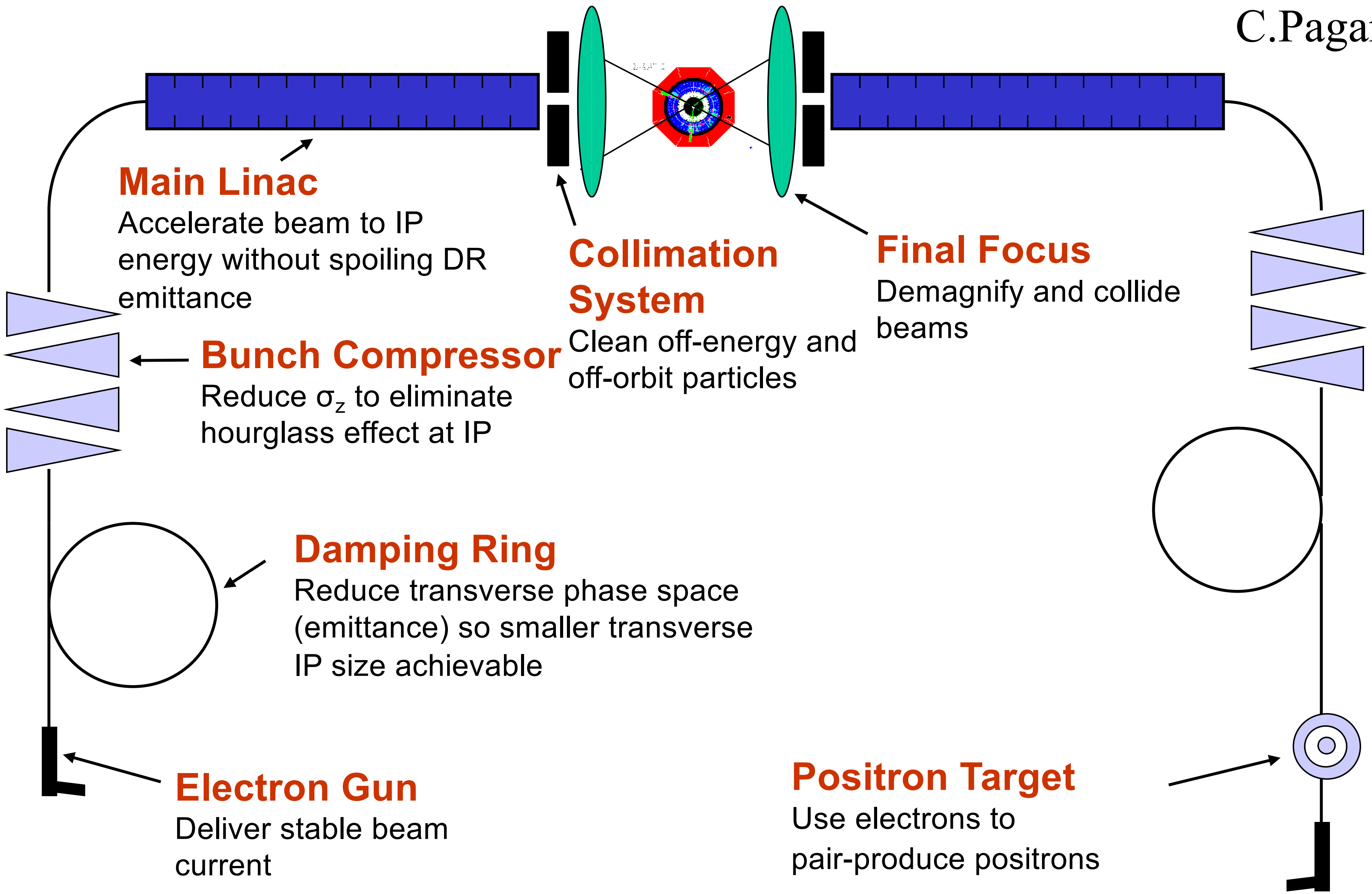
Last lecture, we arrived at:

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

- 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)

Generic Linear Collider

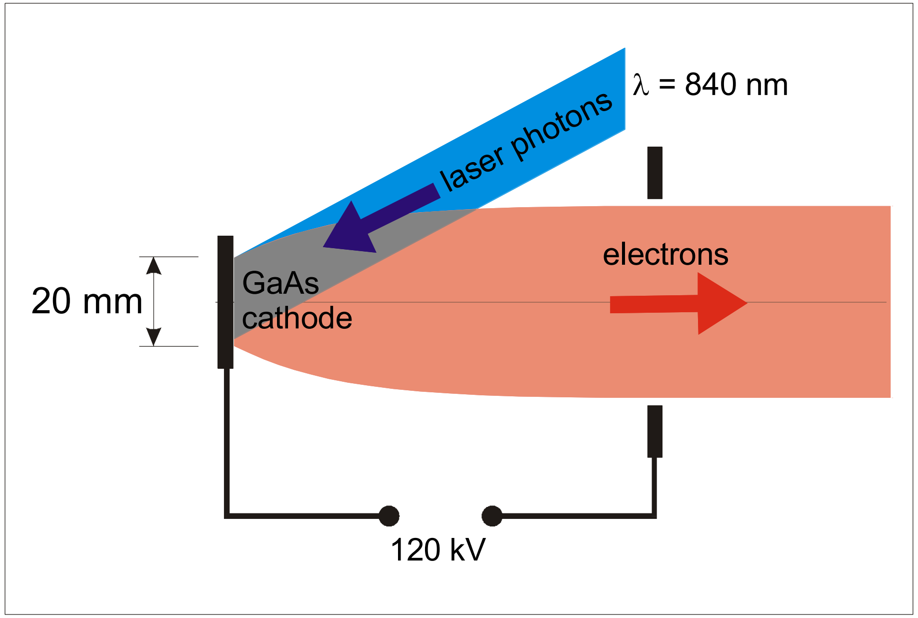
C.Pagani



- will see the different elements in the following…

e+ e- sources

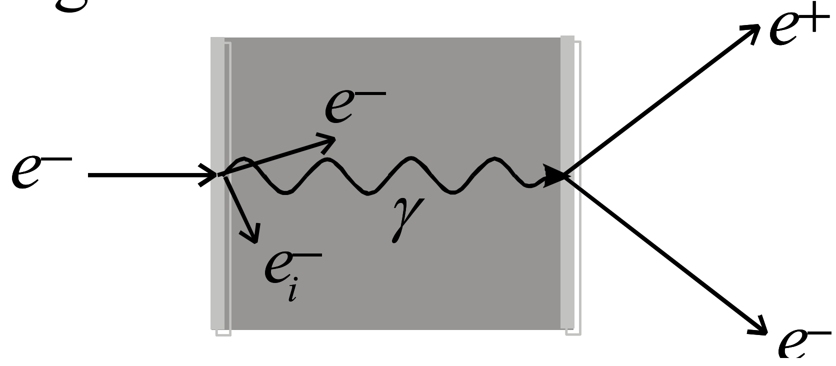
- we need large number of bunches of (polarized) leptons
- electron sources:
  - laser-driven DC photo injector
  - circularly polarized photons on GaAs cathode (incompatible with RF gun)
  - $\varepsilon_n \sim 50\ \mu\text{m rad}$
    factor ~10 in x plane
    factor ~500 in y plane
    too large!!!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



