*Largely based on the lectures given by F. Tecker at the Graduate Accelerator Physics Course – John Adams Institute for Accelerator Science (Oxford), March 2025.*

# Linear Colliders

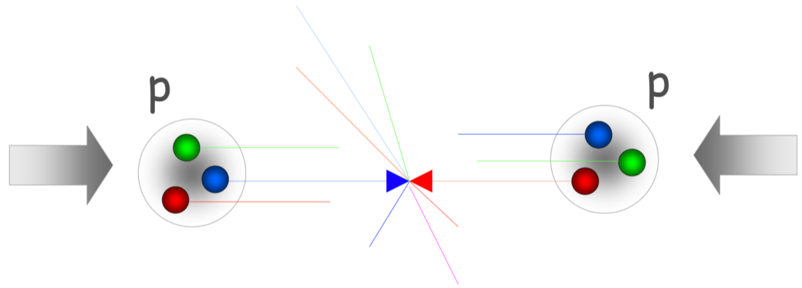
R. Corsini

# Outline of the lectures

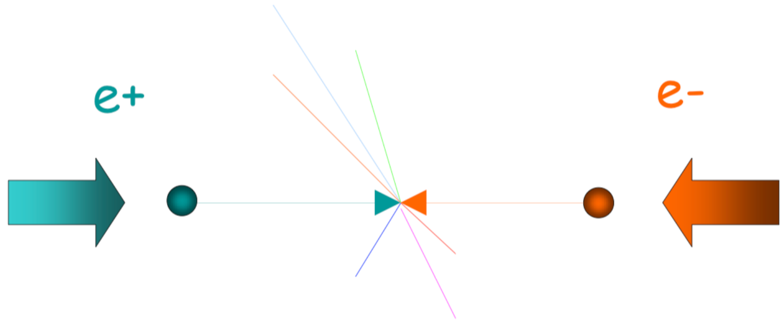
- Introduction:
  - The basics
  - A bit of history: from SLC to the present LC projects
- Luminosity & parameters optimization
- Introduction to linear collider proposals, ILC & CLIC
- Subsystems:
  - Sources
  - Damping Ring
  - Bunch Compressors
  - Main linac
  - Beam Dynamics, wake-fields and alignment
  - RF System
  - Beam Delivery System
- The superconducting solution: ILC
- The Two-Beam solution: CLIC

# Colliders: Choice of Particles

- Hadron collisions (p, ions):
  - Compound particles (mix of quarks, anti-quarks and gluons)
  - Parton energy spread, energy available < $E_{cm}$
  - Can only use $P_T$ conservation
  - QCD processes produce large background

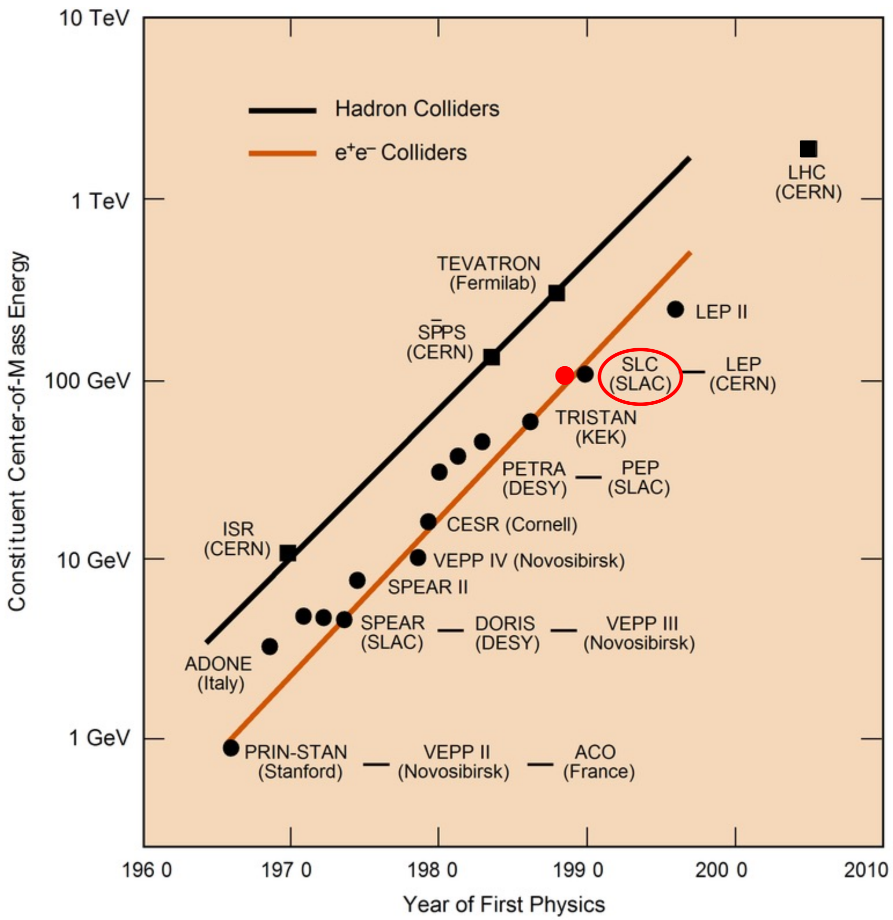



- Lepton collisions(e-, e+, muons):
  - Elementary particles ⇒ all energy available
  - Well defined initial state
  - Momentum conservation eases decay produce analysis
  - Less background
  - Polarization




- Photons also possible

# The path to higher energies



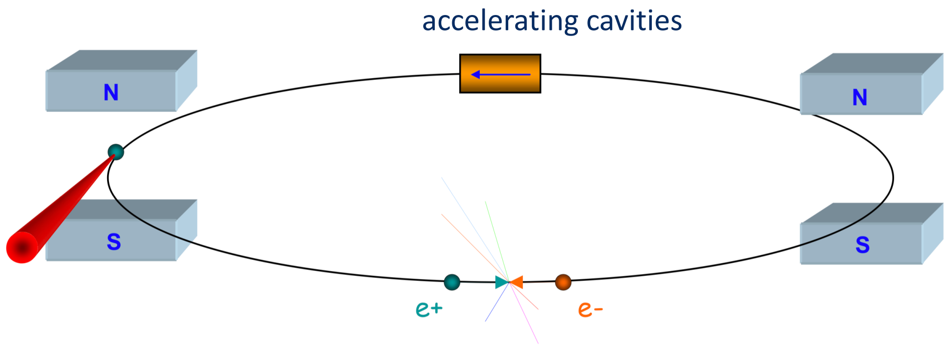

- History:
  - Energy constantly increasing with time
  - Hadron Colliders
    at the energy frontier
  - Lepton Colliders
    for precision physics
- LHC has found the Higgs with $m_H$ = 126 GeV/$c^2$
- A future Lepton Collider (Higgs factory) would complement LHC physics ⇒ precision measurements of the Higgs boson characteristics
- Recommended in the 2020 Update of the European Strategy for Particle Physics

# Circular vs. Linear Lepton Collider

Accelerates beam over many turns
Can use beam many times in collision

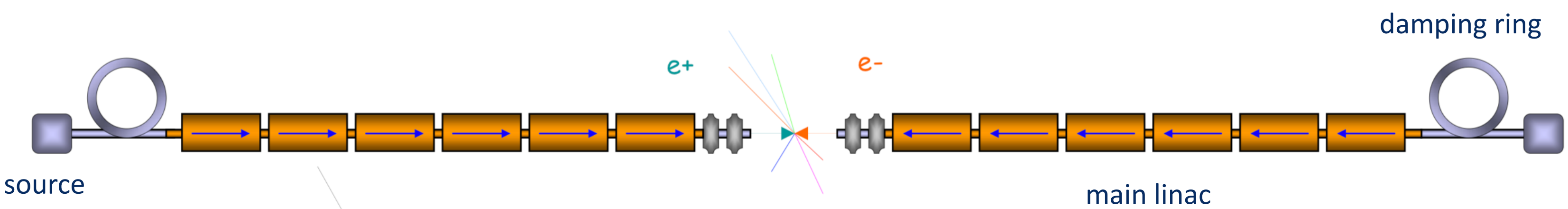
However, charged particles emit synchrotron radiation in a magnetic field

$$\Delta E_{turn} = \frac{4}{3}\pi \frac{r_e}{(m_o c^2)^3} \frac{E^4}{\rho}$$




For light particles synchrotron radiation can be large

- At LEP lost 2.75GeV/turn for E = 105 GeV




Almost no radiation in a linac ⇒ No energy loss!

Beam has to achieve final energy in single pass
Must achieve luminosity with single beam collision

# Scaling of a lepton ring collider to high energies

Need a larger lepton storage ring to compensate for synchrotron radiation losses.
LEP had already a L = 27 km, for $E_{cm}$= 200 GeV

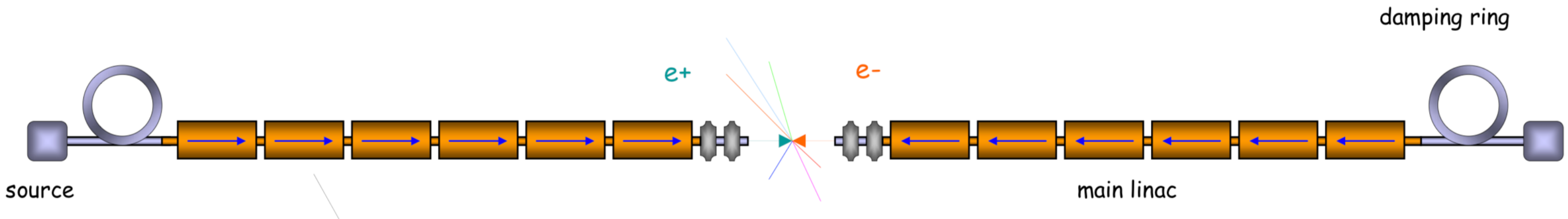
- Synchrotron radiation:
  - Emitted power $$P = \frac{2}{3}\frac{r_e c}{(m_o c^2)^3}\frac{E^4}{\rho^2}$$ scales with $E^4$ !!
  - Energy loss/turn $$\Delta E_{turn} = \frac{4}{3}\pi\frac{r_e}{(m_o c^2)^3}\frac{E^4}{\rho}$$ must be replaced by the RF system
- RF costs: $€_{RF} \propto \Delta E_{turn} \propto E^4/\rho$
- Linear costs (magnets, tunnel, etc.) $€_{lin} \propto \rho$

⇒ Optimum when $€_{lin} \propto €_{RF}$ ⇒ $\rho \propto E^2$

Must increase radius quadratically with energy

⇒ The size and the optimized cost scale as $E^2$ as well as the energy loss per turn (was already ~3% at LEP)

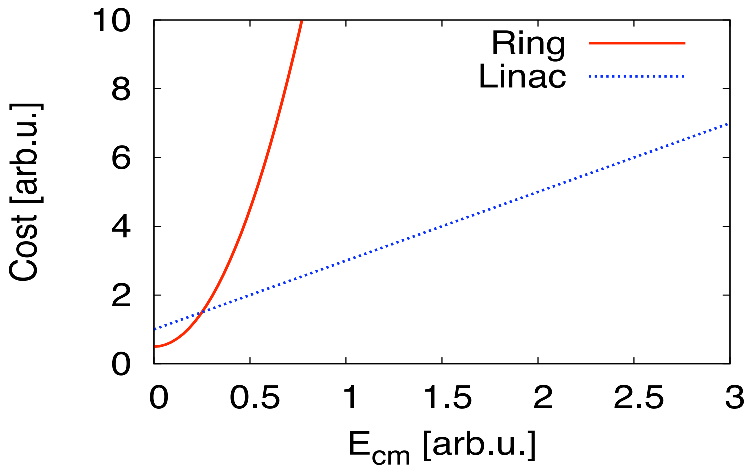
# Scaling of a lepton linear collider to high energies



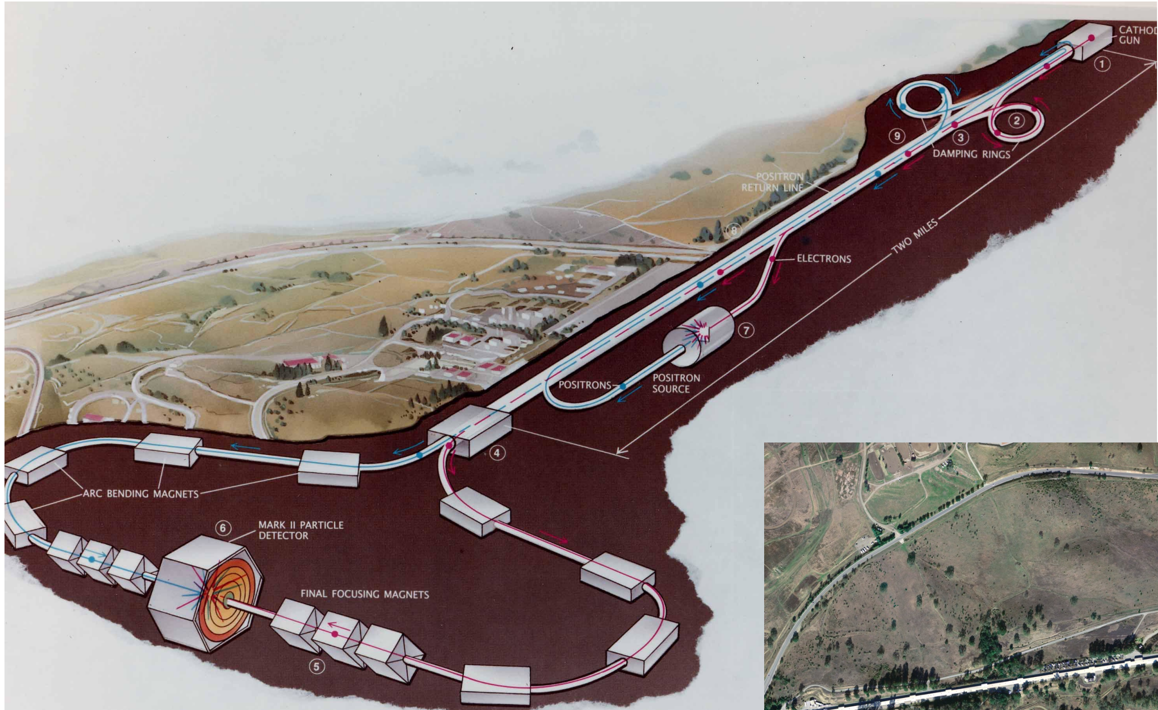

- NO bending magnets ⇒ NO synchrotron radiation

- Accelerating structures are used only once for each colliding beam
  ⇒ need lots of them !!!

