LCWS MiniSchool

Online, March 15^{h}, 2021

Electron-Positron Colliders

energy and luminosity, damping rings, polarization,…

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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<u>Contents:</u>

- **Introduction:** Acceleration, Luminosity, Colliders, …
- **Acceleration:** Cavities, Key Parameters, nc and sc Linacs
- **Acc. Phys. Basics:** Emittance, Optical Functions and Resonances, …
- **Luminosity:** Crossing Angle, Hourglass, Beam-Beam, …
- **Add. Systems:** Polarization, Damping Rings, …
- **e^+-e^- Projects:** ILC, CLIC, FCC-ee, CEPC

Accelerators for Particle Physics

Particle Physicists wish list comprises the following:

- TeV beams of all kind of particles (γ, e, μ, p, …)
- highest luminosity, that means in particular:
  a) premium beam quality and performance
  b) ultimate intensity while having stable beam delivery all the time
- polarized particles of all kinds (preferably antiparticles like e^+ and $\overline{p}$)
- enough free space to place huge detectors

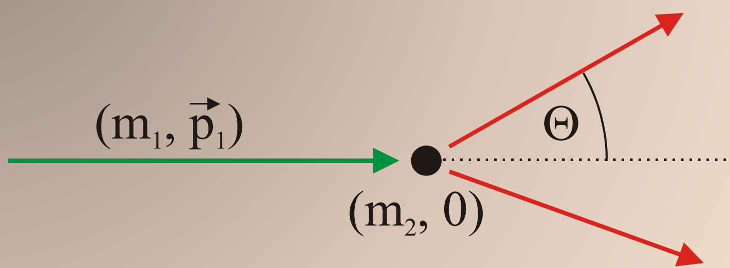
2 Classes of High-Energy Accelerators:

- **Hadron Colliders**: Highest achievable energies
  → **"discovery potential"**
- **e^+ - e^- Colliders**: well-known and understood electromagnetic vertex
  → **"precision machines"**

Why Colliders?

(Units: $\hbar = c = 1$)

Fixed Target Experiment

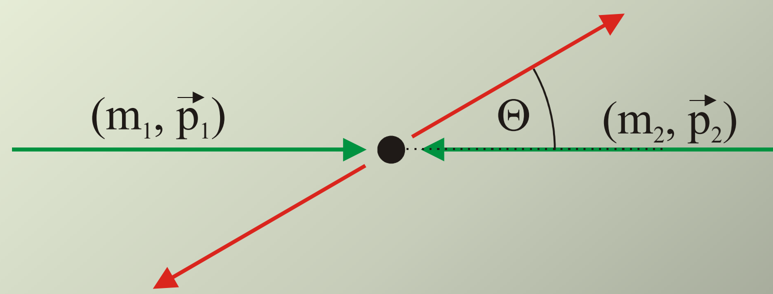


$$S = P_1 + P_2 = (E_1 + m_2, \vec{p}_1 + \vec{p}_2)$$

$$\vec{\beta}_{CMS} = \frac{\vec{p}_1}{E_1 + m_2}$$

$$M_{inv}{}^2 = S^2 = 2E_1 m_2 + m_1{}^2 + m_2{}^2$$

Colliding Beams



$$S = P_1 + P_2 = (E_1 + E_2, \vec{p}_1 + \vec{p}_2)$$

$$\vec{\beta}_{CMS} = \frac{\vec{p}_1 + \vec{p}_2}{E_1 + E_2} = 0$$

$$M_{inv}{}^2 = S^2 = (E_1 + E_2)^2$$

Example: p-p Collisions, want $S = 1$ TeV

requires:

$E = 500$ TeV (Fixed Target) **$E = 0.5$ TeV** (Colliding Beams)

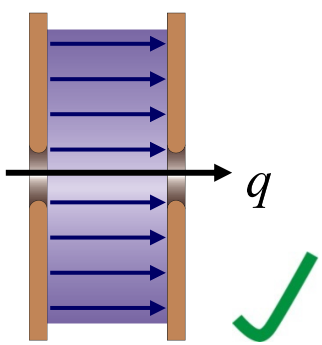
Beam Acceleration

Charged particles are influenced by the Lorentz force: $\vec{F} = e \cdot \vec{E} + e \cdot \left(\vec{v} \times \vec{B} \right)$