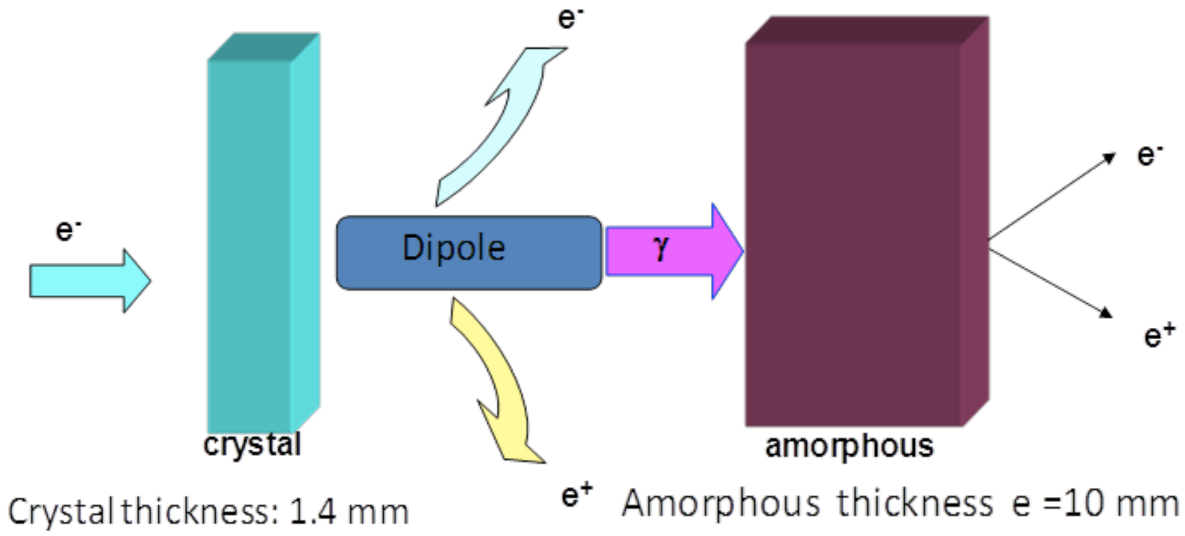
  - RF bunching system to generate bunch structure for the linac
  - (or laser with bunch time structure => even higher space charge)

e+ source

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



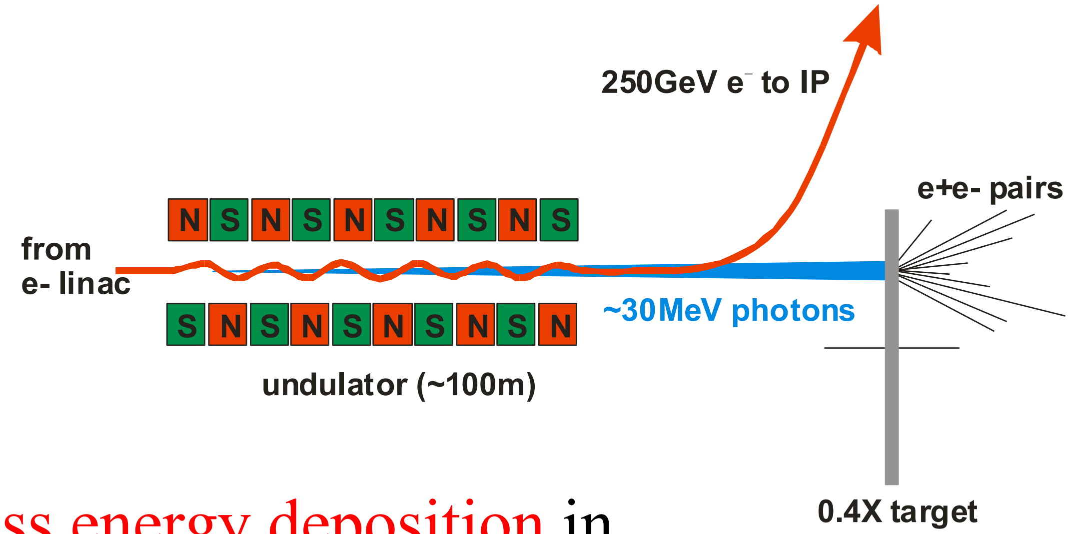
- Hybrid source:
  crystal +
  amorphous target
- enhanced photon flux
  by channeling effect



- positrons are captured in accelerating structure inside solenoid and accelerated

e+ source

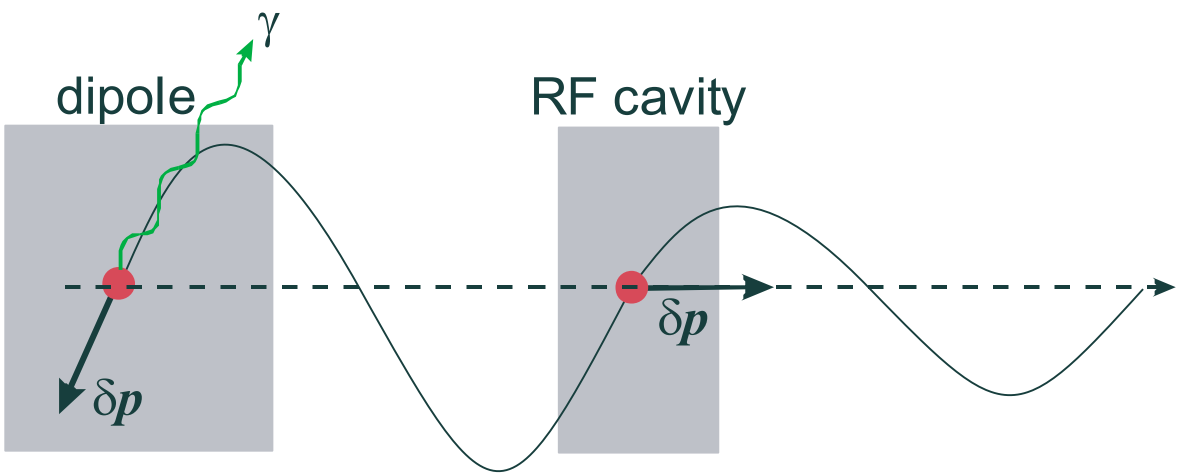
- undulator source:
  high energy e- produce photons in wiggler magnet + thin conversion target



- ~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 μm 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

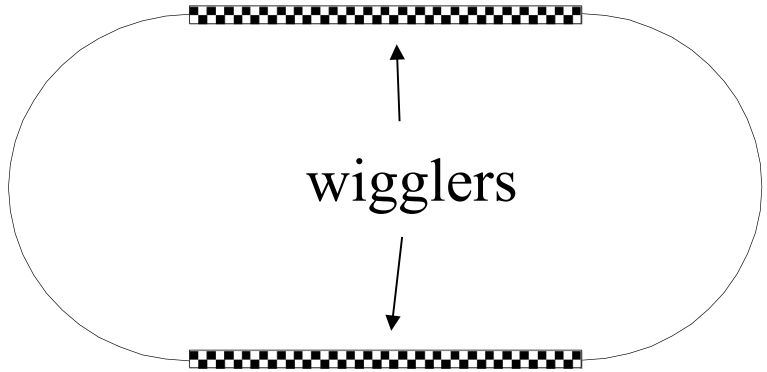
LEP: E ~ 90 GeV, P ~ 15000 GeV/s, τ_D ~ 12 ms

Damping rings

- $\tau_D \propto \dfrac{\rho^2}{E^3}$ suggests high-energy for a small ring. But
  - required RF power: $P_{RF} \propto \dfrac{E^4}{\rho^2} \times n_b N$
  - equilibrium emittance: $\varepsilon_{n,x} \propto \dfrac{E^2}{\rho}$ 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

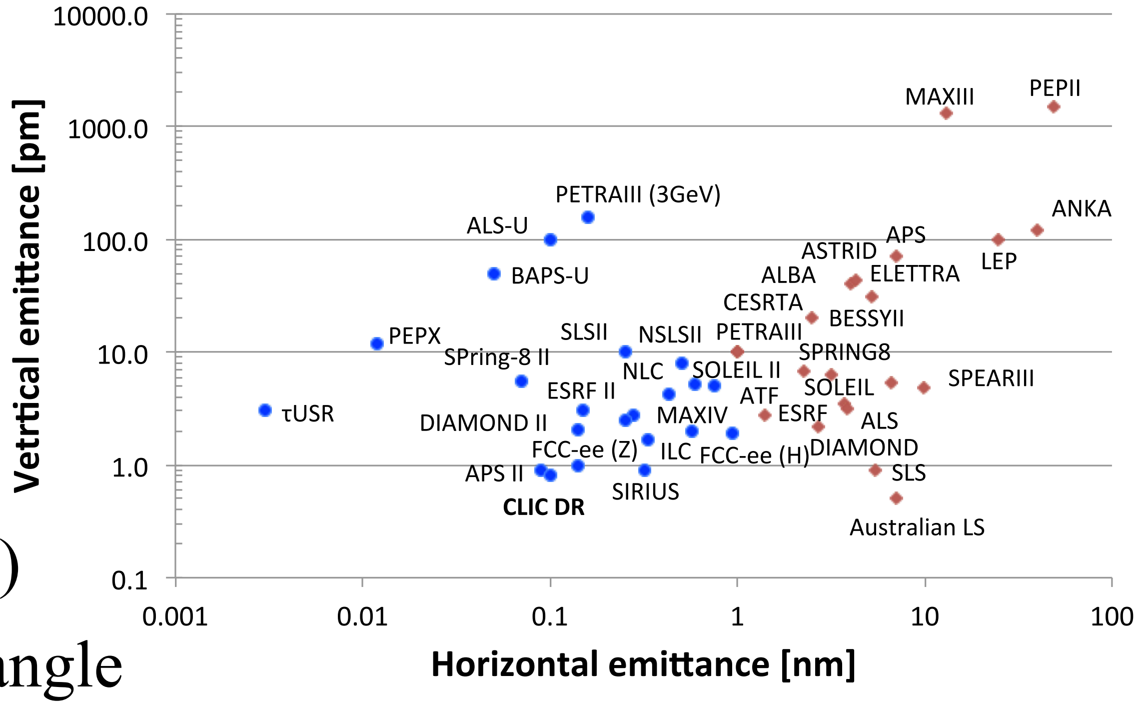
L_{wiggler} total length of wiggler

- Energy loss in wiggler:

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

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

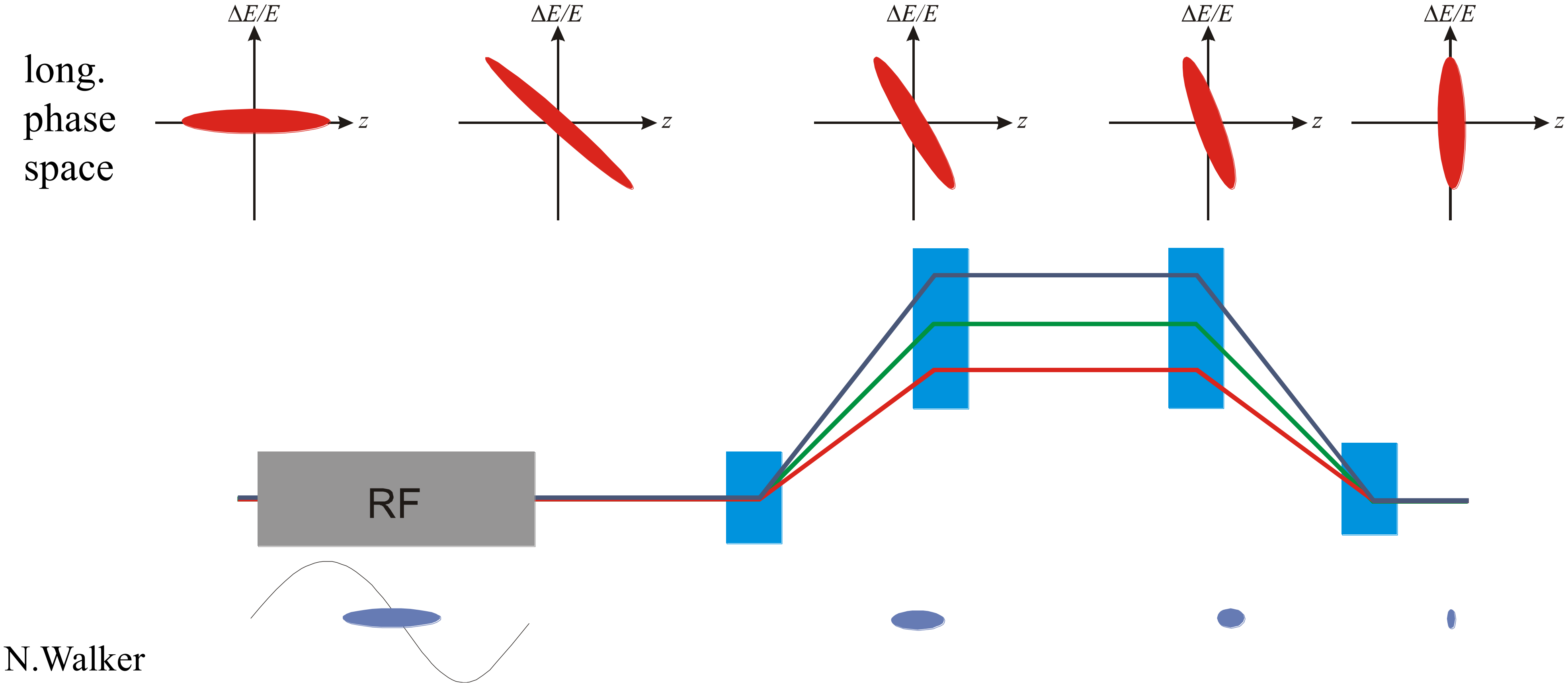
Damping ring: emittance limits



- 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: $\Delta y \approx 30$ μm
  $\Rightarrow$ 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 ($\sigma_z \ \delta$ = 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

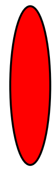
RF cavity

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

compress at low energy

The linear bunch compressor

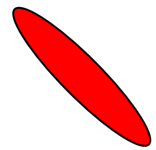
- chicane (dispersive section) linear part $z_1 \approx z_0 + R_{56}\delta$
- Minimum bunch length for upright ellipse
  $\Rightarrow$ correlation $\langle z\delta \rangle = 0$