⇒ Cost and size scaling linearly with E



# The first linear Collider, SLC



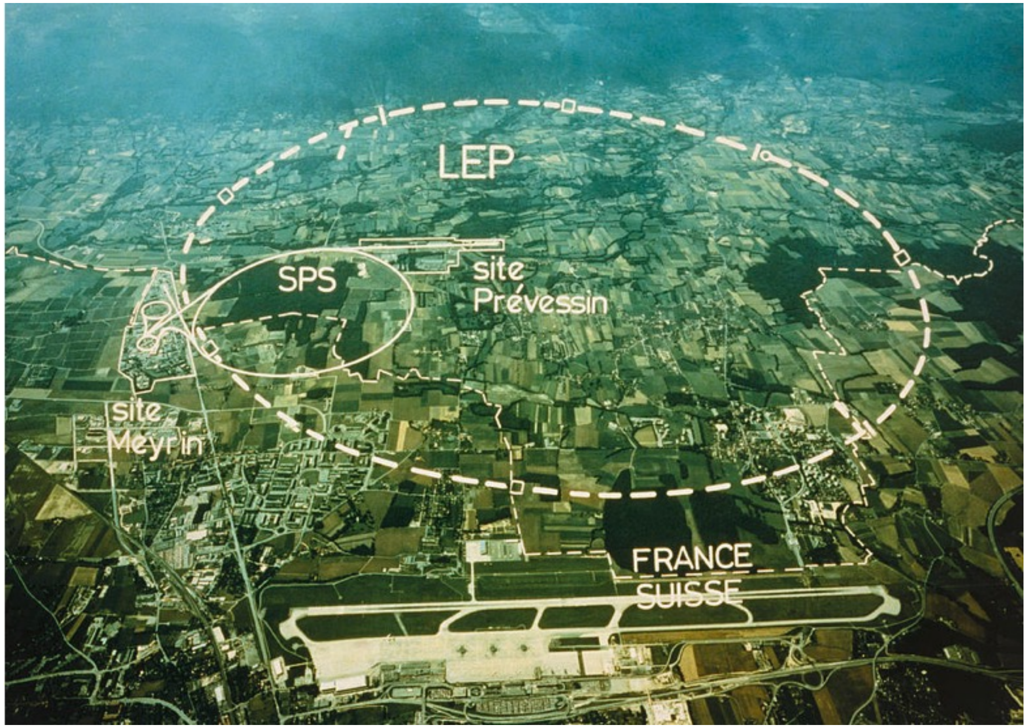

- Built to study the Z-boson $Z_0$ (and to demonstrate the feasibility of a linear collider)
- In order to reduce cost, used a single linac for both $e^+$ and $e^-$, followed by a long double arc

SLAC Linear Collider

Linac length = 3 km

| | |
|---|---|
| Energy | 92 GeV |
| Luminosity | $1 \times 10^{30}$ |

# The Large Electron Positron (LEP) collider ring

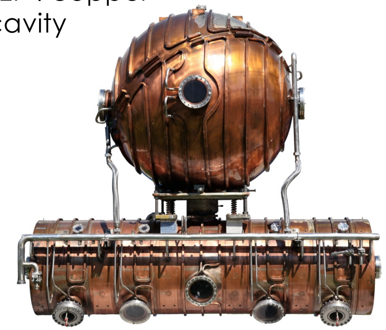



Ring length = 27 km

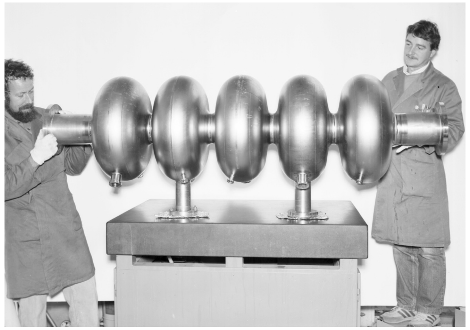
- Operated initially at the $Z_0$ energy, later upgraded with superconducting cavities to allow for W bosons production

| | |
|---|---|
| Energy | 92 GeV ⇒ 209 GeV |
| Luminosity | 1 x $10^{32}$ |

LEP I copper cavity



LEP II superconducting cavity



LEP – the largest electron-positron accelerator ever built – was dismantled in 2000

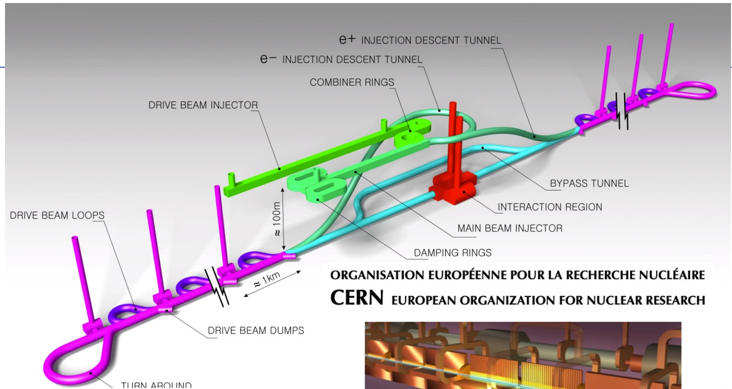
Its 27-kilometre tunnel now hosts the LHC

# Linear Collider Projects, ~ 1990 to now

**Linear Colliders: Overall and Final Focus Parameters – 500 GeV (c.m.)**

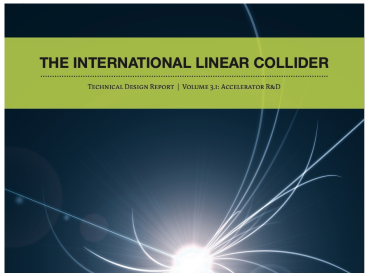
| | TESLA* | SBLC | JLC (S) | JLC (C) | JLC (X) | NLC | VLEPP | CLIC |
|---|---|---|---|---|---|---|---|---|
| Initial energy (c.of .m.) (GeV) | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| RF frequency of main linac (GHz) | 1.3 | 3 | 2.8 | 5.7 | 11.4 | 11.4 | 14 | 30 |
| Nominal Luminosity ($10^{33}$ $cm^{-2}s^{-2}$)† | 2.6 | 2.2 | 5.2 | 7.3 | 5.1 | 5.3 | 12.3 | 0.7-3.4 |
| Actual luminosity ($10^{33}$ $cm^{-2}s^{-2}$)† | 6.1 | 3.75 | 4.3 | 6.1 | 5.2 | 7.1 | 9.3 | 1.07-4.8 |
| Linac repetition rate (Hz) | 10 | 50 | 50 | 100 | 150 | 180 | 300 | 2530-1210 |
| No. of particles/bunch at IP ($10^{10}$) | 5.15 | 2.9 | 1.44 | 1.0 | .63 | .65 | 20 | .8 |
| No. of bunches/pulse | 800 | 125 | 50 | 72 | 85 | 90 | 1 | 1-10 |
| Bunch separation (nsec) | 1000 | 16.0 | 5.6 | 2.8 | 1.4 | 1.4 | – | .67 |
| Beam power/beam (MW) | 16.5 | 7.26 | 1.3 | 2.9 | 3.2 | 4.2 | 2.4 | .8-3.9 |
| Damping ring energy (GeV) | 4.0 | 3.15 | 2.0 | 2.0 | 2.0 | 2.0 | 3.0 | 2.15 |
| Main linac gradient, unloaded/loaded††(MV/m) | 25/25 | 21/17 | 31/– | 40/32 | 73/58 | 50/37 | 100/91 | 80/78 |
| Total two-linac length (km) | 29 | 33 | 22.1 | 18.8 | 10.4 | 15.6 | 7 | 8.8 |
| Total beam delivery length (km) | 3 | 3 | 3.6 | 3.6 | 3.6 | 4.4 | 3 | 2.4 |
| $\gamma\epsilon_x/\gamma\epsilon_y$ ($m$-$rad \times 10^{-8}$) | 2000/100 | 1000/50 | 330/4.8 | 330/4.8 | 330/4.8 | 500/5 | 2000/7.5 | 300/15 |
| $\beta^*_x/\beta^*_y$ (mm) | 25/2 | 22/0.8 | 10/0.1 | 10/0.1 | 10/0.1 | 10/0.1 | 100/0.1 | 10/0.18 |
| $\sigma^*_x/\sigma^*_y$ (nm) before pinch | 1000/64 | 670/28 | 260/3.0 | 260/3.0 | 260/3.0 | 320/3.2 | 2000/4 | 247/7.4 |
| $\sigma^*_z$ ($\mu$m) | 1000 | 500 | 120 | 120 | 90 | 100 | 750 | 200 |
| Crossing Angle at IP (mrad) | 0 | 3 | 6.4 | 6.0 | 6.1 | 20 | 6 | 1 |
| Disruptions $D_x/D_y$ | 0.56/8.7 | .36/8.5 | .29/25 | .20/18 | .096/8.3 | .07/7.3 | .4/215 | 0.29/9.8 |
| $H_D$ | 2.3 | 1.8 | 1.6 | 1.4 | 1.4 | 1.34 | 2.0 | 1.42 |
| Upsilon sub-zero | .02 | .037 | .20 | .14 | .12 | .089 | .059 | 0.07 |
| Upsilon effective | .03 | .042 | .22 | .144 | .12 | .090 | .074 | .075 |
| $\delta_B$ (%) | 3.3 | 3.2 | 12.7 | 6.5 | 3.5 | 2.4 | 13.3 | 3.6 |
| $n_\gamma$ (no. of $\gamma$'s per $e$) | 2.7 | 1.9 | 2.2 | 1.5 | .94 | .8 | 5.0 | 1.35 |
| $N_{pairs}$($p_T^{min}$=20 MeV/c,$\theta_{min}$=0.15) | 19.0 | 8.8 | 31.6 | 10.3 | 2.9 | 2.0 | 1700 | 3.0 |
| $N_{hadrons}$/crossing | 0.17 | 0.10 | 0.98 | 0.23 | 0.05 | 0.03 | 45.9 | 0.05 |
| $N_{jets} \times 10^{-2}$ ($p_T^{min}$=3.2 GeV/c) | 0.16 | 0.14 | 3.4 | 0.66 | 0.14 | 0.08 | 56.4 | 0.10 |

From the 1995 International Linear Collider (ILC) Technical Review Committee (TRC) Report (FERMILAB-PUB-95-438)

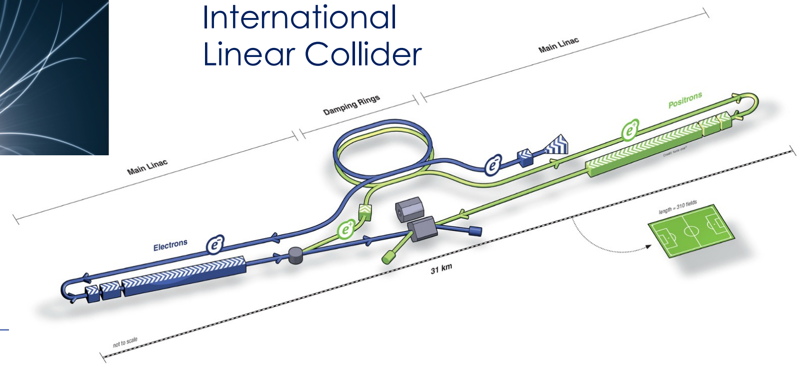


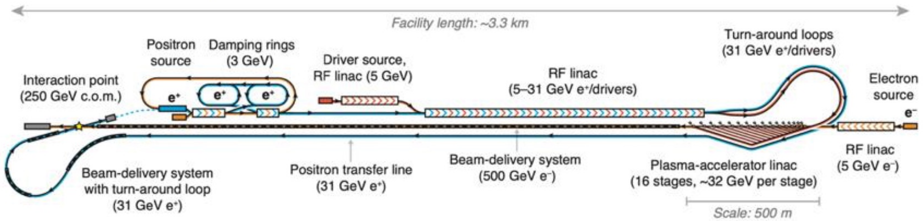


**CLIC**
Compact
Linear Collider




**ILC**
International
Linear Collider




**HALHF**
Hybrid, Asymmetric,
Linear Higgs Factory

# Luminosity

- The performance of particle colliders is usually quantified by the center of mass beam energy $E_{cm}$ and the luminosity $L$
- The luminosity is the quantity that measures the ability of a particle accelerator to produce the required number of useful interactions.
  In particular, it is the proportionality factor between the number of events per second $dR/dt$ and the cross section $\sigma_p$:

$$dR/dt = L \cdot \sigma_p$$

The unit of the luminosity is $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- A Collider luminosity is approximately given by

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

where:

| | | |
|---|---|---|
| $n_b$ | = | bunches / train |
| $N$ | = | particles per bunch |
| $f_{rep}$ | = | repetition frequency |
| $\sigma_{x,y}$ | = | transverse beam size at IP |
| $H_D$ | = | beam-beam enhancement factor (linear collider: typical value ~2) |

# Luminosity: linear vs. circular colliders



$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

- LHC ring $f_{rep}$ = 11 kHz
- LC $f_{rep}$ = few-100 Hz (power limited)

⇒ factor ~100-1000 in *L* already lost for the LC!

- Must push very hard on beam cross-section at collision:

factor of $10^6$ gain! needed to obtain high luminosity of a few $10^{34}$ $cm^{-2}s^{-1}$

LEP: $\sigma_x \sigma_y \approx 130 \times 6\ \mu m^2$

LC: $\sigma_x \sigma_y \approx (60\text{-}550) \times (1\text{-}5)\ nm^2$

# Luminosity and RF power



Introduce centre-of-mass Energy $E_{cm}$

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y} H_D \Rightarrow L = \frac{\left(n_b N f_{rep} E_{cm}\right) N}{4\pi\sigma_x\sigma_y E_{cm}} H_D$$

Beam power

$$\Rightarrow L = \frac{\eta_{RF} P_{RF} N}{4\pi\sigma_x\sigma_y E_{cm}} H_D$$

- $\eta_{RF}$ is the RF-to-beam power efficiency
- Luminosity $L$ is proportional to the RF power $P_{RF}$ and efficiency $\eta_{RF}$ for a given $E_{cm}$

  - Some numbers:

    | | |
    |---|---|
    | $E_{cm}$ | = 500 GeV |
    | $N$ | = $10^{10}$ |
    | $n_b$ | = 100 |
    | $f_{rep}$ | = 100 Hz |

  - Need to include efficiencies:

    | | |
    |---|---|
    | RF→beam | range 20-60% |
    | Wall plug→RF | range 28-40% |

AC power: a few hundred MW to accelerate beams for a high luminosity
⇒ This limits the practically achievable energy and luminosity

# Luminosity: effects at the interaction point

$$L = \frac{1}{4\pi E_{cm}} \left(\eta_{RF} P_{RF}\right) \left( \frac{N}{\sigma_x \sigma_y} H_D \right)$$

- Choice of acceleration technology (NC vs SC):
  - Efficiency
  - Available power

- Strong focusing needed for small beam size
  - Optical aberrations
  - Issues with stability and tolerances
- Beam-Beam effects:

  Strong self focusing (pinch effect) ⇒
  - increases Luminosity

  Photon emission (Beamstrahlung) ⇒
  - dilutes Luminosity spectrum
  - creates detector background

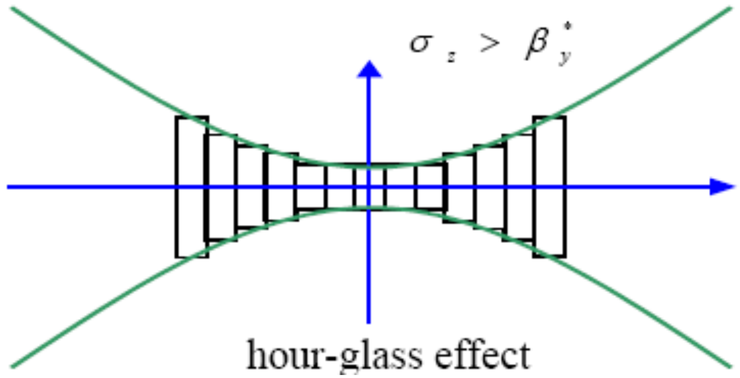
# Limit on beam size: Hourglass effect

- β-function at the interaction point follows

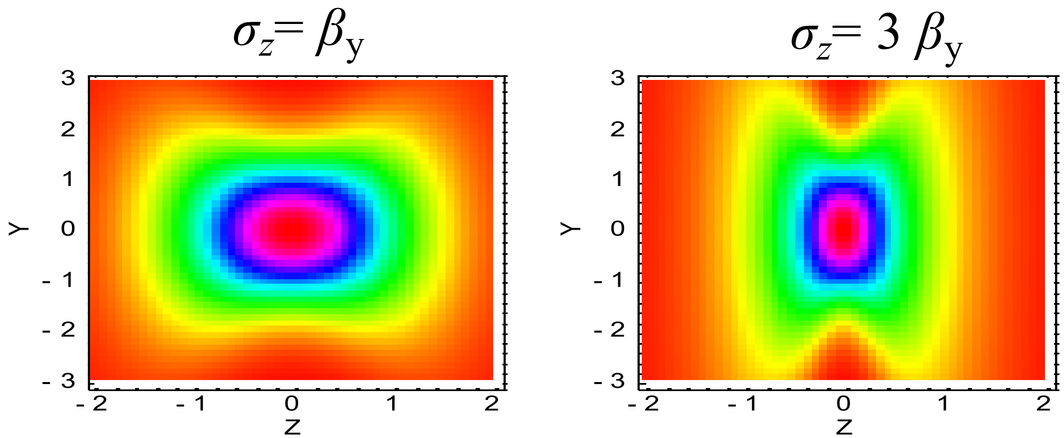
$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