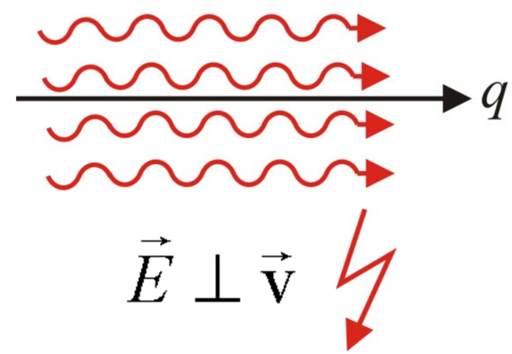
Energy gain: $\Delta W_{kin} = \int \vec{F} \cdot d\vec{s} = e \cdot \int E_{\parallel} \cdot ds = e \cdot U$

→ We need a longitudinal electrical field $E_{\parallel}$!

Capacitor:



Light beam:



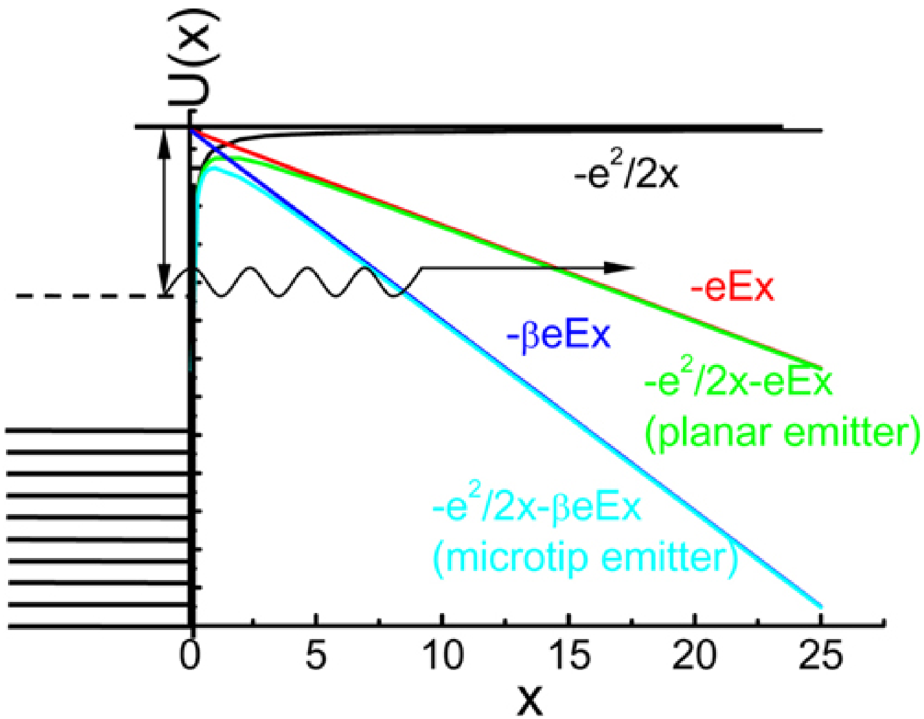
Field Emission / Breakdown

Coulomb-Potential:

$$U = \int \vec{F} \bullet d\vec{s} = \frac{q^2}{4\pi\varepsilon_0} \int \frac{ds}{r^2} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{-q^2}{2r}$$

homogeneous E-Field:

$$U = \int \vec{F} \bullet d\vec{s} = \int q\vec{E} \bullet d\vec{s} = -qEr$$



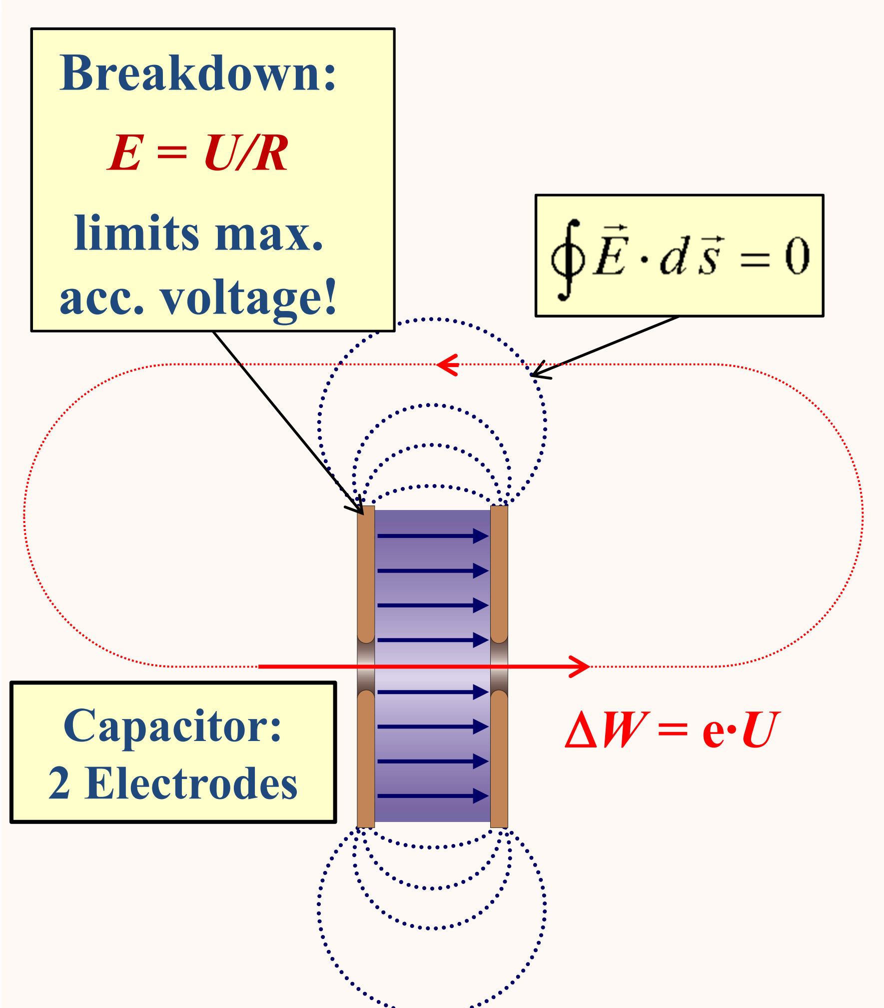
Tunneling!
Enhancement
Factor β !!