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

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

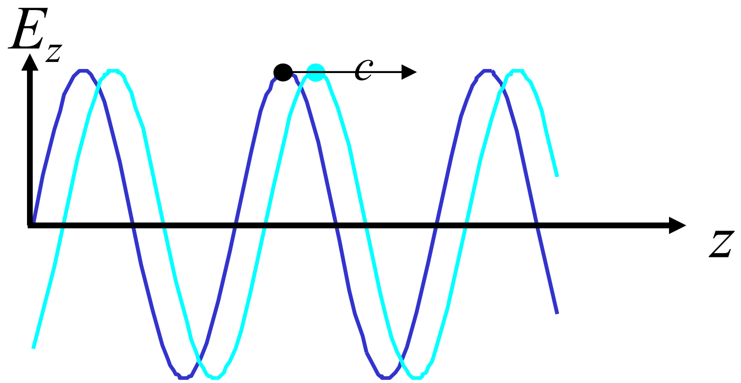
Bunch compressor - Example

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

- 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

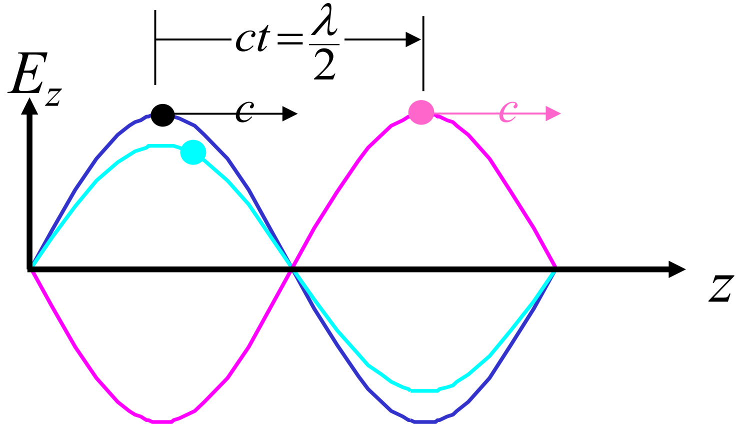
The Main Linac

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

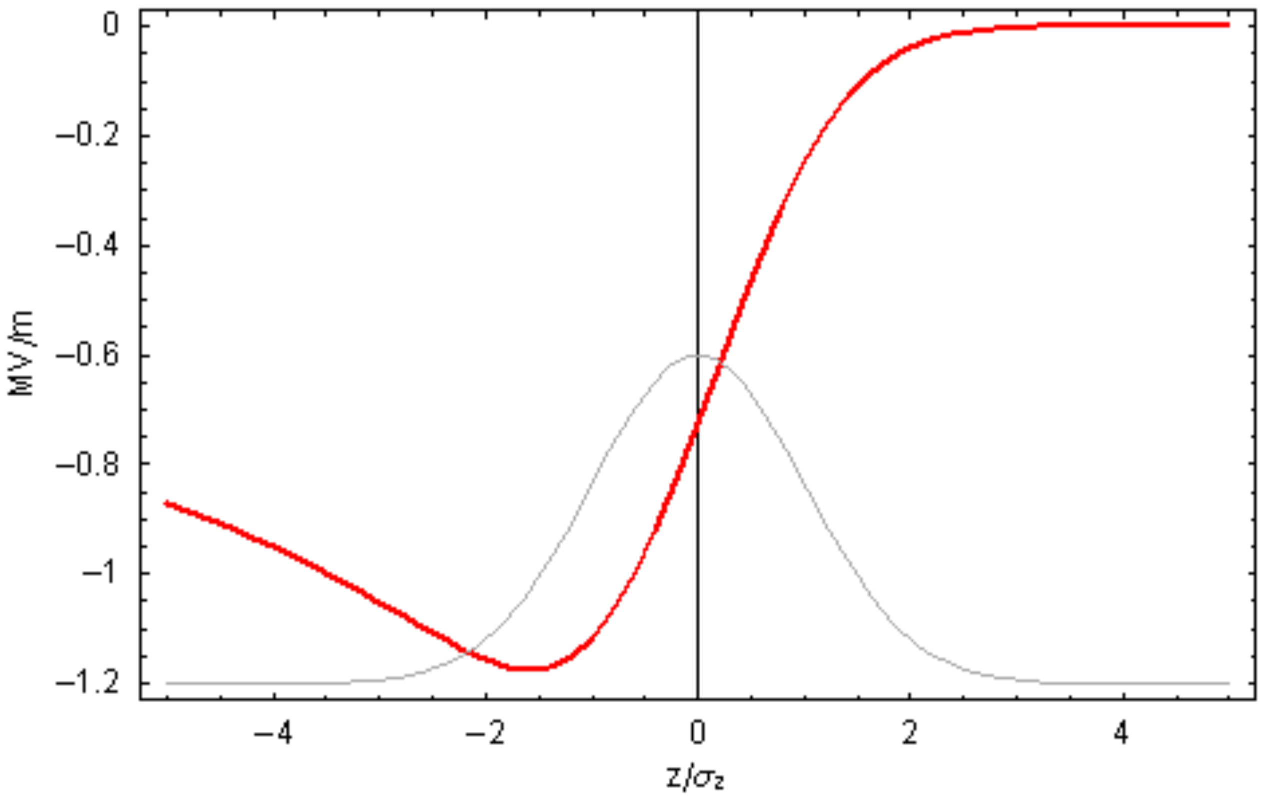


<u>standing wave cavity</u>:

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

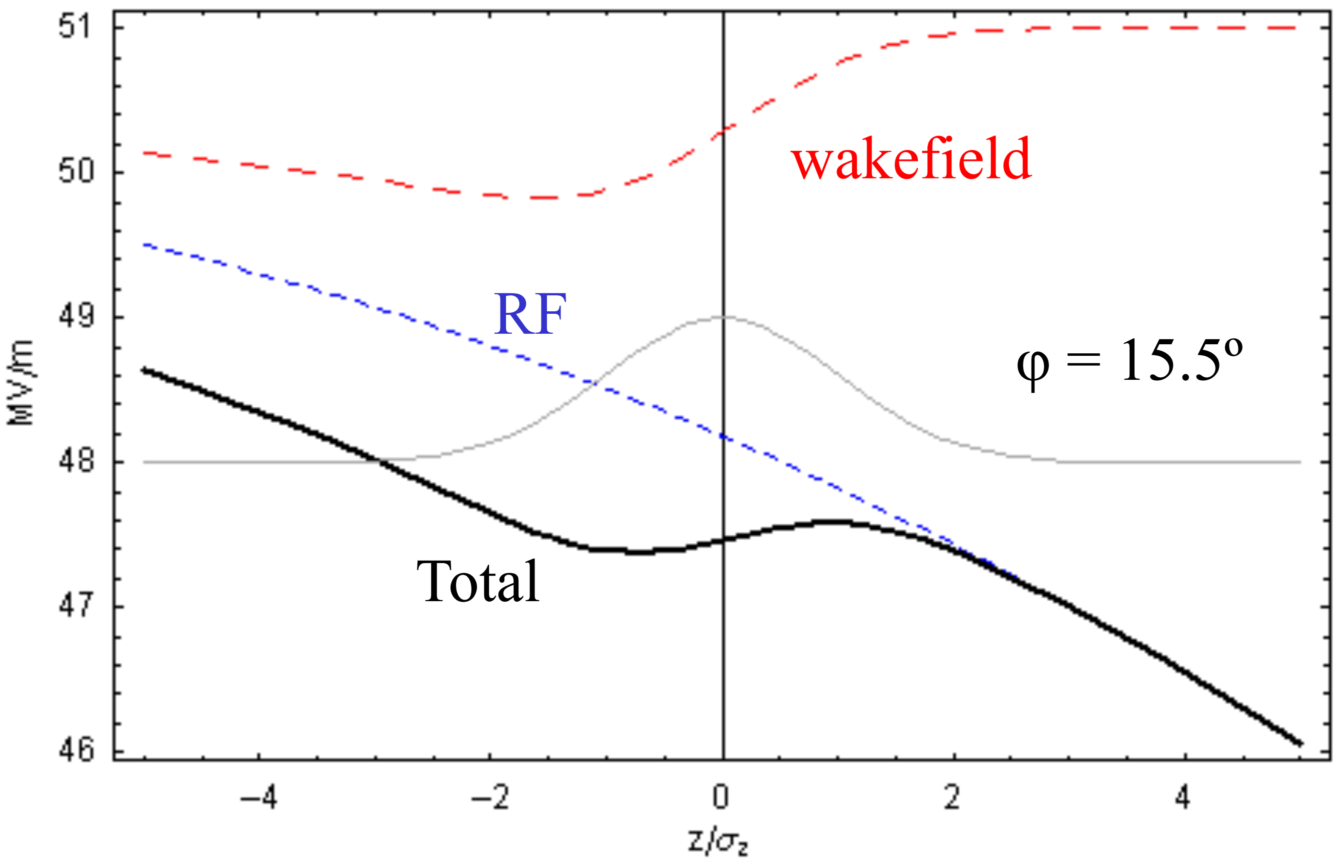
Single bunch effects: longitudinal

- 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



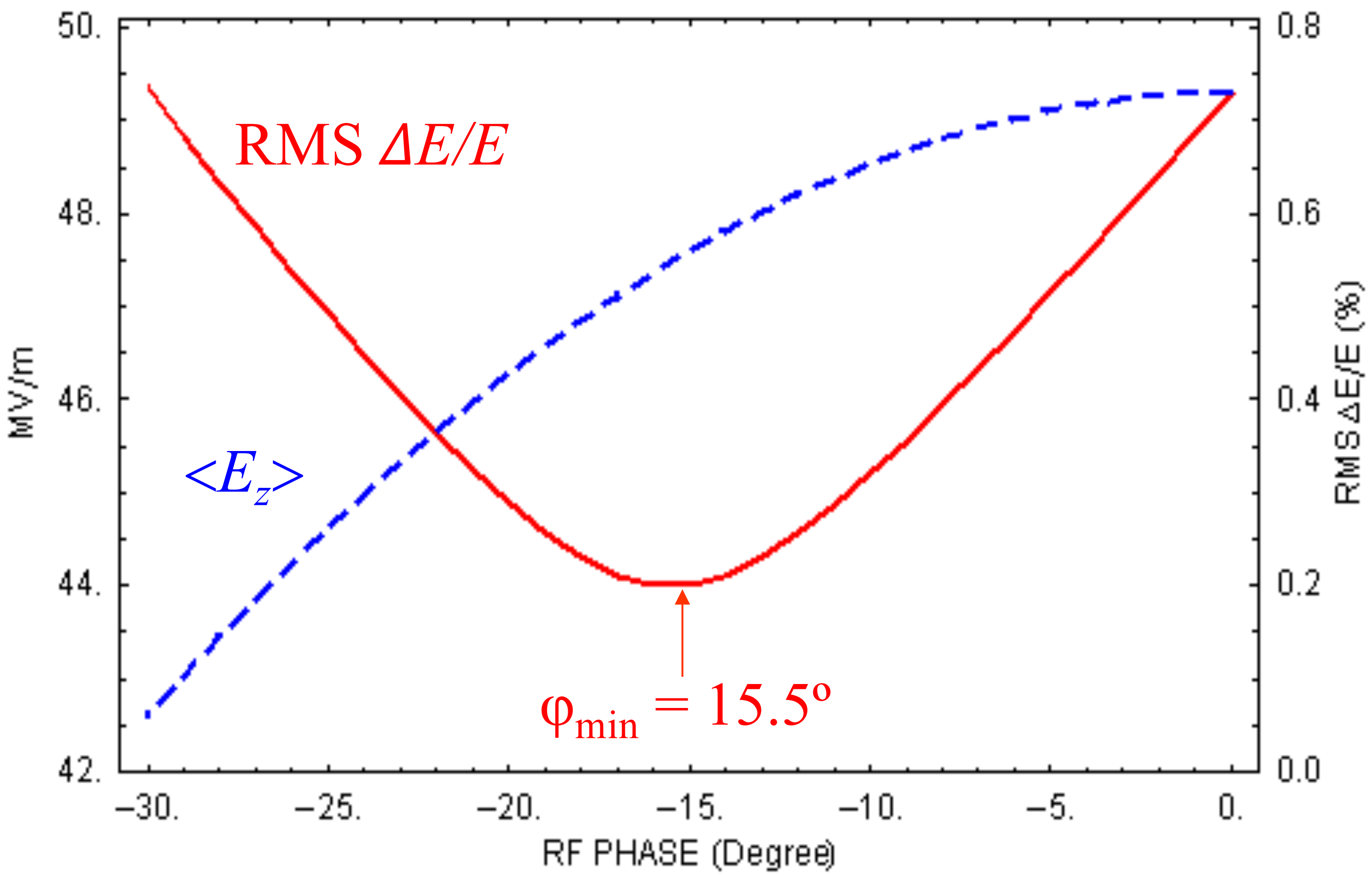
Beam-loading compensation

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



Beam-loading compensation

- Minimize momentum spread



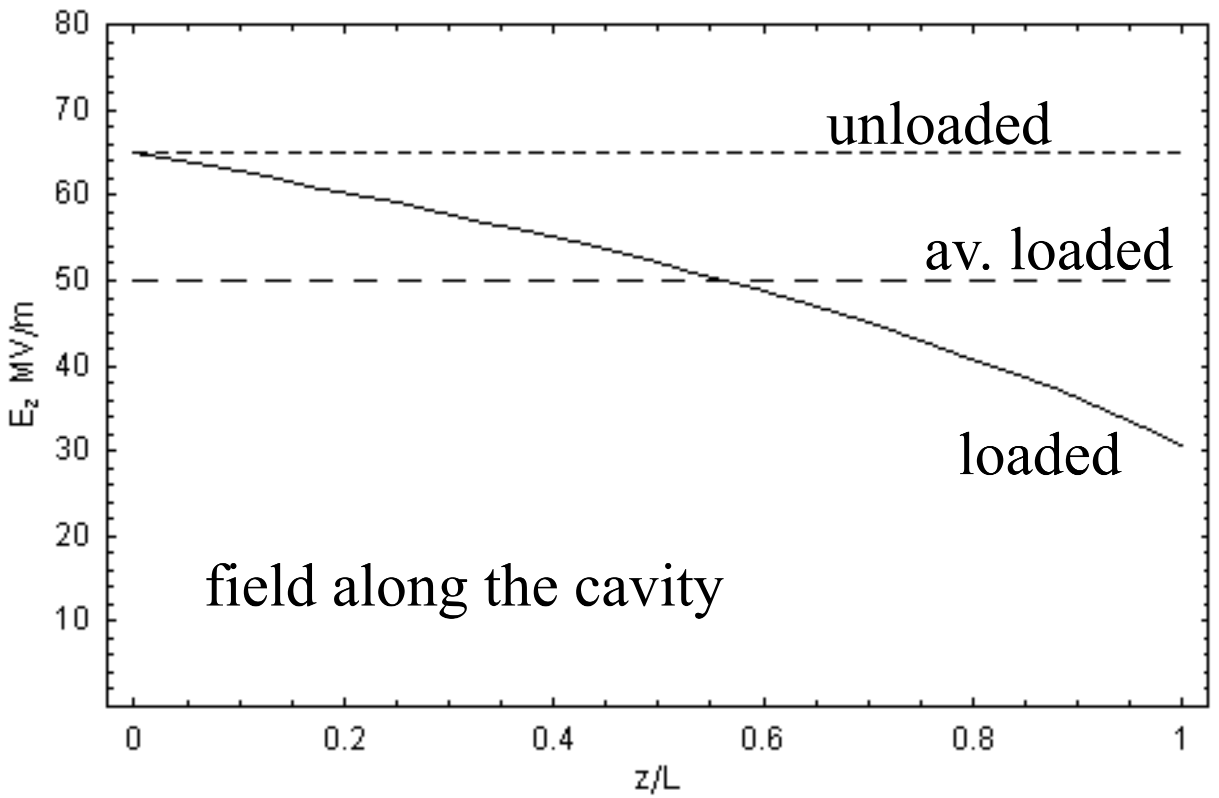
TW Cavity: Beam Loading

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

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

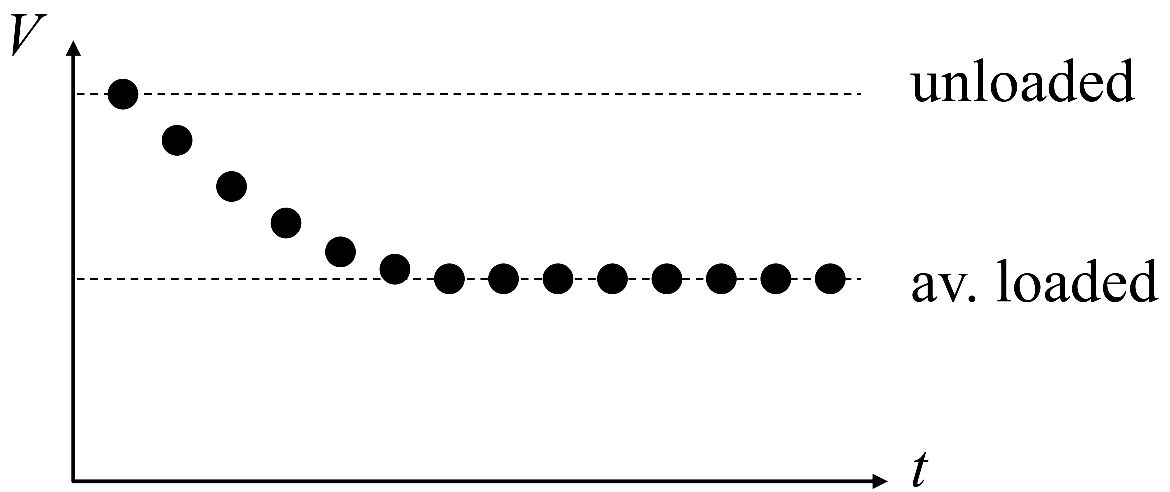
r_s shunt impedence

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

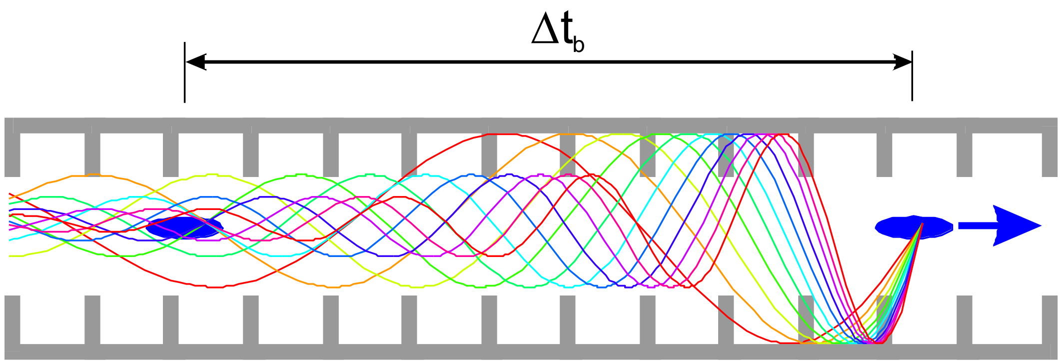
- With superconducting standing wave (SW) cavities:
- Little losses to cavity walls
- You can afford long RF pulse with
  - Many bunches
  - Large time between the bunches
- RF feed-back to compensate beam-loading before the next bunch arrives