$\beta^*$ beta function at the IP

N.B.: $\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$



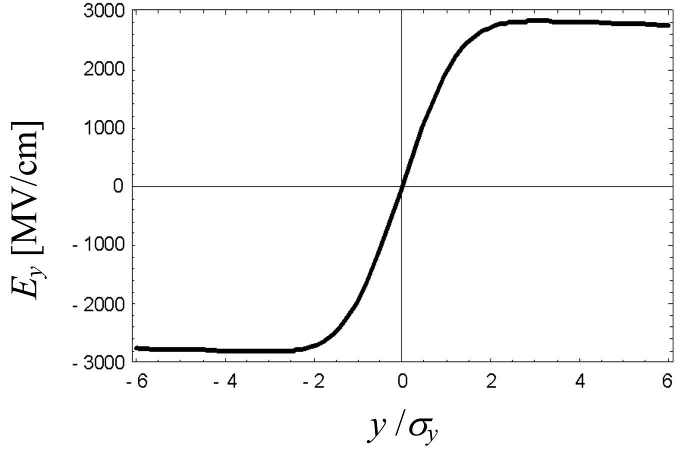

- Desirable to have $\sigma_z \leq \beta_y$ ⇒ short bunch length for high luminosity

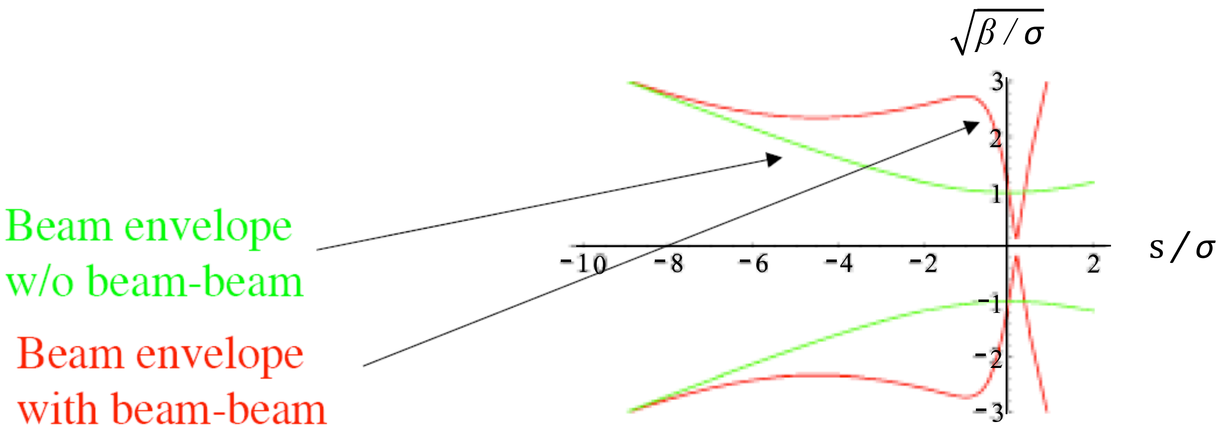



N.Walker

# Beam-beam effects: pinch

- Strong electromagnetic field of the opposing bunch:
  - Deflects the particles "beam-beam kick"
  - Focuses the bunches "pinch effect"
  - Luminosity enhancement factor $H_D$

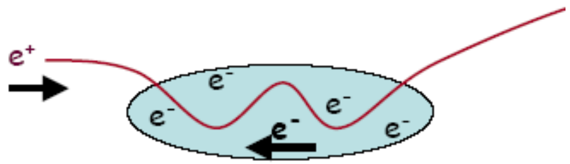


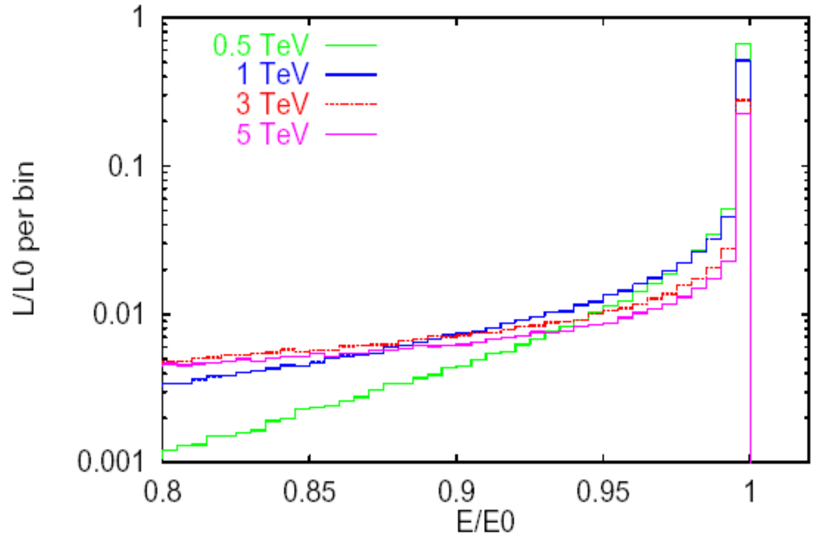
# Beamstrahlung



- “Synchrotron radiation” in the field of the opposing bunch (beamstrahlung)




⇒ energy loss




- Smears out luminosity spectrum

- Creates $e^+e^-$ pairs background in detector

- Quantified by Disruption parameter

$$D_{x,y} = \frac{2 r_e N \sigma_z}{\gamma \sigma_{x,y} \left( \sigma_x + \sigma_y \right)}$$

# Beamstrahlung: minimizing the energy loss



- RMS relative energy loss by beamstrahlung

$$\delta_{BS} \approx 0.86 \frac{r_e^3}{2m_0c^2}\left(\frac{E_{cm}}{\sigma_z}\right)\frac{N^2}{(\sigma_x+\sigma_y)^2}$$

- We want
  - $\sigma_x$ and $\sigma_y$ small for high luminosity
  - $(\sigma_x + \sigma_y)$ large for small $\delta_{BS}$ ⇒ better luminosity spectrum

- Use flat beams with $\sigma_x \gg \sigma_y$

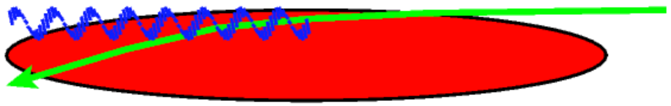
increase luminosity by small $\sigma_y$

and minimise $\delta_{BS}$ by (relatively) large $\sigma_x$

$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z}\right)\frac{N^2}{\sigma_x^2}$$

# Beam-beam Effect

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

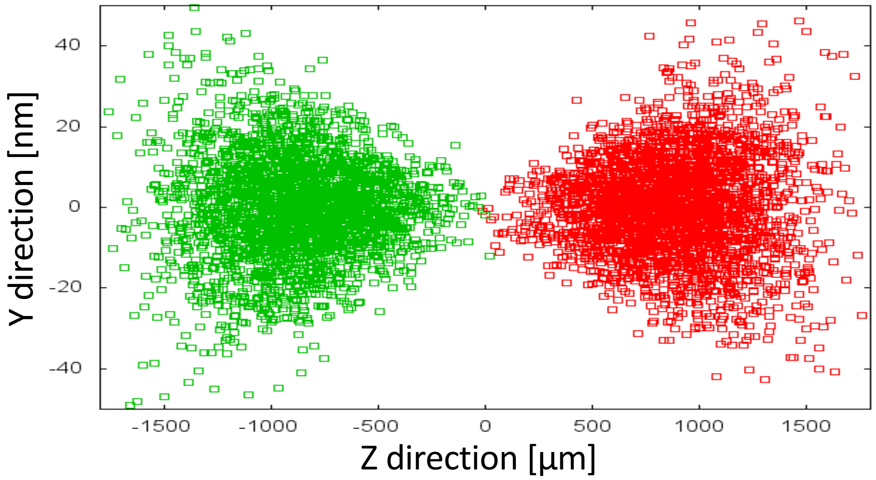


Intense beams to reach
high luminosity

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

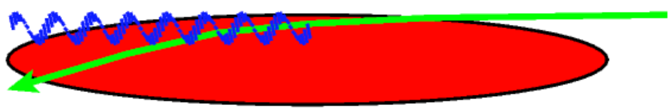
Beam-beam force switched off

*D. Schulte*



# Beam-beam Effect

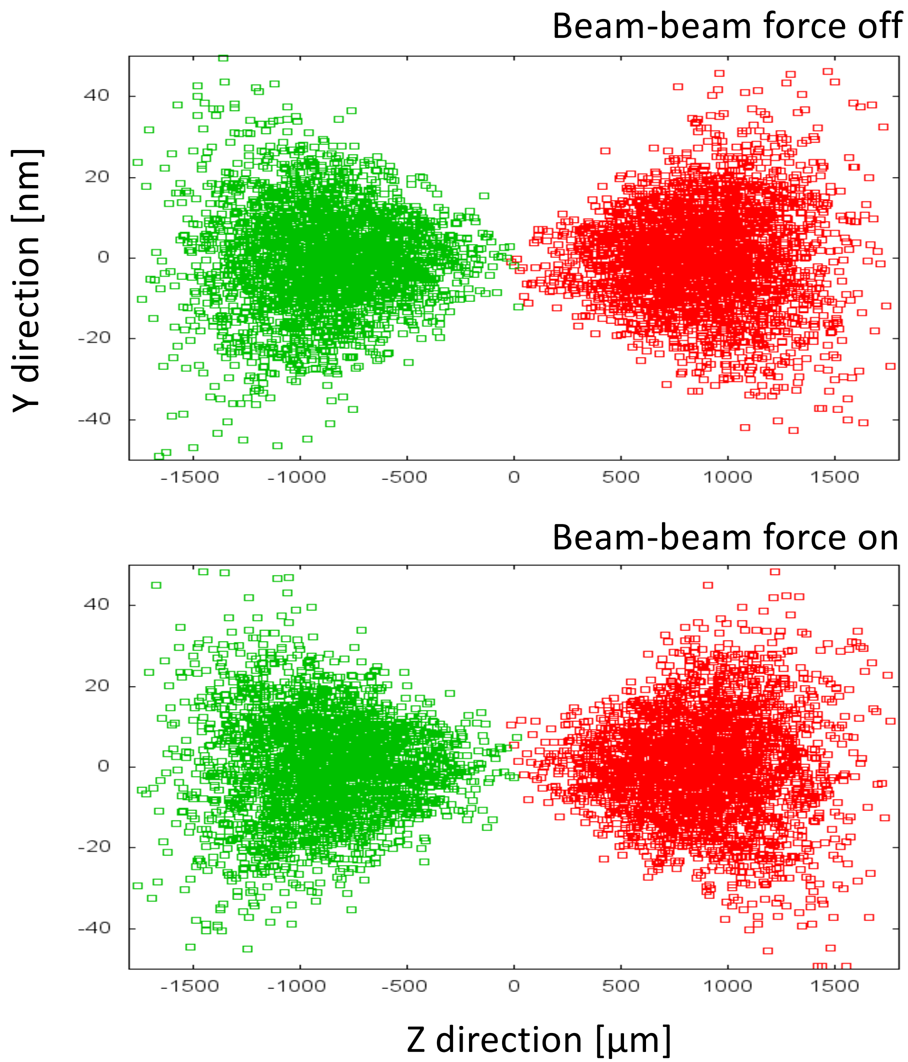
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



Beam focus each other

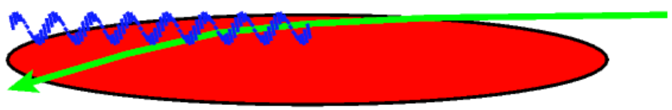
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

*D. Schulte*



# Beam-beam Effect

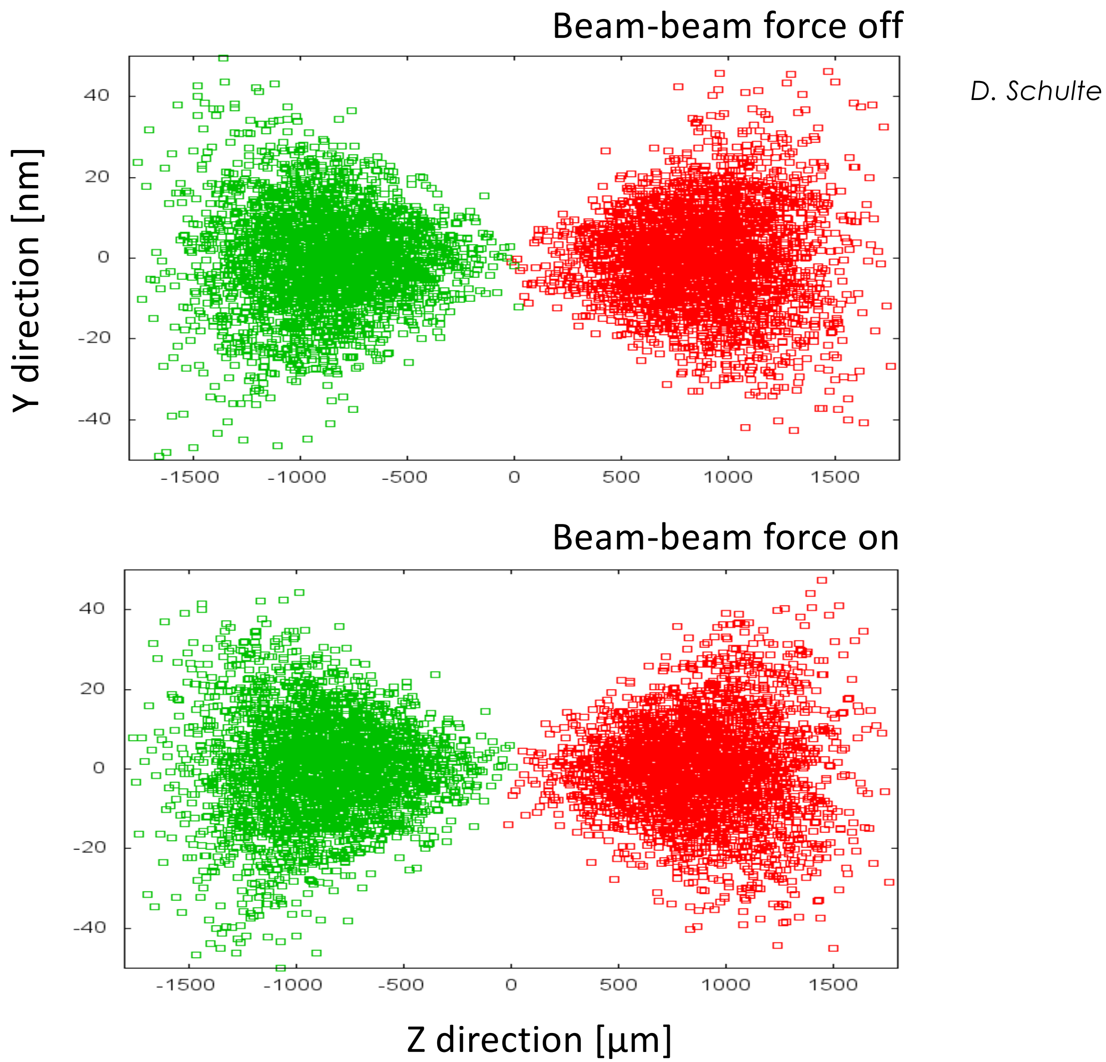
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