DC

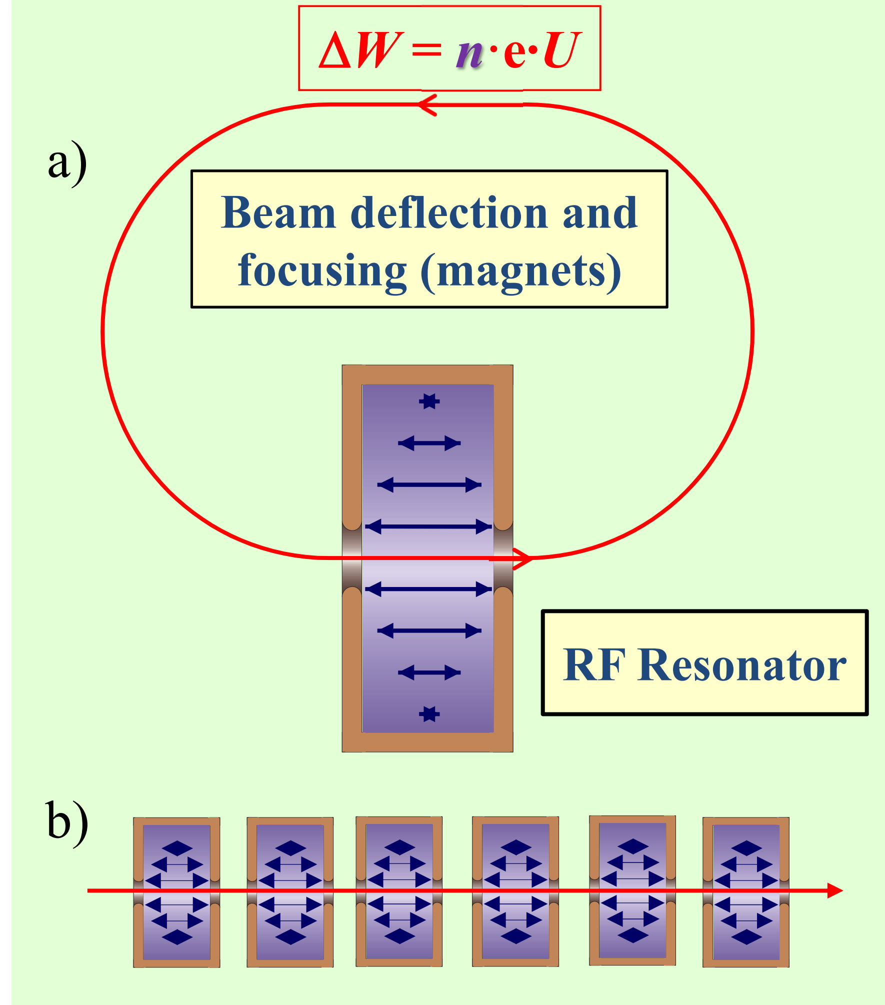
AC

$E_{max} \leq 10 - 100$ MV/m

Beam Acceleration

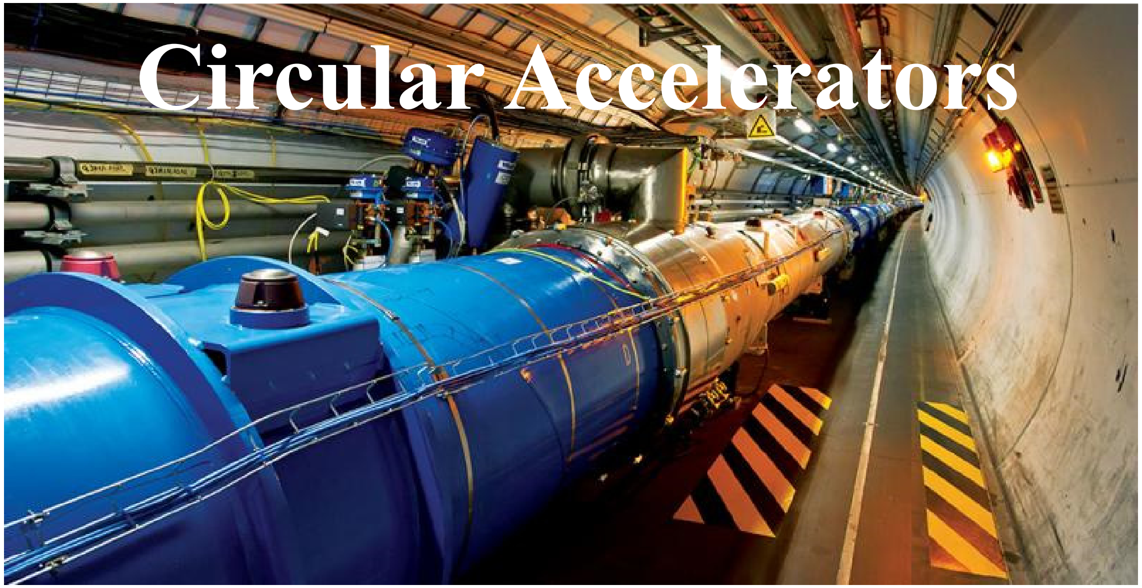


☹ **Electrostatic Acceleration** ☹



☺ **RF-based Acceleration** ☺

Building a TeV Accelerator



Example LHC → e^+e^-:

Bending Magnets: $B = 8.33\text{T}$

Bending Radius: $R = \dfrac{p}{eB}$

Beam Energy E_{kin} = 0.5 TeV!

$$R = \frac{pc}{ecB} = \frac{5\cdot 10^{11}}{3\cdot 10^{8}\cdot 8.33} \approx 200\text{m}$$

$$\Rightarrow \quad L = 2\pi R + x \approx 5\text{km}$$

Example XFEL → e^+e^-:

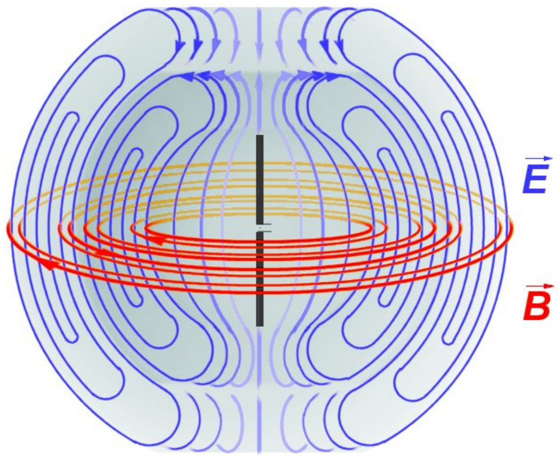
Achieved: $U_{accel} = 29.5$ MV/m

Beam Energy $2E_{kin}$ = 1 TeV!