=> 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

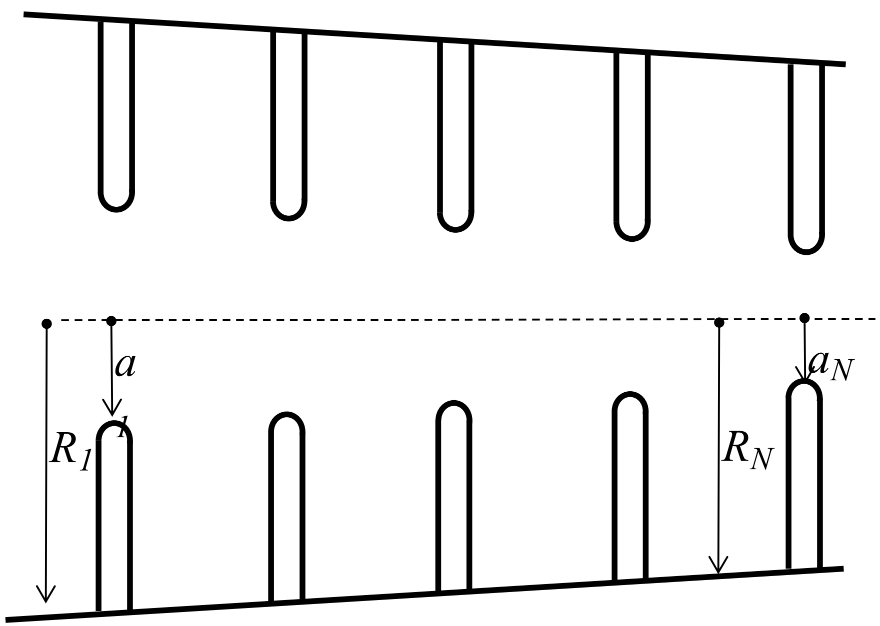
Linac: transverse wakefields



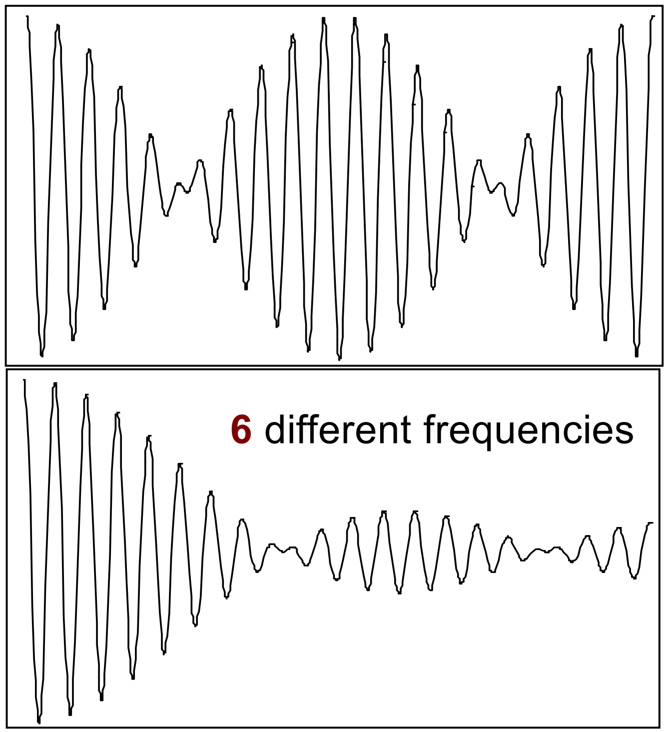
- Bunches induce field in the cavities
- Later bunches are perturbed by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!