Emit beamstrahlung

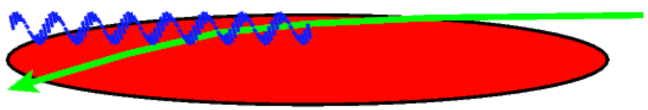
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$



# Beam-beam Effect

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

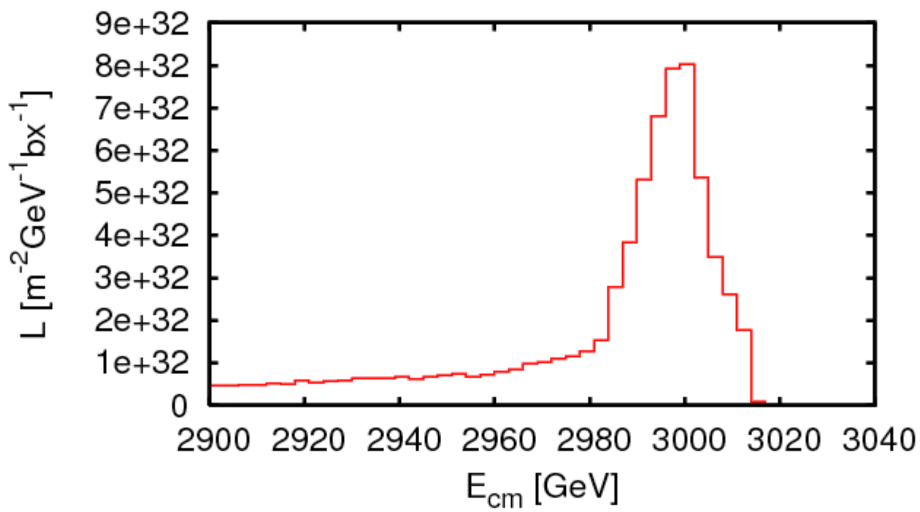


Develop luminosity spectrum

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

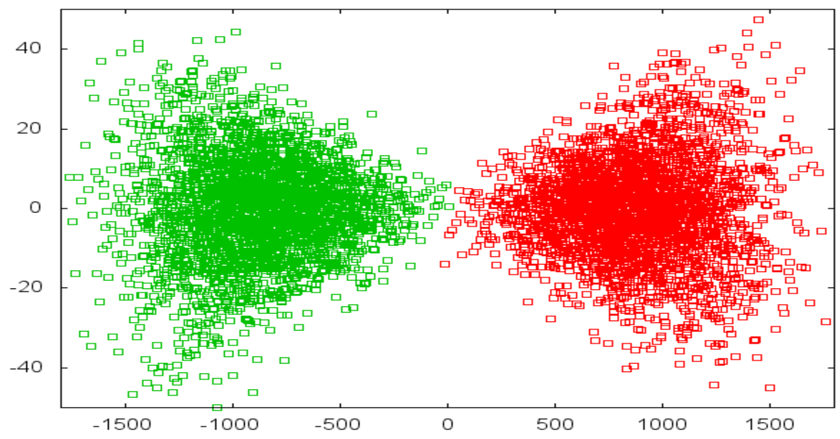
$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$




*D. Schulte*

Beam-beam force on




Z direction [μm]

# Luminosity: more scaling …

- Substitute $$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z}\right)\frac{N^2}{\sigma_x^2}$$ into $$L = \frac{1}{4\pi E_{cm}}(\eta_{RF} P_{RF})\left(\frac{N}{\sigma_x \sigma_y} H_D\right)$$

- We get $$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS}\sigma_z}}{\sigma_y}$$

- Now use $$\sigma_y = \sqrt{\frac{\beta_y \varepsilon_{n,y}}{\gamma}}$$

- Then $$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \sqrt{\frac{\delta_{BS}\gamma}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} \underbrace{\sqrt{\frac{\sigma_z}{\beta_y}}}_{\sim 1 \text{ (hourglass effect)}}$$

# The ‘final’ scaling for LC Luminosity

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

- 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 is implied (i.e., small $\beta_y$ and hence small $\sigma_z$)
- Could also allow higher beamstrahlung $\delta_{BS}$ if willing to live with the consequences (luminosity spread and background)
  - Above result is for the low beamstrahlung regime where $\delta_{BS}$ ~ few %
  - Slightly different result for high beamstrahlung regime

# What matters in a linear collider ?

Energy reach

$$E_{cm} \approx L_{linac} G_{acc}$$

→ High gradient

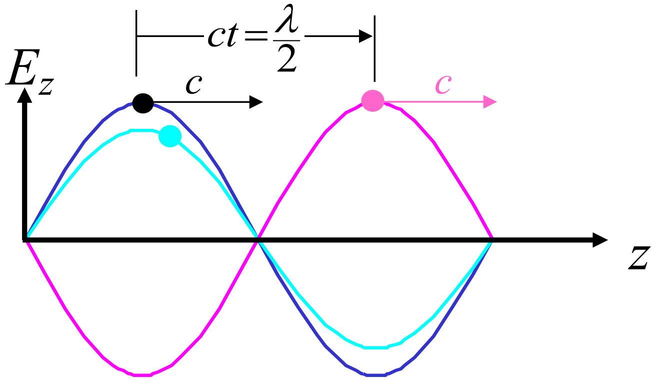
Luminosity

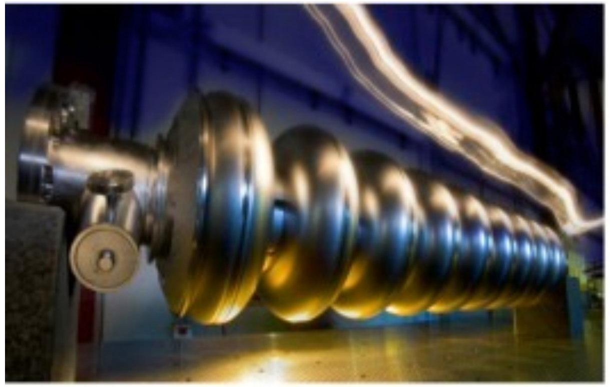
$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^* \sigma_y^*} \times H_D \propto \frac{\eta_{beam}^{AC} P_{AC}}{\varepsilon_y^{1/2}} \frac{\delta_{BS}^{1/2}}{E_{cm}}$$

N.B.: $\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$

- Acceleration efficiency — Superconducting RF (ILC) or Two-beam scheme (CLIC)
- Generation of small emittance — Damping rings
- Conservation of small emittance — Wake-fields, alignment, stability
- Extremely small beam spot at IP — Beam delivery system, stability

# Acceleration cavities



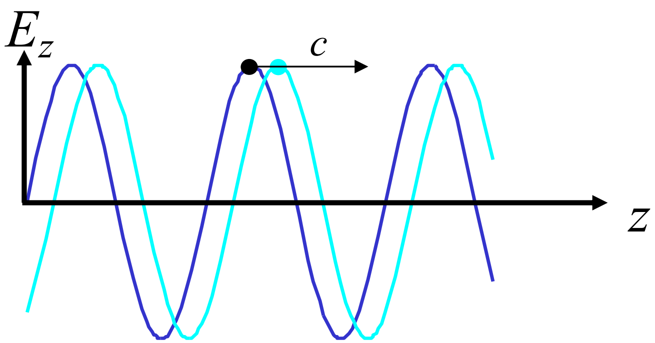
Superconducting
(Niobium)

Normal
Conducting
(Copper)

Standing wave cavity:

bunch sees field:

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




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

bunch sees constant field:

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

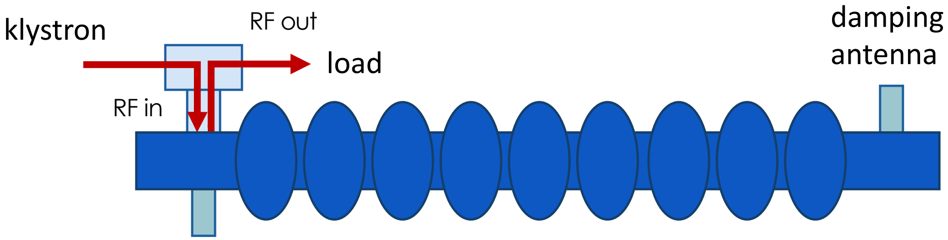
# ILC Cavities



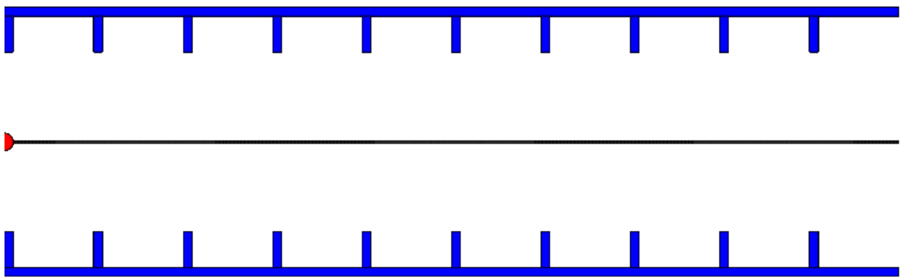
Superconducting cavity (Ni at 2 K)

RF frequency is 1.3 GHz, 23 cm wavelength

Length is 9 cells = 4.5 wavelengths = 1 m



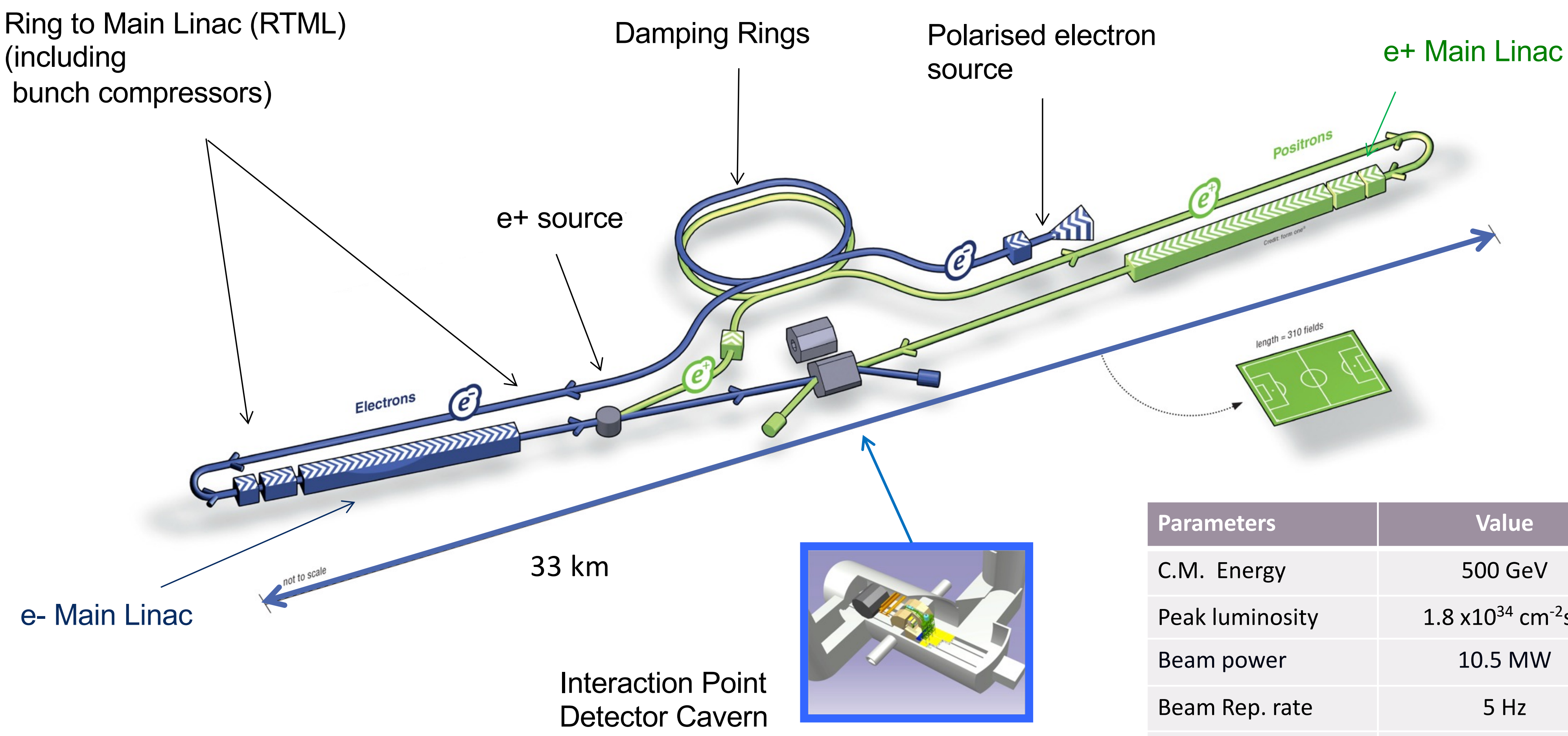

Standing wave structure



Gradient is 31.5 MV/m

Need about 16000 cavities

# International Linear Collider - ILC




| Parameters | Value |
|---|---|
| C.M. Energy | 500 GeV |
| Peak luminosity | $1.8 \times 10^{34}$ cm$^{-2}$s$^{-1}$ |
| Beam power | 10.5 MW |
| Beam Rep. rate | 5 Hz |
| E gradient | 31.5 MV/m +/-20% |

ILC Scheme | © www.form-one.de

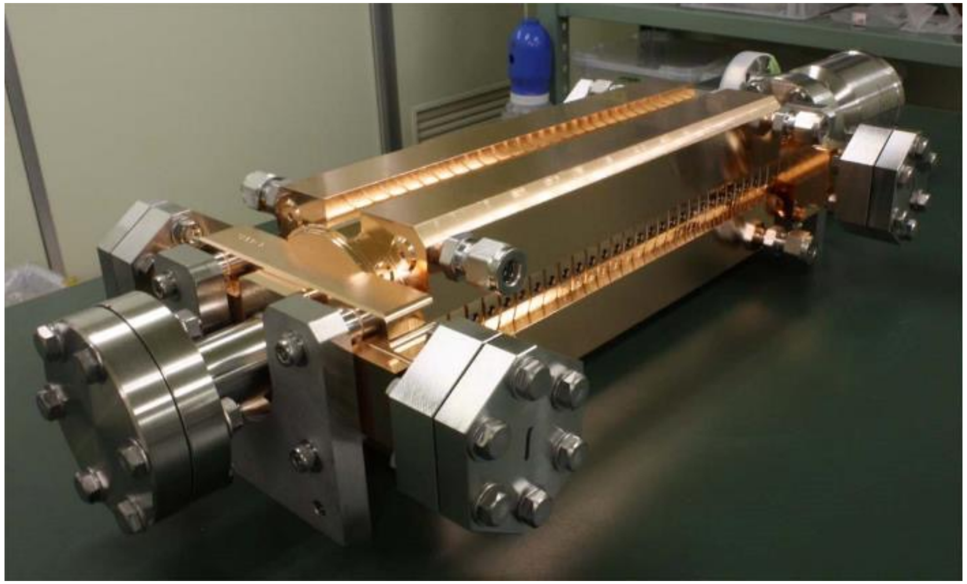
# CLIC accelerating structure

12 GHz, 23 cm long, normal conducting
Loaded gradient 100MV/m

⇒ Allows to reach higher energies
⇒ 140,000 structures at 3TeV

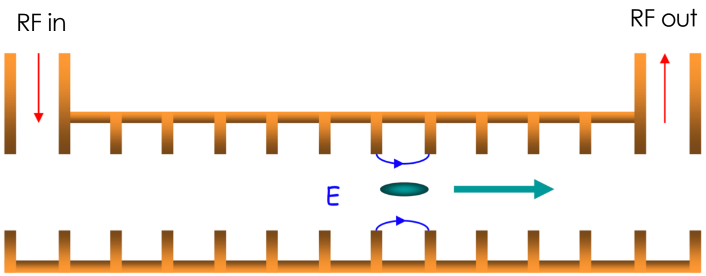
losses in the walls and in the load

⇒ 50 RF bursts per second
⇒ 240 ns, 60 MW, 312 bunches
⇒ Power during pulse 8.5 x $10^6$ MW (3000 x ILC)