$$\Rightarrow \quad L = \frac{2E_{kin}}{U_{accel}} + x \approx 50\text{km}$$

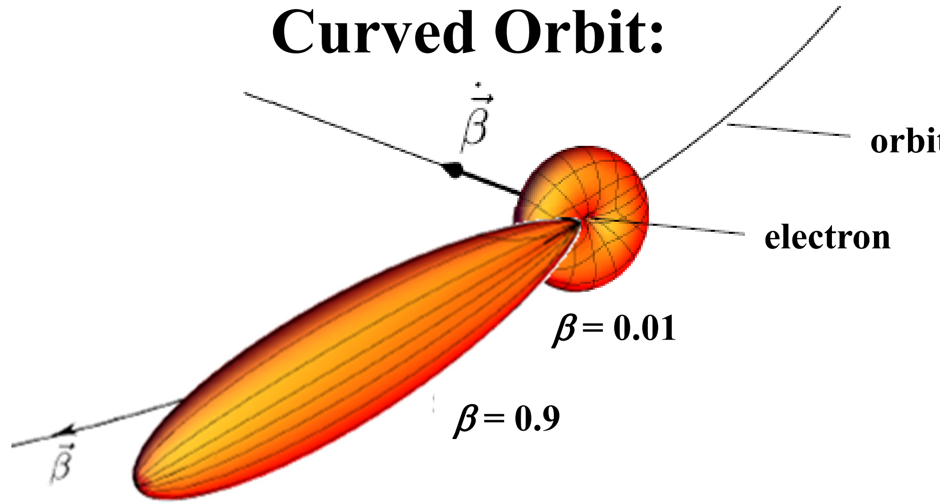
Acceleration ↔ Radiation:

Hertz Dipole:



$$P = \frac{e^2}{12\pi\varepsilon_0 c^3} \cdot \omega^4 d^2$$

Curved Orbit:



$$P = \frac{e^2 c}{6\pi\varepsilon_0} \cdot \frac{\gamma^4}{R^2}$$

„Circumference Voltage“ (electrons):

$$U\,[\mathrm{kV}] = 88.5 \cdot \frac{E^4\,[\mathrm{GeV}^4]}{R\,[\mathrm{m}]}$$

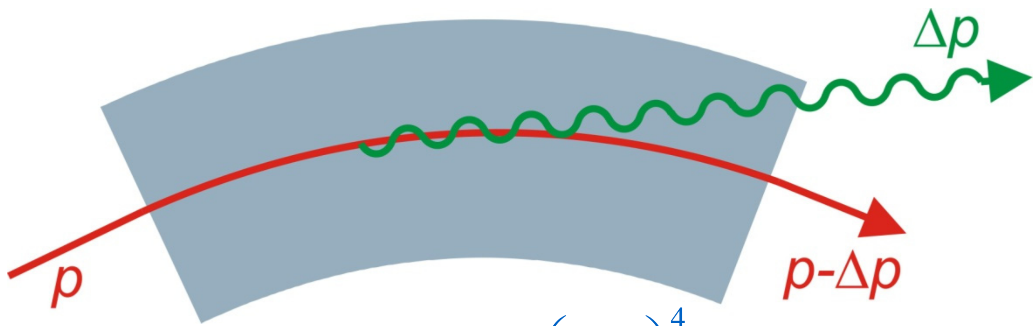
Limitations in Circular Accelerators

Electrons:

→ Synchrotron Radiation

energy loss per turn:

$$\Delta W[\text{keV}] = 88.5 \cdot \frac{E^4[\text{GeV}^4]}{R[\text{m}]}$$



Protons: $\dfrac{\Delta W_p}{\Delta W_e} = \left(\dfrac{m_e}{m_p}\right)^4 \approx 10^{-13}$

Example:

LHC bending radius $R = 2.8\text{km}$ (circumference = 27km)

electron beam energy $E_{\text{kin}} = 500\text{GeV} = 0.5\text{TeV}$:

→ energy loss per turn $\Delta W = 2$ TeV!!!