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

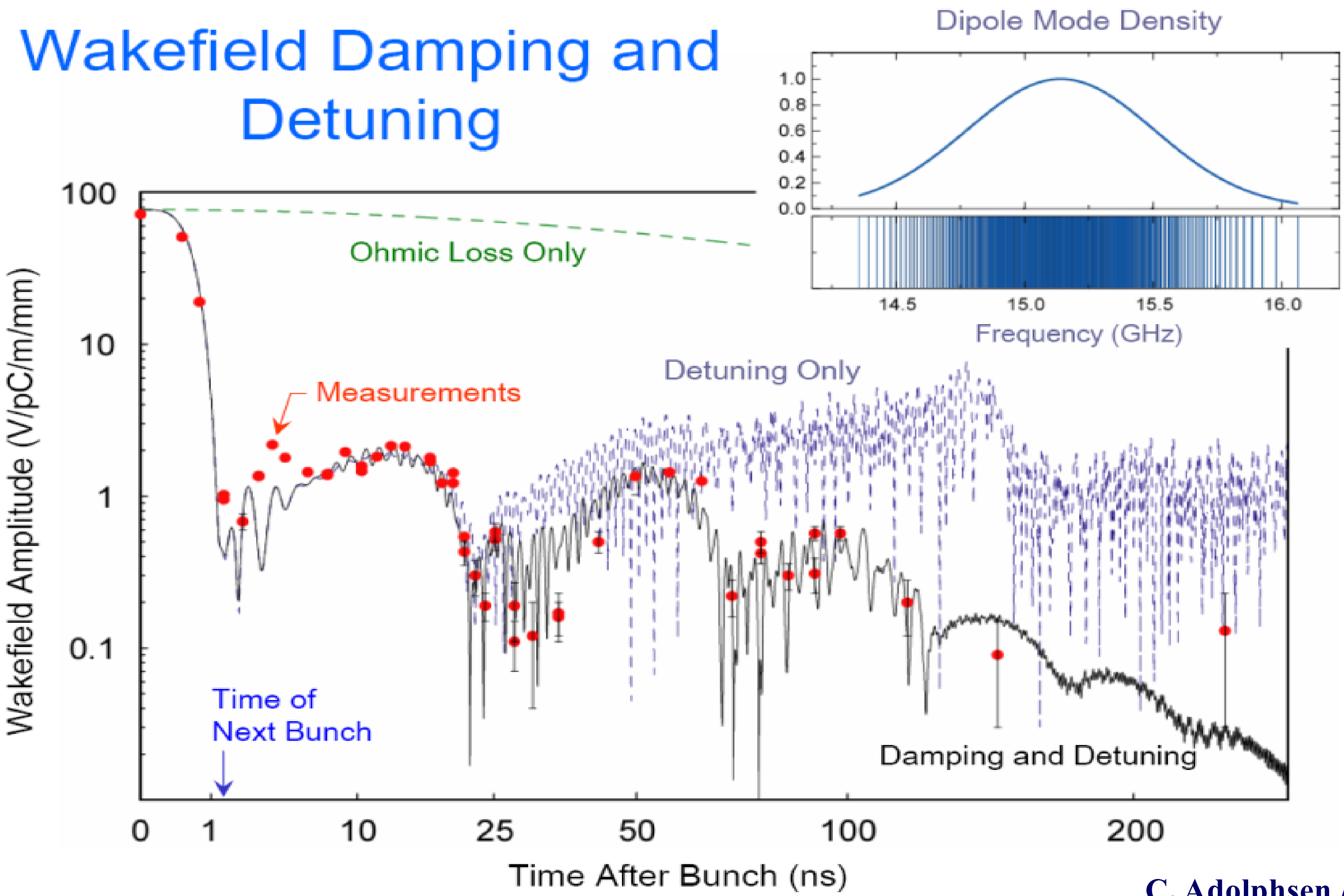


Long range wake of a dipole mode spread over **2** different frequencies



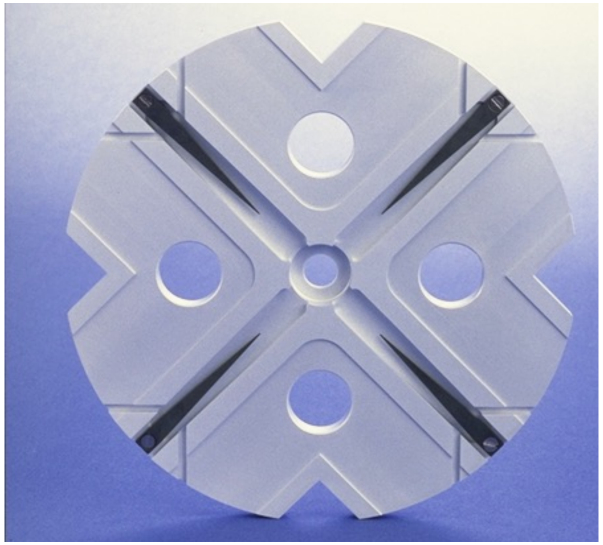
Damping and detuning

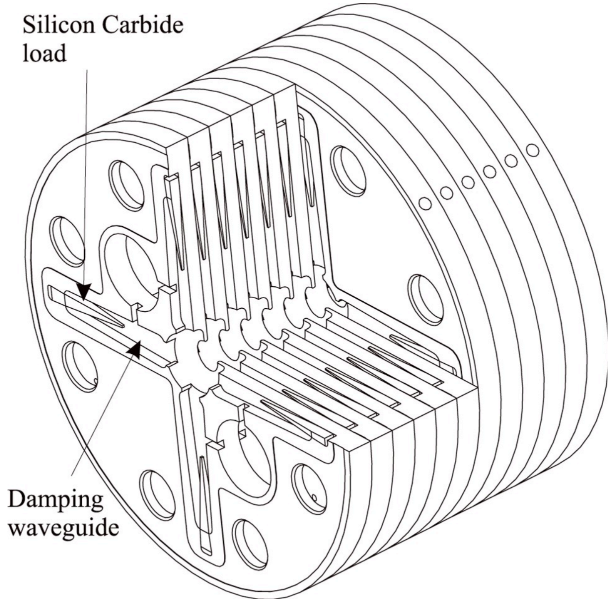
- Slight random detuning between cells makes HOMs decohere quickly
- Will recohere later: need to be damped (HOM dampers)



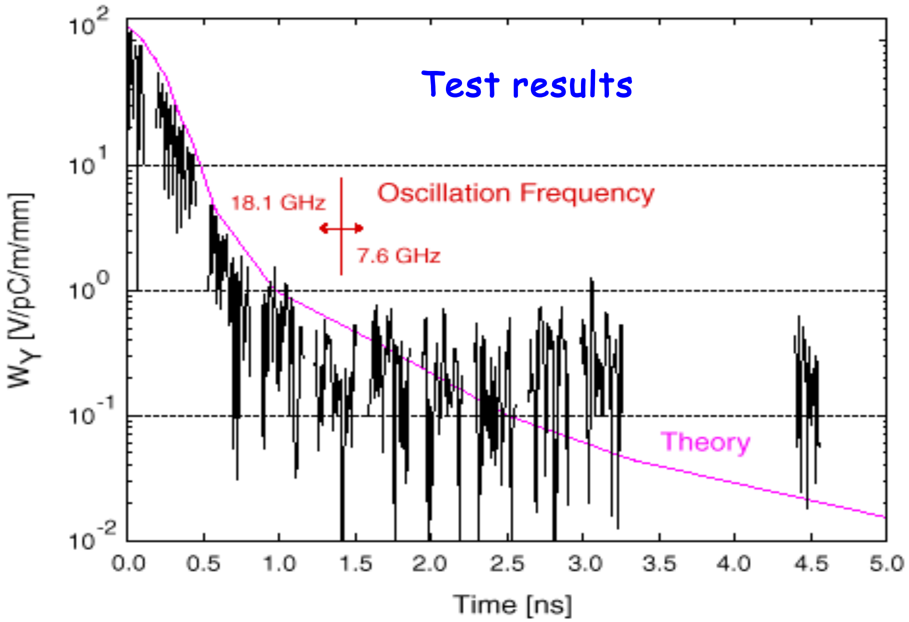
C. Adolphsen / SLAC

HOM damping



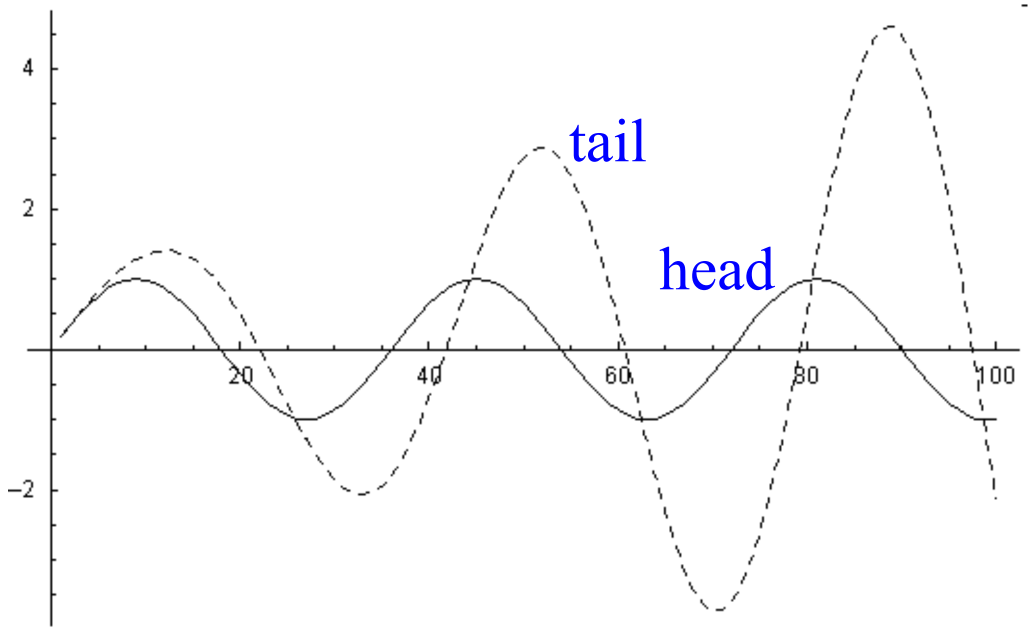


- Each cell damped by 4 radial WG
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped



Single bunch wakefields

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



Tail particle
Equation of motion:

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

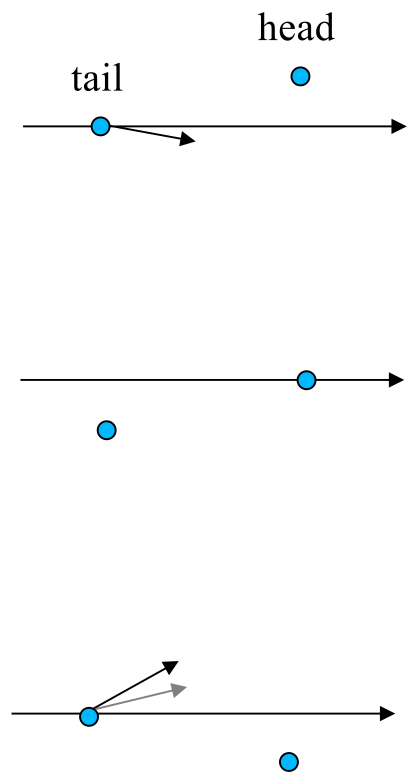
Driven Oscillator !!

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 ≈βθ
- $\pi/2$ in phase further (π in total):
  - -x displacement, tail kicked by –θ
  - 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:

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

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

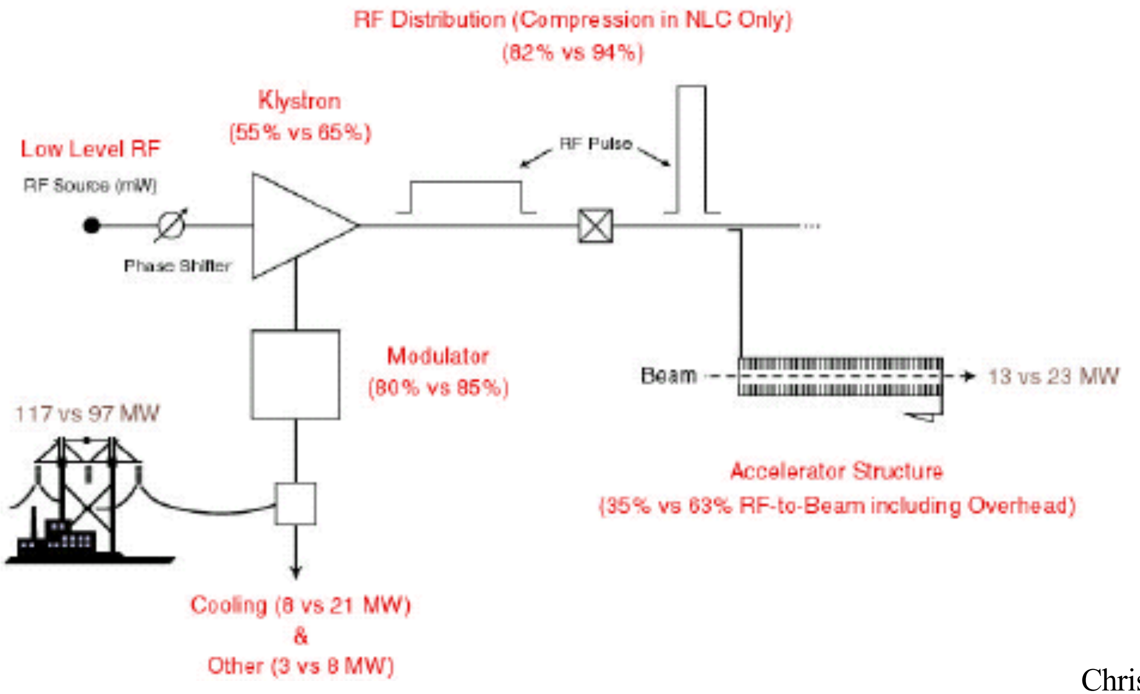
- BNS damping does not cure random cavity misalignment
- Emittance growth: $$\Delta\varepsilon \approx \delta Y_{RMS}^2 \left[\pi\varepsilon_0 N r_e W_\perp (2\sigma_z)\right]^2 \frac{L_{acc}\bar{\beta}_i}{2\alpha G}\left[\left(\frac{E_f}{E_i}\right)^\alpha - 1\right]$$