Power flow
- 1/3 lost in cavity walls
- 1/3 in filling the structure and into load
- 1/3 into the beam

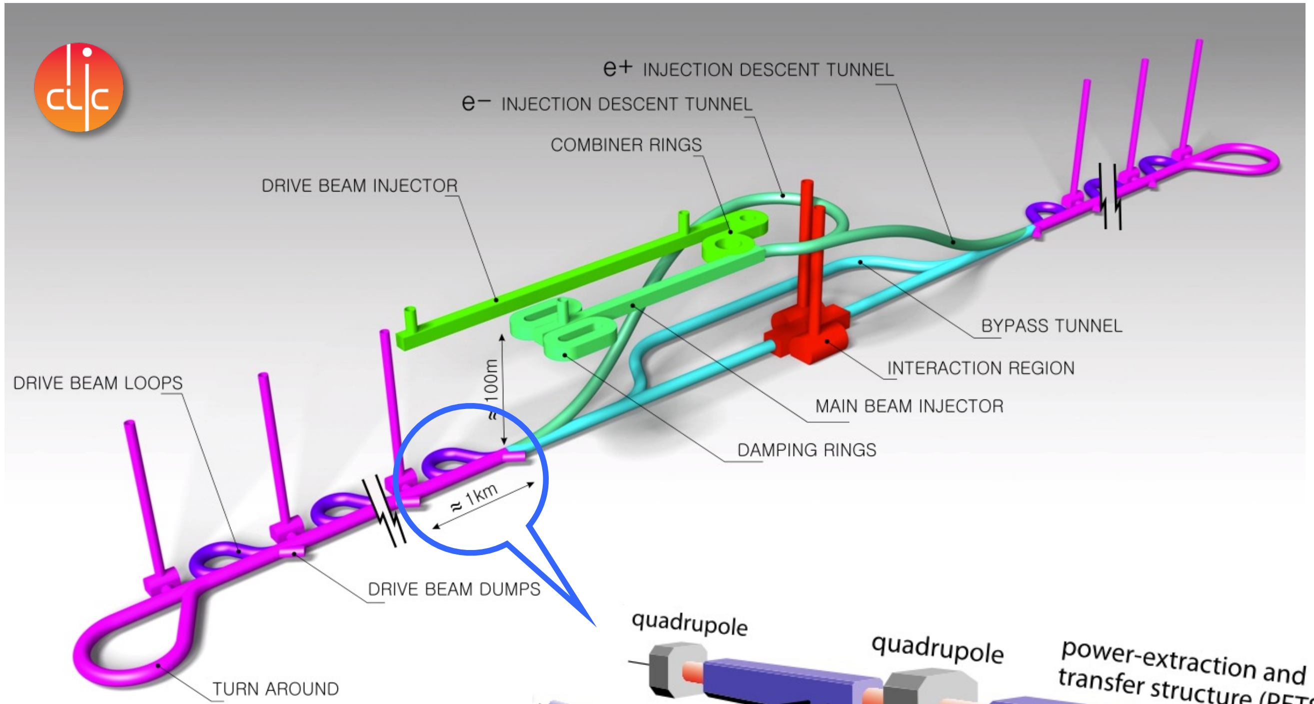
Average RF power about 3kW/m
About 1kW/m into beam

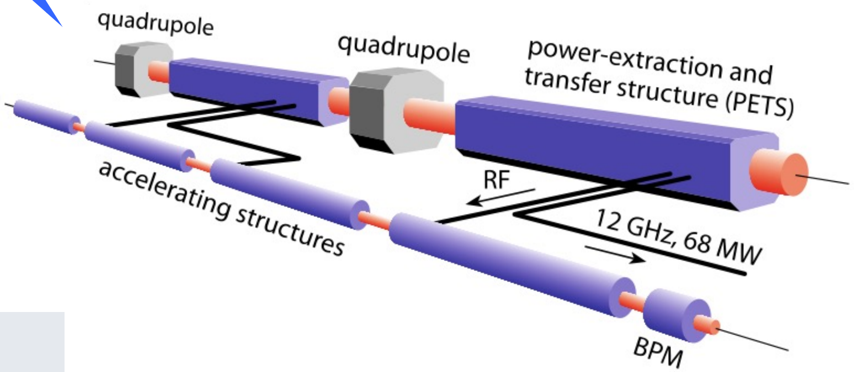



Travelling wave

Particles "surf" the electromagnetic wave

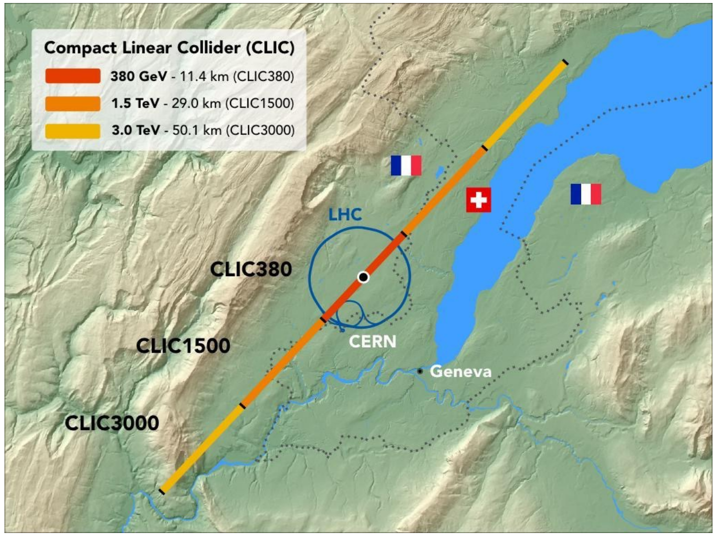
# The Compact Linear Collider - CLIC




L = 6 x$10^{34}$ $cm^{-2}s^{-1}$ at 3 TeV

Beam power 30 MW at 3 TeV




CLIC can be built in stages of increasing collision energy: starting from 380 GeV, then ~ 1- 2 TeV, and up to a final energy of 3 TeV.

To limit the collider length, the accelerating gradient must be very high - CLIC aims at 100 MV/m, 20 times higher than the LHC.

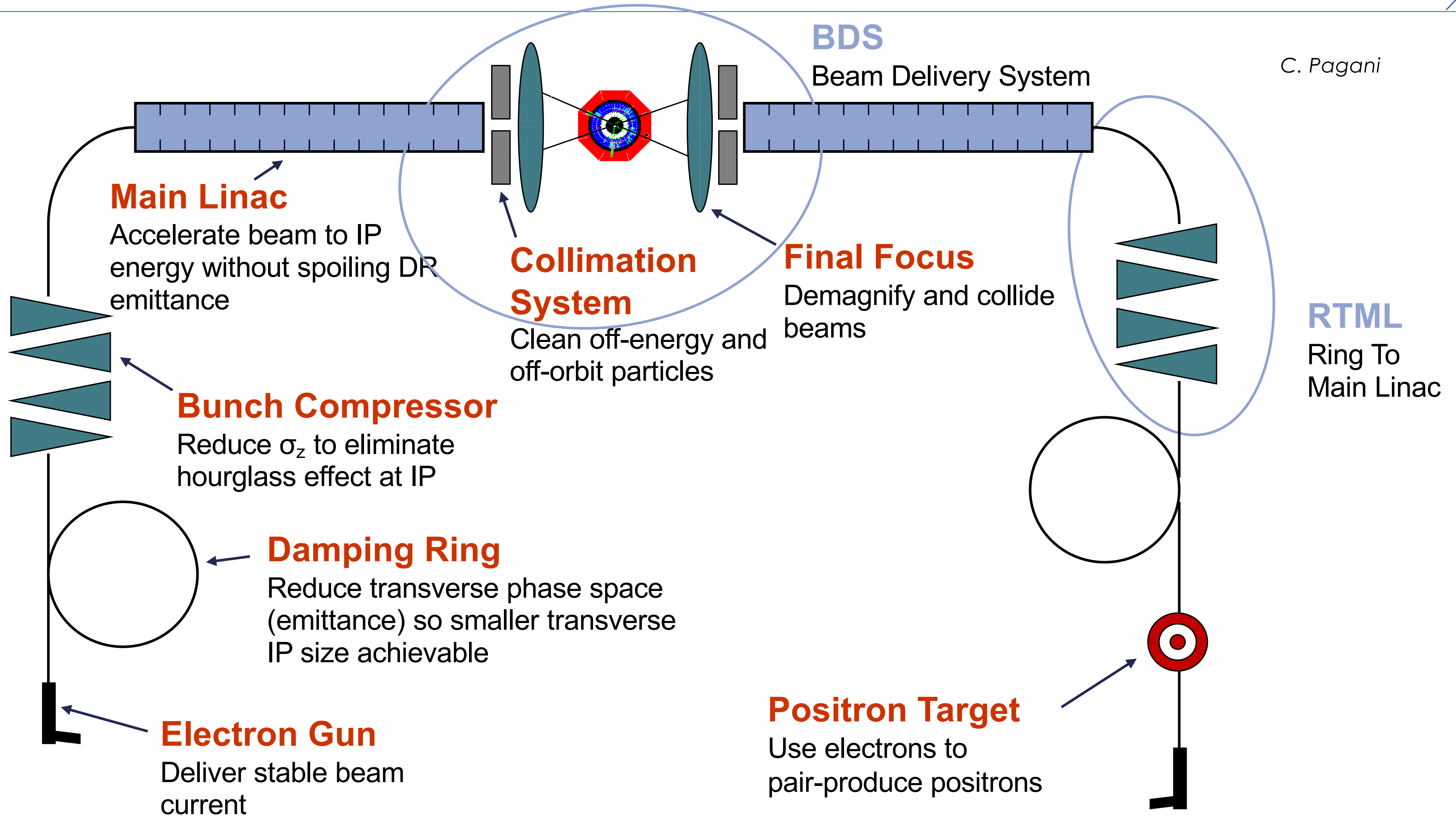
CLIC is based on a two-beam acceleration scheme, in which a high current e- beam (the drive beam) is decelerated in special structures (PETS), and the generated RF power is used to accelerate the main beam.

# ILC and CLIC Main Parameters

| Parameter | Symbol [unit] | SLC | ILC | CLIC | CLIC |
|---|---|---|---|---|---|
| Centre of mass energy | $E_{cm}$ [GeV] | 92 | 500 | 380 | 3000 |
| Luminosity | L [$10^{34}cm^{-2}s^{-1}$] | 0.0003 | 1.8 | 1.5 | 6 |
| Luminosity in peak | $L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$] | 0.0003 | 1 | 0.9 | 2 |
| Gradient | G [MV/m] | 20 | 31.5 | 72 | 100 |
| Particles per bunch | N [$10^9$] | 37 | 20 | 5.2 | 3.72 |
| Bunch length | $\sigma_z$ [μm] | 1000 | 300 | 70 | 44 |
| Collision beam size | $\sigma_{x,y}$ [nm/nm] | 1700/600 | 474/5.9 | 143/2.9 | 40/1 |
| Vertical emittance | $\varepsilon_{x,y}$ [nm] | 3000 | 35 | 30 | 20* |
| Bunches per pulse | $n_b$ | 1 | 1312 | 352 | 312 |
| Bunch distance | Δz [mm] | - | 554 | 0.5 | 0.5 |
| Repetition rate | $f_r$ [Hz] | 120 | 5 | 50 | 50 |

# End part I

# Generic Linear Collider



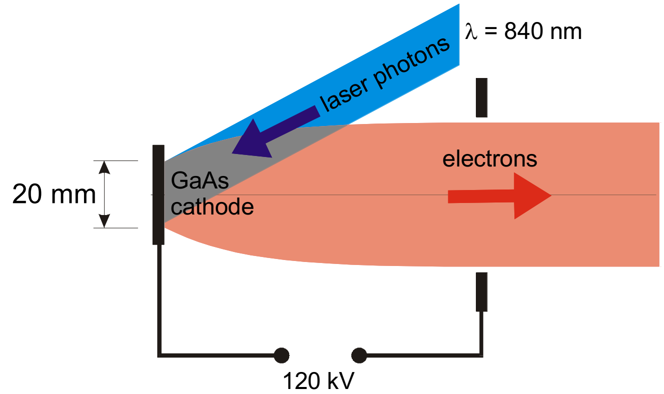
# e- source



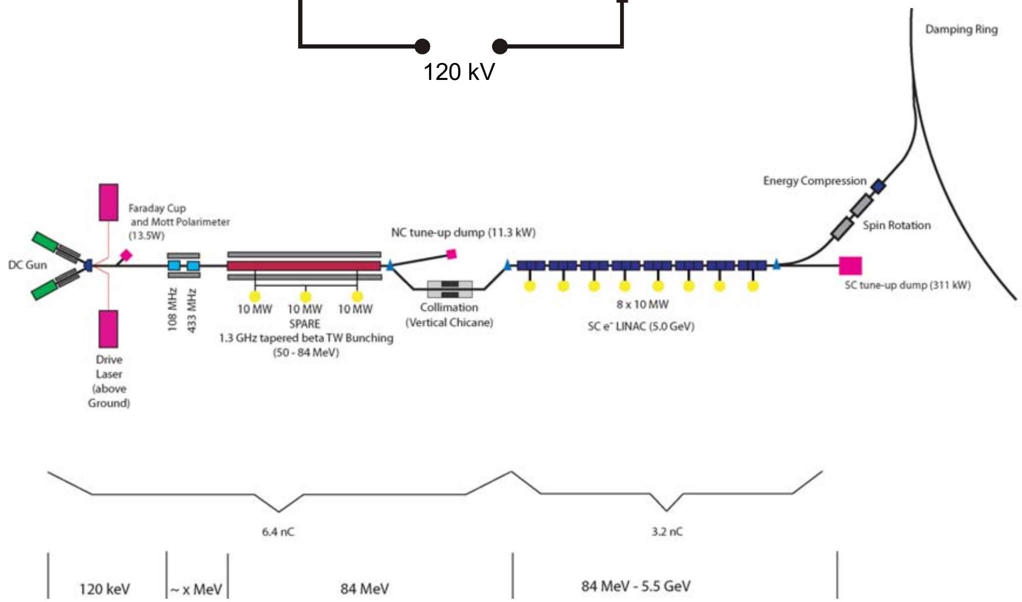
We need large number of bunches of (polarized) electrons – “standard” solution:

- laser-driven DC photo injector
  - circularly polarized photons on GaAs cathode (incompatible with RF gun)
  - $\varepsilon_n$ ~ 50 µm rad too large by:
    factor ~10 in x plane
    factor ~500 in y plane
  - dominated by space charge

  ⇒ need a damping ring



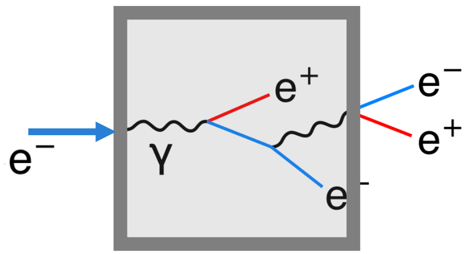

- Laser + RF bunching system generate and capture the bunch structure adapted to the linac for further acceleration



# e+ source - conventional

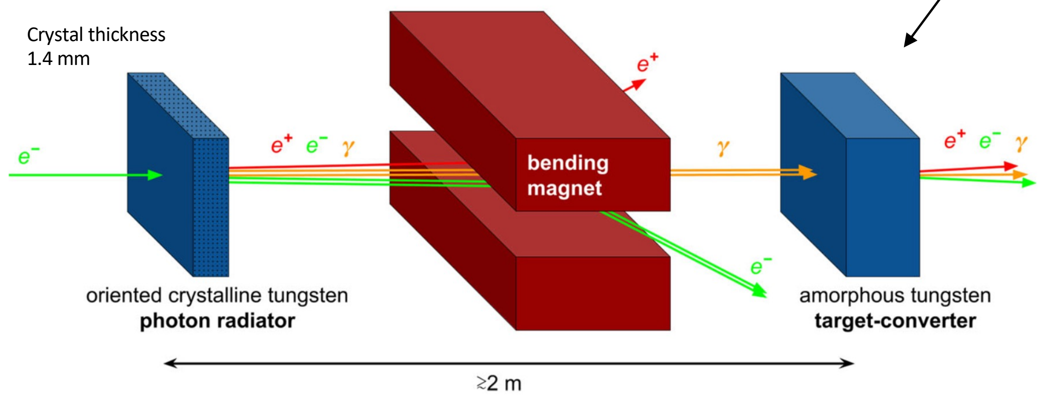
## Basic mechanism: pair production in target material

- Standard method: ‘thick’ target
  primary e- generate photons
  these convert into pairs




Limitation: energy deposition in target

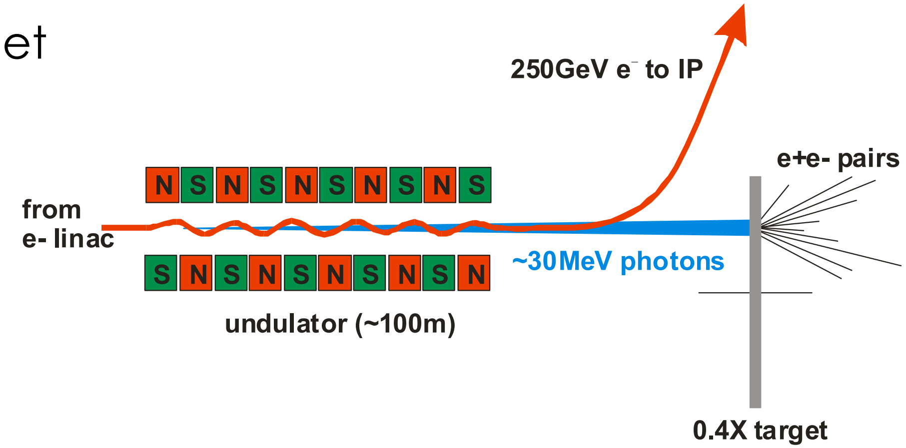
- Hybrid source:
  - Crystal + Amorphous target
  - Enhanced photon flux by channeling effect




- Positrons are captured in accelerating structure inside solenoids and accelerated

# e+ source – undulator (ILC, alternative)

Undulator source:
high energy $e^-$ produce photons in undulator magnet
+ thin conversion target



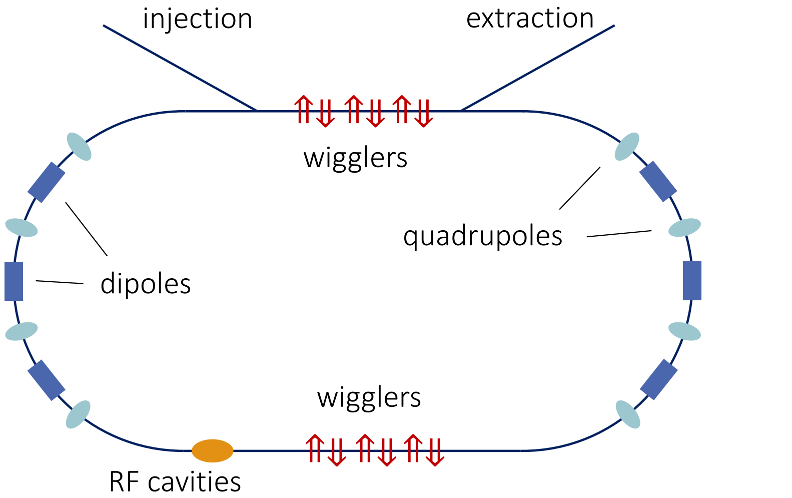

- ~0.4 rad. length ⇒ much less energy deposition in the target (5 kW compared to 20 kW)
  ⇒ no parallel targets needed
- Smaller emittance due to less coulomb scattering (factor ~2) but still much bigger than needed $\varepsilon_n$ ~ 10.000 μm rad
- Could produce polarised $e^+$ by helical undulator
- But: need very high initial electron energy > 150 GeV !

- Use primary $e^-$ beam
- Consequences for the commissioning and operation!

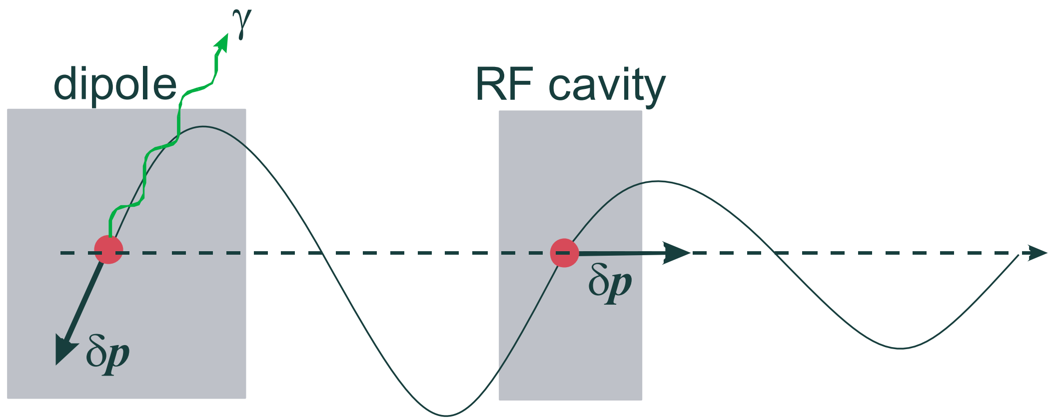
# Damping rings



- $e^-$ and particularly $e^+$ from the source have a much too high transverse $\varepsilon_n$
  ⇒ we have to reduce it (cooling)
- Solution: use synchrotron radiation in a damping ring




Layout of essential damping ring




Mechanism of radiation damping

- γ emission with transverse component
- Acceleration only in longitudinal direction

} radiation damping!!!

# Damping rings



- Exponential damping to equilibrium emittance:

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

initial emittance (~0.01 m rad for e+) → $\varepsilon_i$

final emittance → $\varepsilon_f$

equilibrium emittance → $\varepsilon_{eq}$

damping time → $\tau_D$

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

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

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

*P* - emitted radiation power

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

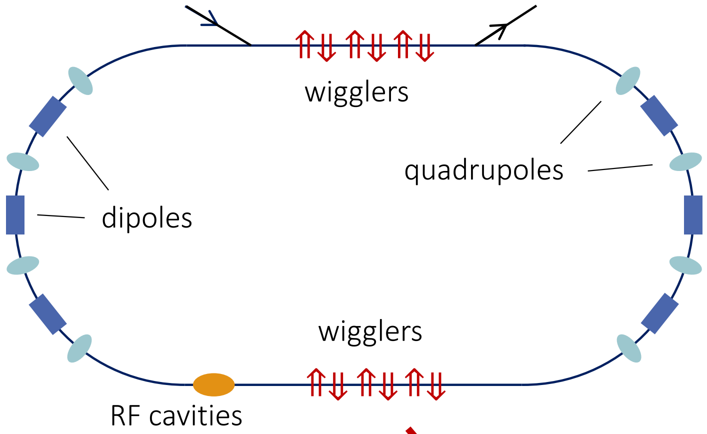
# Damping rings

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

# Damping Wigglers

Insert wigglers in straight sections in the damping ring



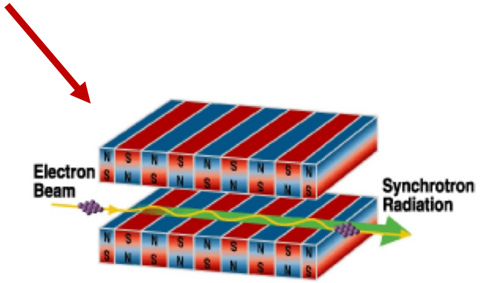

- Average power radiated per electron with wiggler straight sections

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

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

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

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



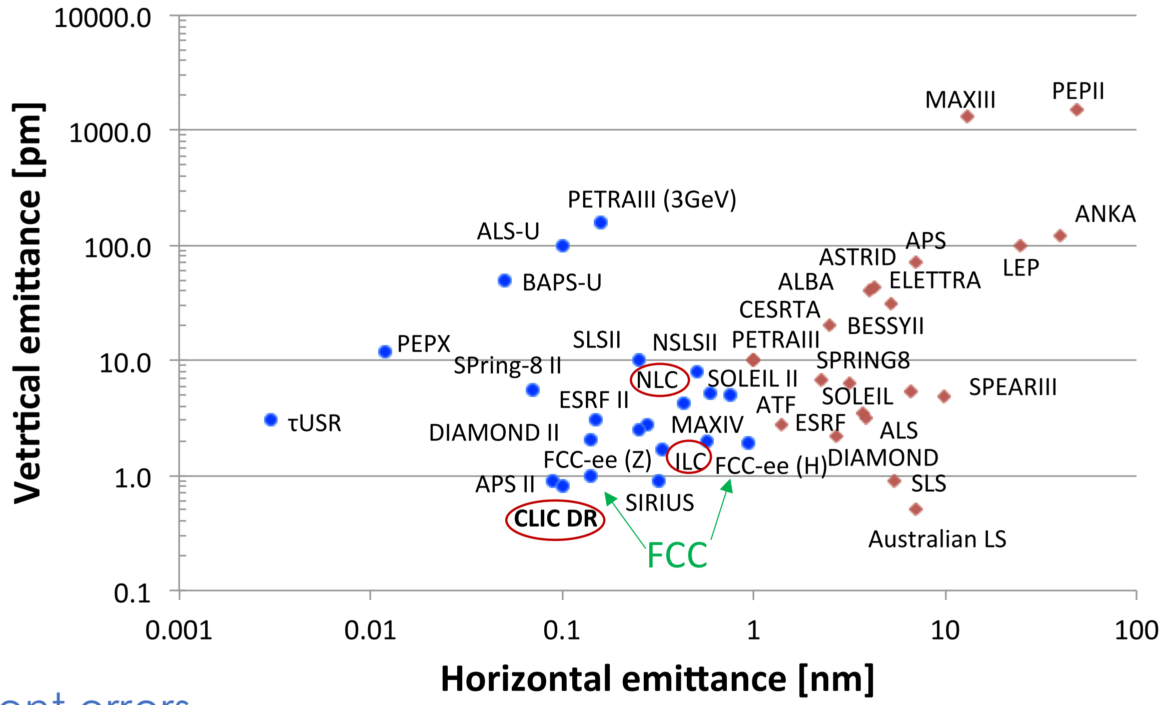

- Energy loss in wiggler:

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

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

# Damping ring: emittance limits

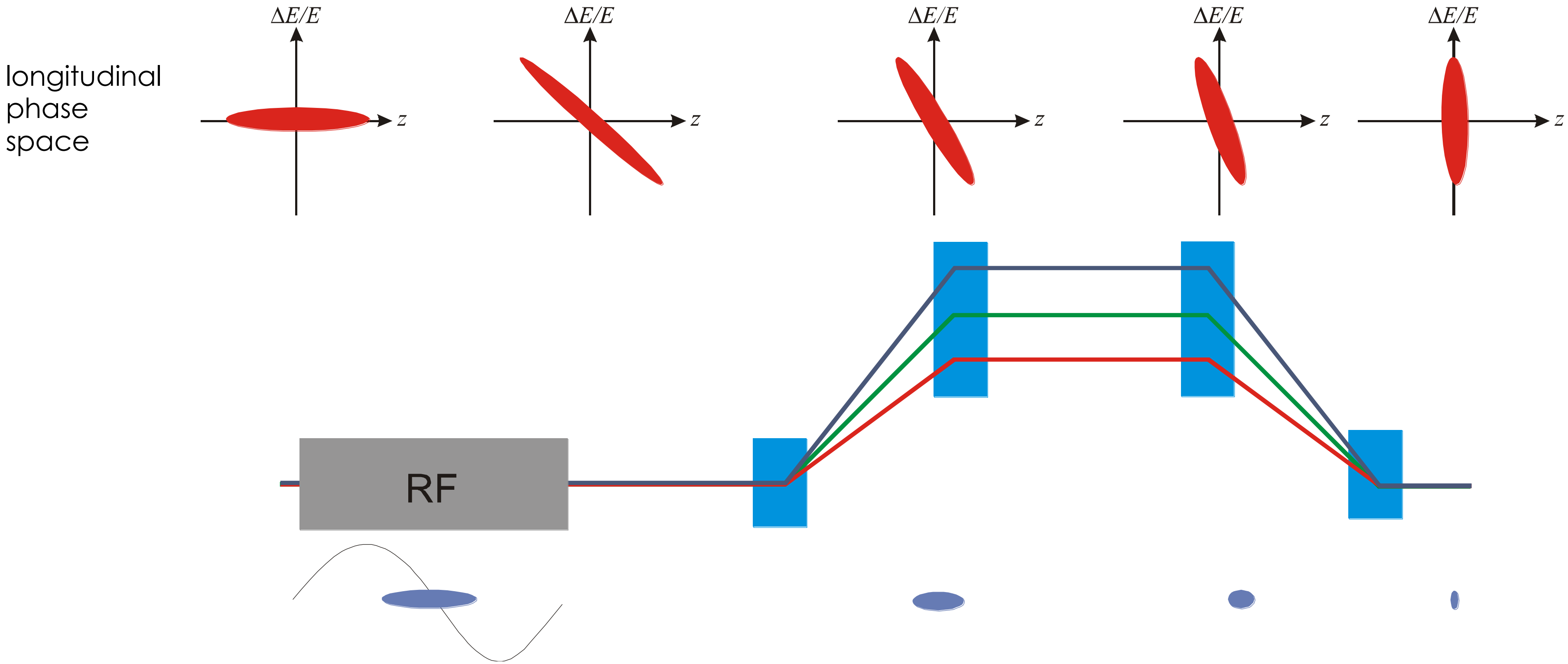
- Horizontal emittance $\varepsilon_x$ defined by lattice
- Theoretical vertical emittance $\varepsilon_y$ limited by
  - Space charge
  - Intra-beam scattering (IBS)
  - Photon emission opening angle