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 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

RF systems

- Need efficient acceleration in main linac
- 4 primary components:
  - Modulators: convert line AC → pulsed DC for klystrons
  - Klystrons: convert DC → RF at given frequency
  - RF distribution: transport RF power → accelerating structures
    evtl. RF pulse compression
  - Accelerating structures: transfer RF power → beam

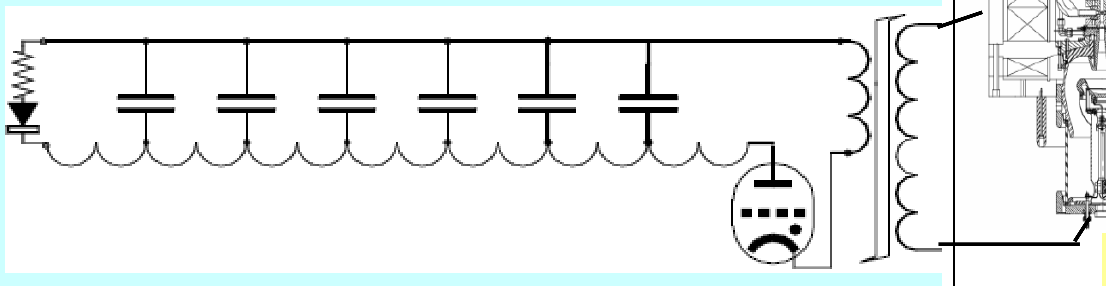


Chris Adolphsen

RF systems

Modulator

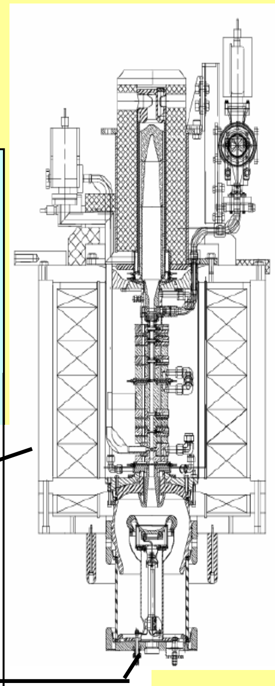
Energy storage in capacitors
charged up to 20-50 kV (between pulses)



High voltage switching and
voltage transformer
rise time > 300 ns

Or solid state device

Klystron



U 150 -500 kV
I 100 -500 A
f 0.2 -20 GHz

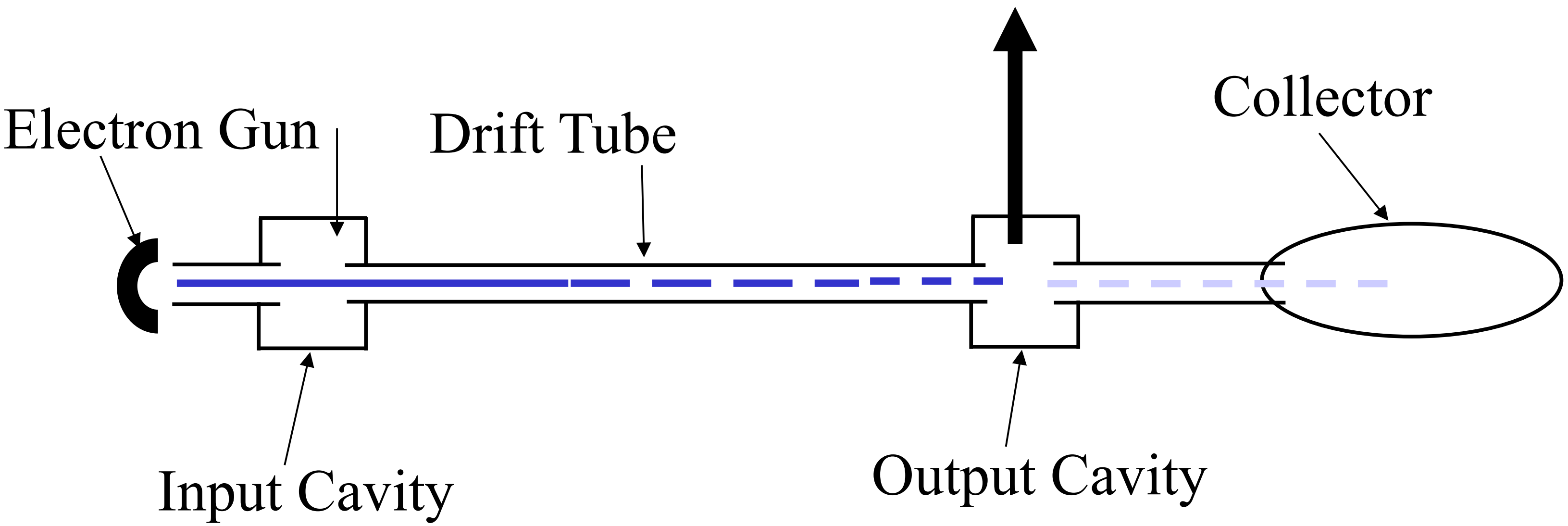
P_{ave} < 1.5 MW
P_{peak} < 150 MW

efficiency 40-70%

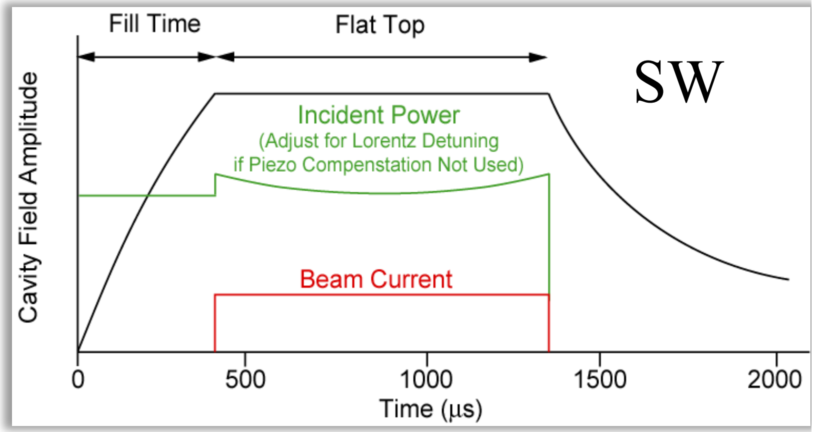
=> ***for power efficient operation pulse length t_P >> 300 ns favourable***

Klystrons

- narrow-band vacuum-tube amplifier at microwave frequencies (an electron-beam device).
- low-power signal at the design frequency excites input cavity
- Velocity modulation becomes time modulation in the drift tube
- Bunched beam excites output cavity



RF efficiency: cavities



- Fields established after cavity fill time
- Only then the beam pulse can start
- Steady state: power to beam, cavity losses, and (for TW) output coupler

- Efficiency: $$\eta_{RF\rightarrow beam} = \underbrace{\frac{P_{beam}}{P_{beam} + P_{loss} + P_{out}}}_{\approx 1 \text{ for SC SW cavities}} \frac{T_{beam}}{T_{fill} + T_{beam}}$$

- NC TW cavities have smaller fill time T_{fill}