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

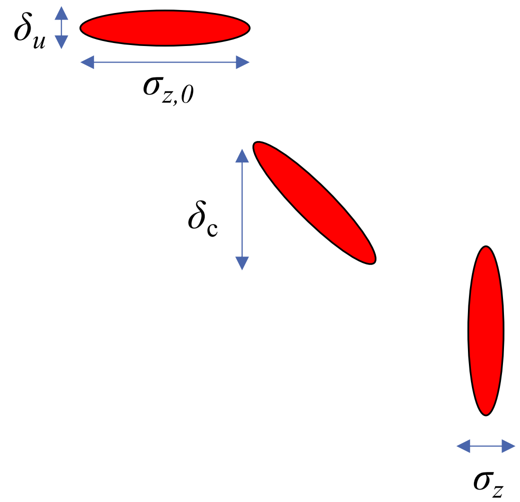
# Bunch compression

- Bunch length $\sigma_z$ from damping ring: ~ few mm
- Required at IP: ~ few 100 μm or shorter
- Solution: introduce energy/time correlation and compress with magnetic chicane:



# The linear bunch compressor

| | |
|---|---|
| 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 | $\delta_C$ |
| 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

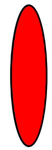
$$\delta_c \approx \frac{k_{RF} V_{RF} \sigma_{z,0}}{E} \Leftrightarrow V_{RF} = \frac{E \delta_c}{k_{RF} \, \sigma_{z,0}} = \frac{E}{k_{RF}} \left( \frac{\delta_u}{\sigma_{z,0}} \right) \sqrt{F_c^2 - 1}$$

compress at low energy

# Note: The linear bunch compressor

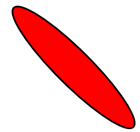
- Chicane (dispersive section) linear part $z_1 \approx z_0 + R_{56}\delta$

- Minimum bunch length for upright ellipse
  ⇒ correlation



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

- 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 ($\delta_c \gg \delta_u$)

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

# Bunch compressor - Example

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

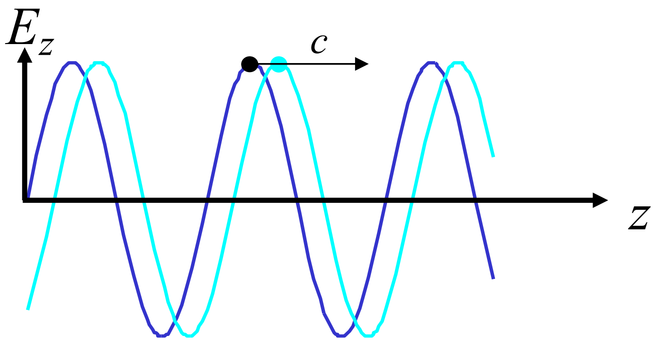
- Remark: we get a large energy spread after compression

  ⇒ large chromatic effects in the linac

⇒ use a two-stage compression with acceleration in between
to reduce relative energy spread along the line

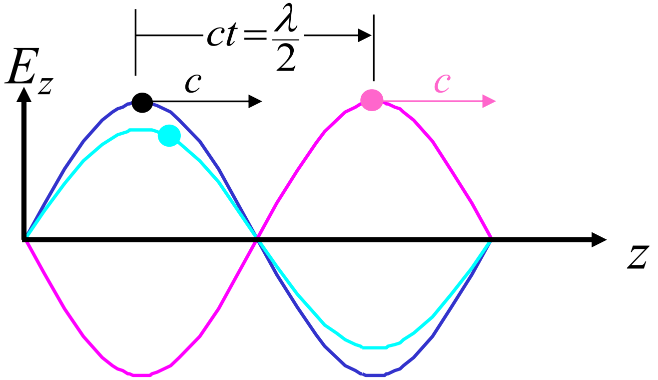
# The Main Linac

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

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

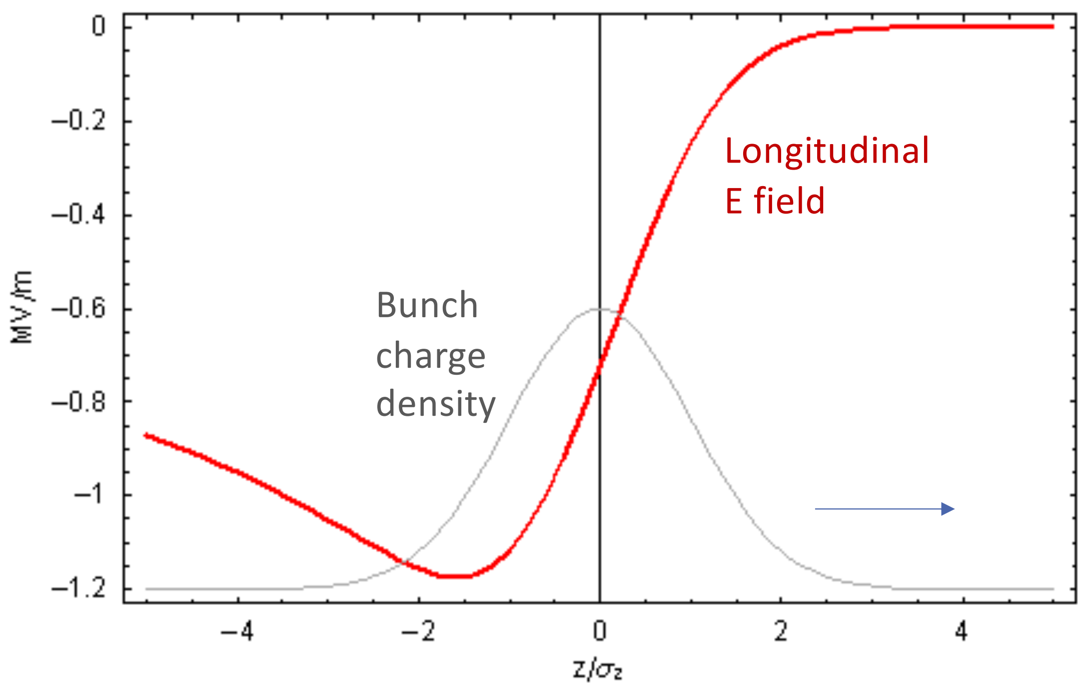
# Single bunch effects: longitudinal

Beam absorbs RF power ⇒ decreasing RF field in cavities

- Single bunch beam loading = single bunch longitudinal wake field

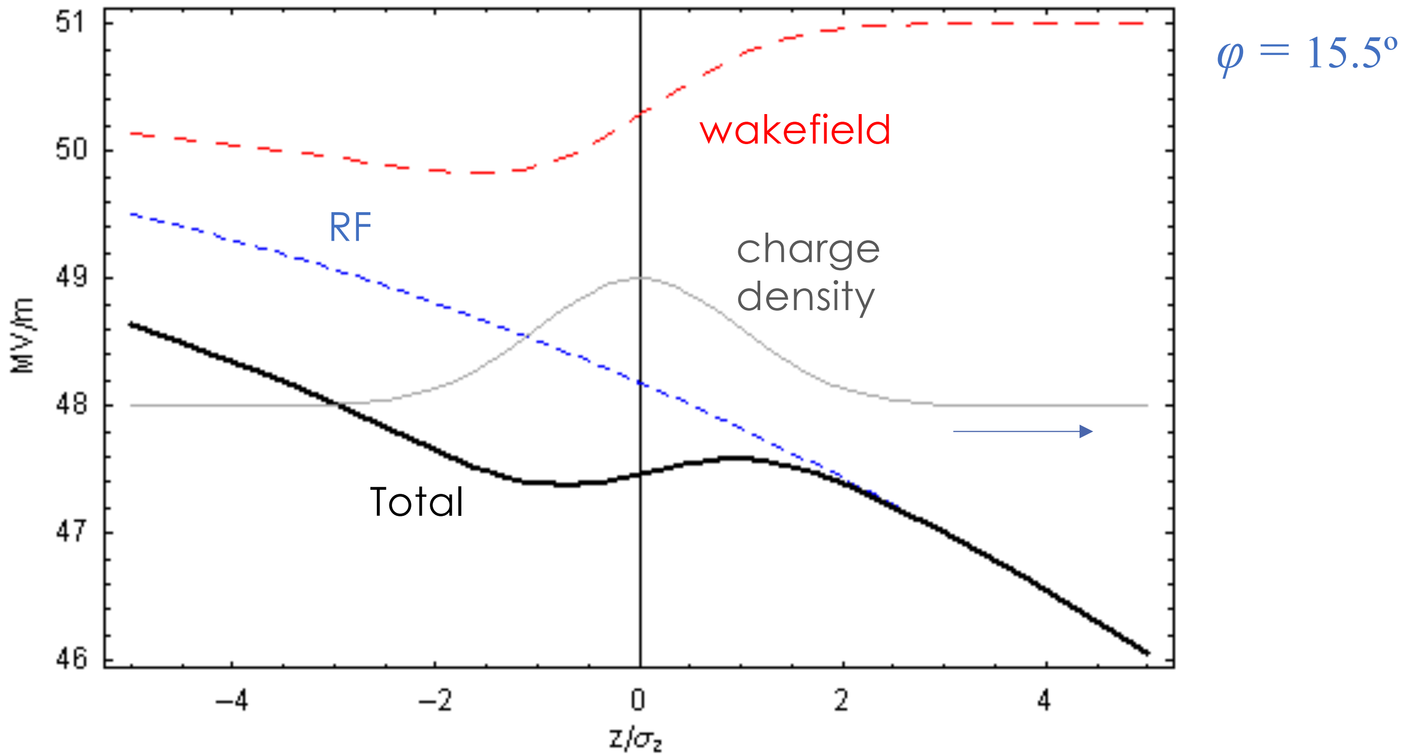
- Particles within a bunch see a decreasing field

  ⇒ energy gain different within a bunch



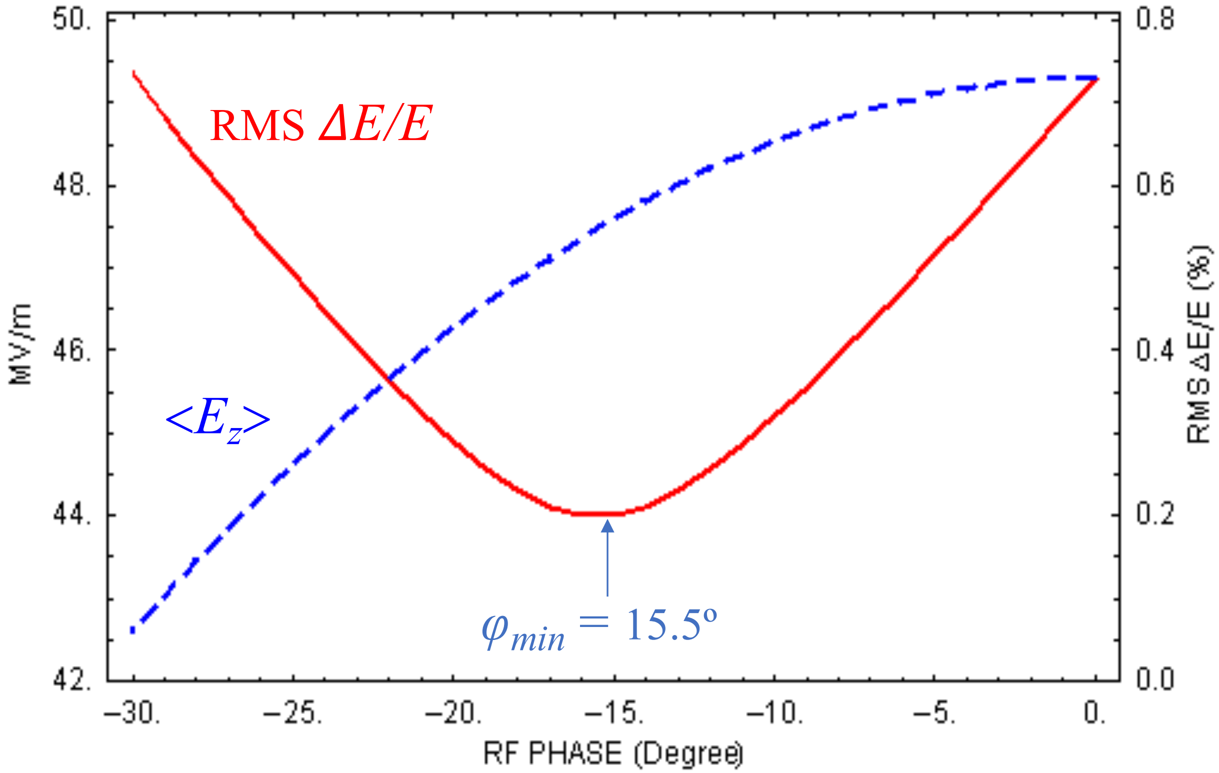
# Beam-loading compensation (single-bunch)

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



# Beam-loading compensation (single bunch)

- Minimize momentum spread



# Travelling Wave Cavity: Beam Loading (multi bunch)

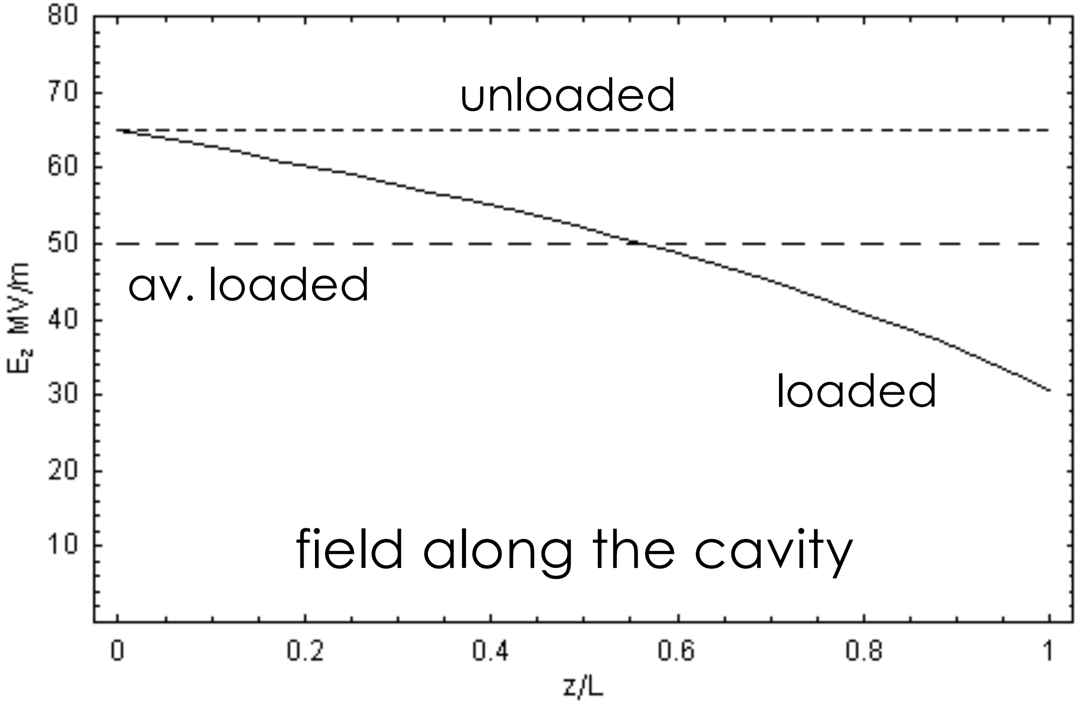
Beam absorbs RF power

⇒ gradient reduced along TW cavity for steady state

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

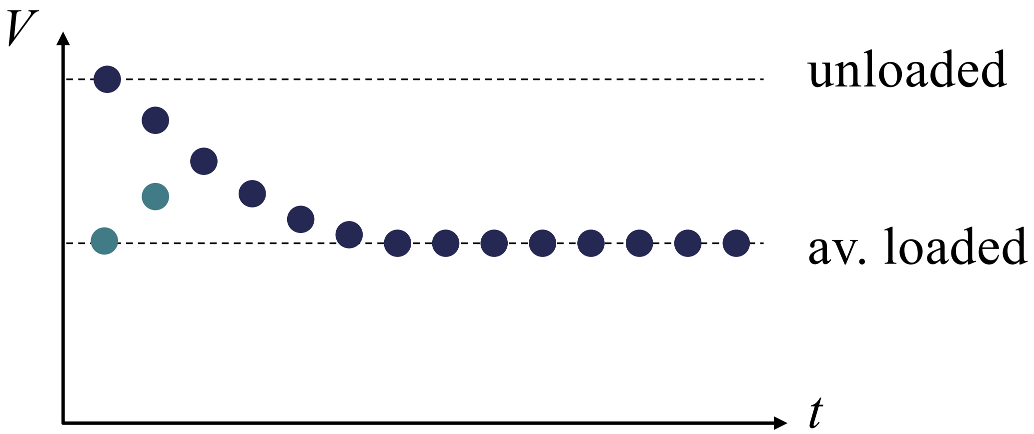
$r_s$ shunt impedence

$I_b$ peak beam current



# TW Cavity: Beam Loading (multi bunch)

- Transient beam loading (multi bunch effect):
  - First bunches see the full unloaded field, energy gain different from steady state
  - 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: Beam Loading (multi bunch)

With superconducting standing wave (SW) cavities:

- Very small 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

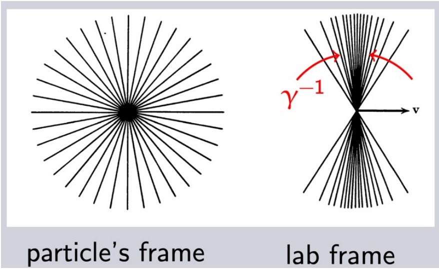
Linac must preserve the small beam sizes (and therefore the emittances), in particular in vertical plane y

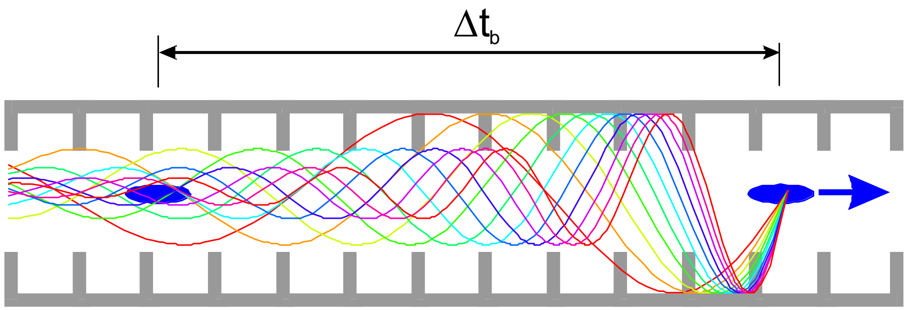
- Possible sources for emittance dilutions are:
  - Dispersive errors, chromaticity: $(\Delta E \rightarrow x, y)$
  - Transverse wakefields: $(z \rightarrow x, y)$
  - Betatron coupling: $(x \rightarrow y)$ and $(y \rightarrow x)$
  - Jitter: $(t \rightarrow x, y)$

- All these can increase the beam size at the IP
- Preserve beam size is fundamental to preserve the luminosity

# Linac: transverse wakefields

Charged particles induce electromagnetic fields in the cavities
⇒ later particles 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

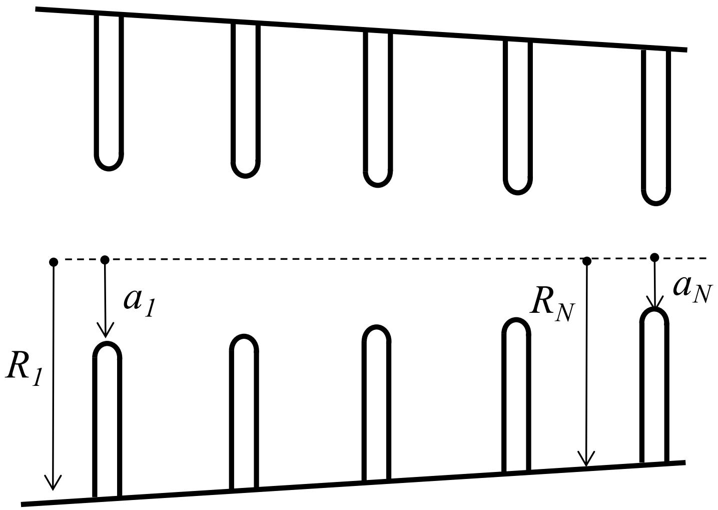
    ⇒ multi-bunch and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!

# Transverse wakefields

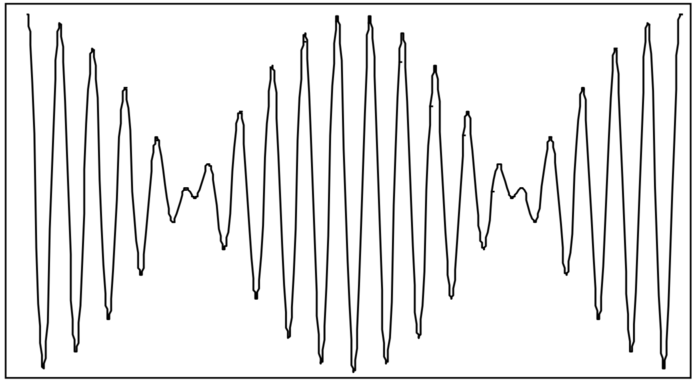


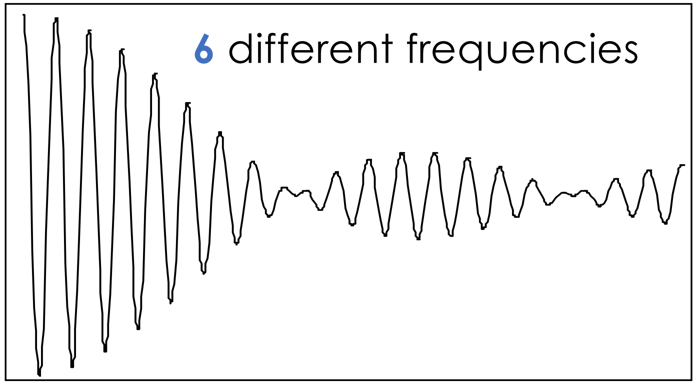
- Effect depends on $a/\lambda$ ($a$ iris aperture) and structure design details
- Transverse wakefields roughly scale as $W_\perp \propto f^3$
- Less important for lower frequency:
  Superconducting (SW) cavities suffer less
- Long-range minimised by structure design

  ⇒ Dipole mode detuning



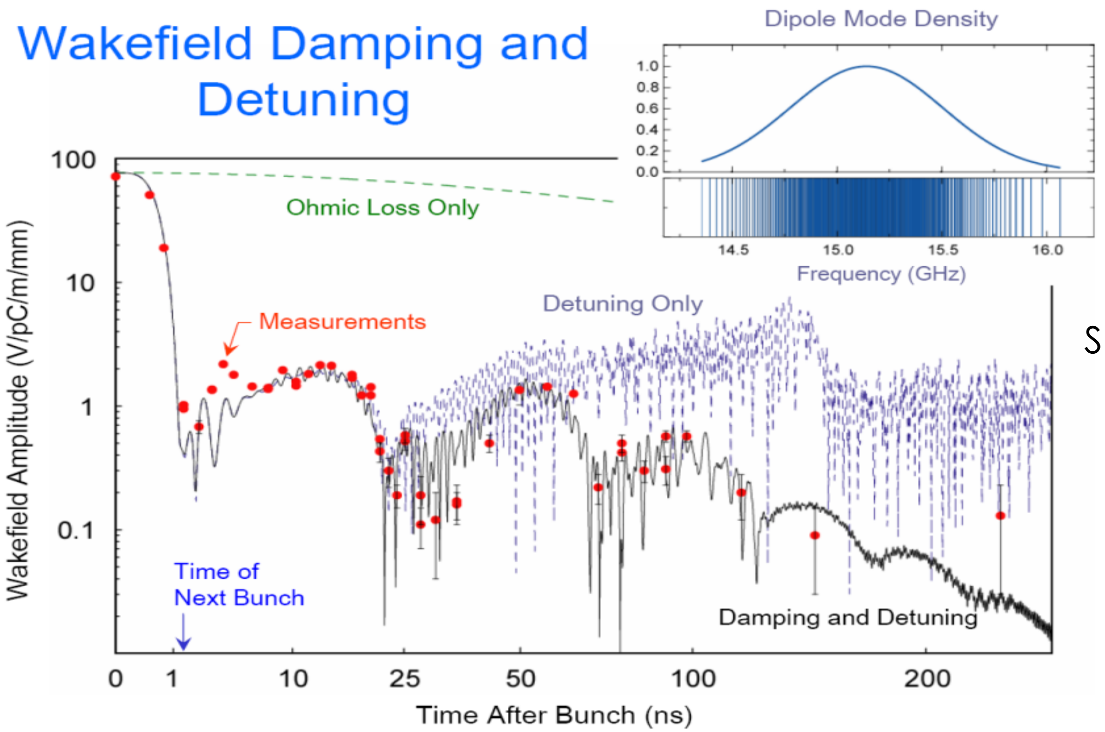

Long range wake of a dipole mode spread over **2** different frequencies





# Damping and detuning

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

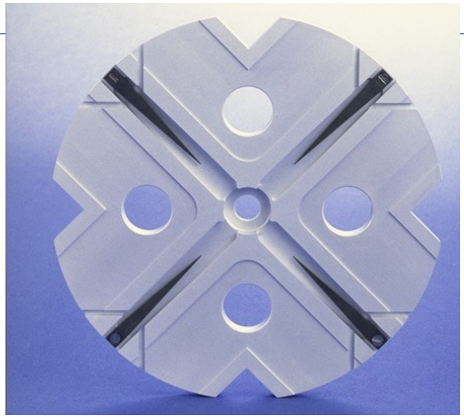


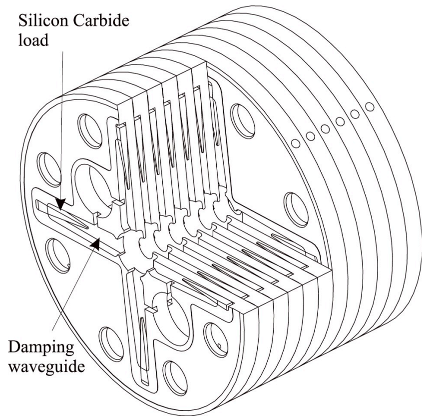

SLAC (NLC)

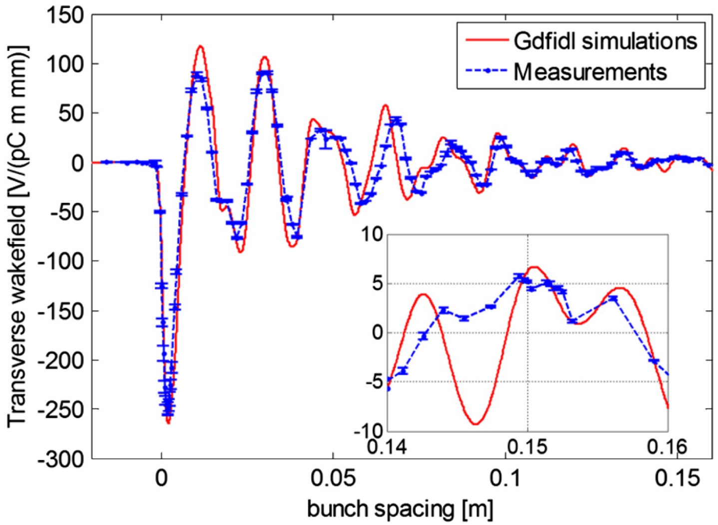
*C. Adolphsen*

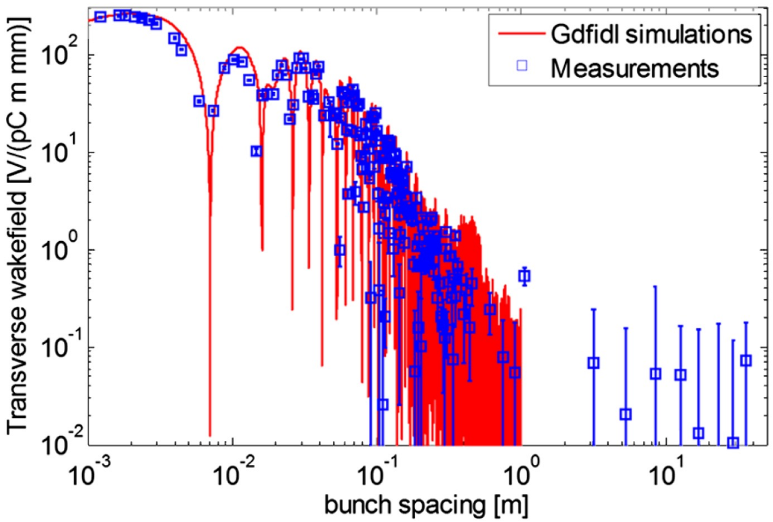
# HOM damping - CLIC

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





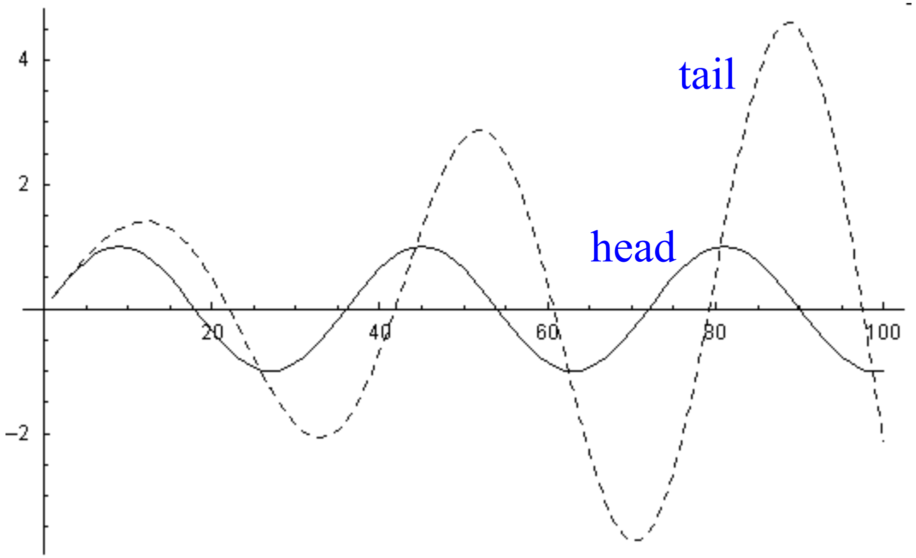




CERN (CLIC)
Measured at FACET (SLAC)

*A. Latina*

# Single bunch (transverse) 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:

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

# BNS damping

- Counteract effective defocusing of tail by wakefield by increased focusing on tail
  BNS ⇒ Balakin, Novokhatski, and Smirnov
- Done by decreasing tail energy with respect to head
- Obtained by longitudinally correlated energy spread
  (less off-crest than longitudinal wakefield compensation)

  ⇒ Transverse wakefields balanced by lattice chromaticity
- 2 particle model:

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

$q_\beta$ fractional $\beta$ 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 |
| $\alpha$ | scaling of the focusing lattice ( ~ 0.5) |
| $G$ | accelerating gradient |
| $E_{i,f}$ | initial and final energy |

- For given (maximum allowed) $\Delta\varepsilon$, 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 $\delta Y_{rms}$
- Partially compensated by: higher $G$, lower $\beta$, lower $N$

# End part II