Acceptable:
$\Delta W < 10$ GeV
→ $R > 500$km!

Large Electron Positron Collider

LEP Parameters:

$E \leq 104.5$ GeV

$R \approx 3.1$ km

$B \approx 0.12$ Tesla

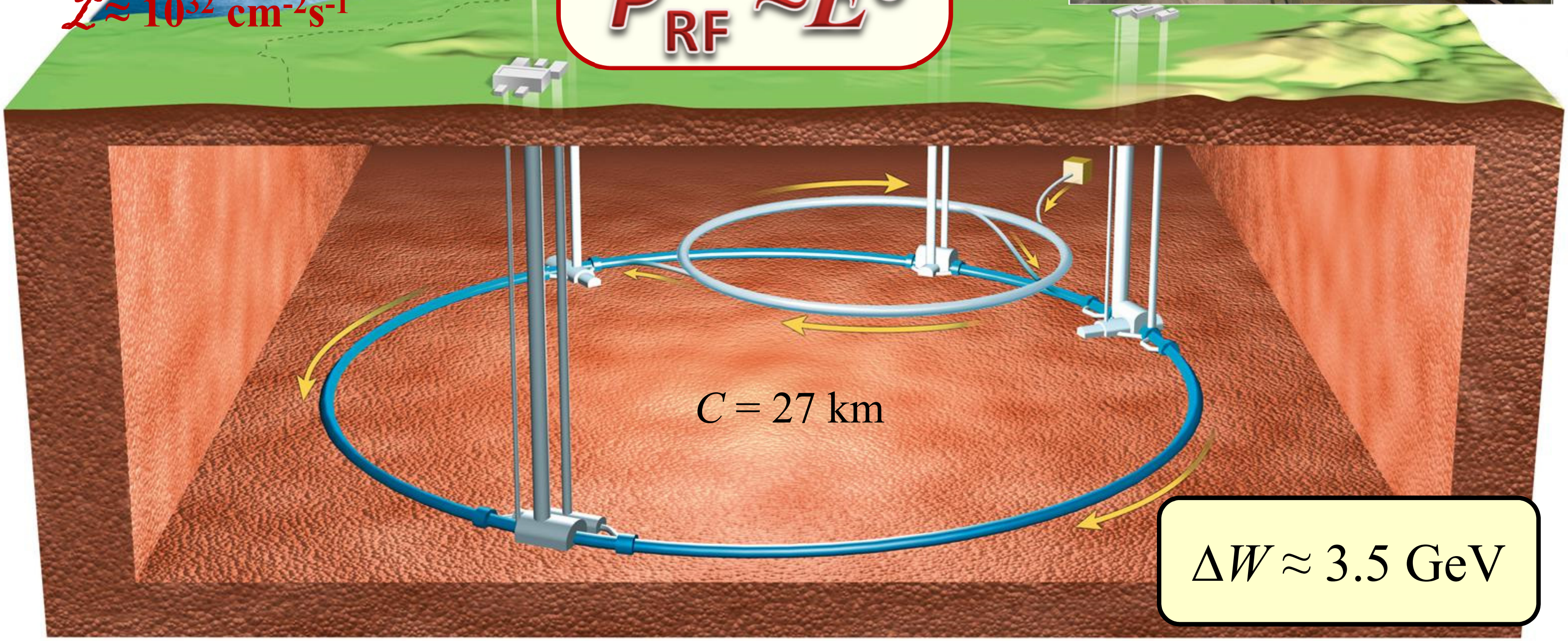
$P_{RF} \approx 30$ MW

$\mathcal{L} \approx 10^{32}$ cm^{-2}s^{-1}

$P_{RF} \sim E^4$

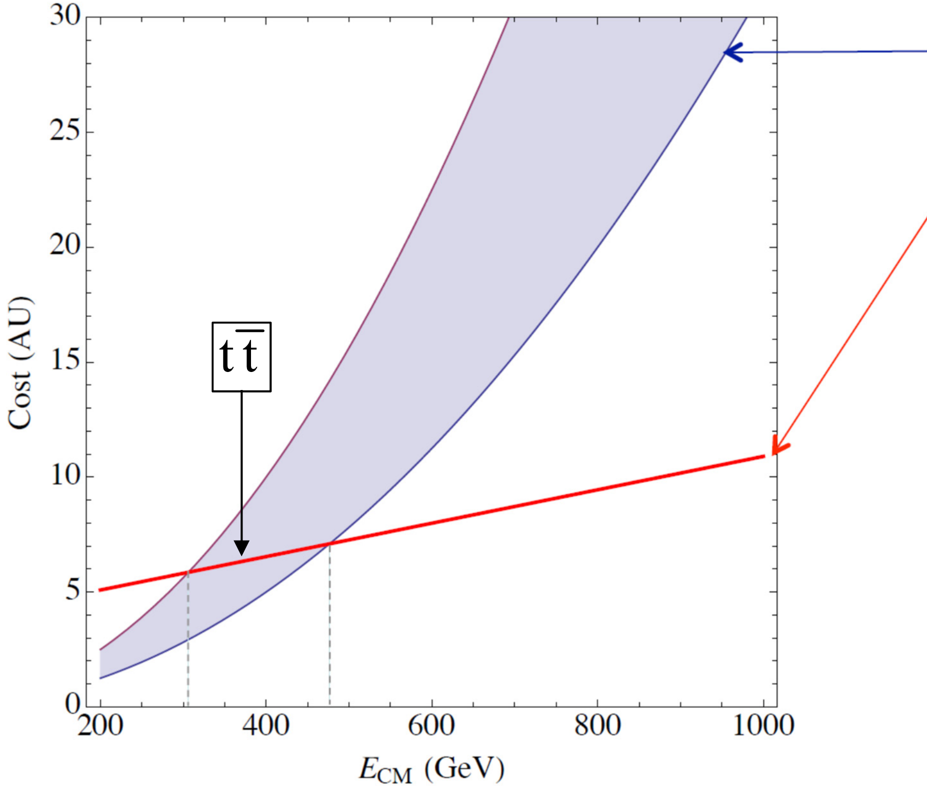
if "upgraded":

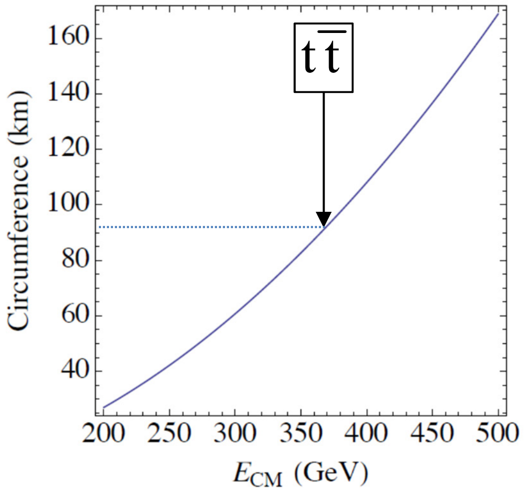
$P_{RF} \sim E^8$



$\Delta W \approx 3.5$ GeV

$ Scaling of Colliders





Linear Collider clearly "wins" @ E_{CM} > 500 GeV!!

Circular Collider: $\$_{RF} \propto \frac{E^4}{R}, \quad \$_{CC} \propto R \quad \Rightarrow$ Optimum: $\frac{E^2}{R} = \text{konst.} \quad \rightarrow \$_{\Sigma} \propto E^2$

Avg. Beam Current

Important for achievement of enough wanted reactions in collisions.

Obviously: the more (colliding particles) the better!

Circular Collider (FCC-ee):

- RF has to compensate SR losses, 50MW per beam acceptable
- max average beam current: $I_{avg} = 29\,\text{mA}\,@\,\text{H},\;\; I_{avg} = 5{,}4\,\text{mA}\,@\,t\bar{t}$

Linear Collider (ILC):

- RF → P_{beam}, but limited: e.g. 5 x 1312 bunches/sec with $N_b = 10^{10}$ particles (ILC)
- max average beam current: $I_{avg} = 11\,\mu\text{A}\,@\,\text{H and }@\,t\bar{t}$

→ has this consequences?

Luminosity

… the unknown divinity …

One of the most important acc. parameter for particle physicists!

- **Luminosity** $$\dot{N} = \sigma \cdot \mathcal{L}$$
- **Integrated Luminosity:** $$\dot{N} = \sigma \cdot \int_{\text{t-meas.}} \mathcal{L} \cdot dt = \sigma \cdot \mathcal{J}$$

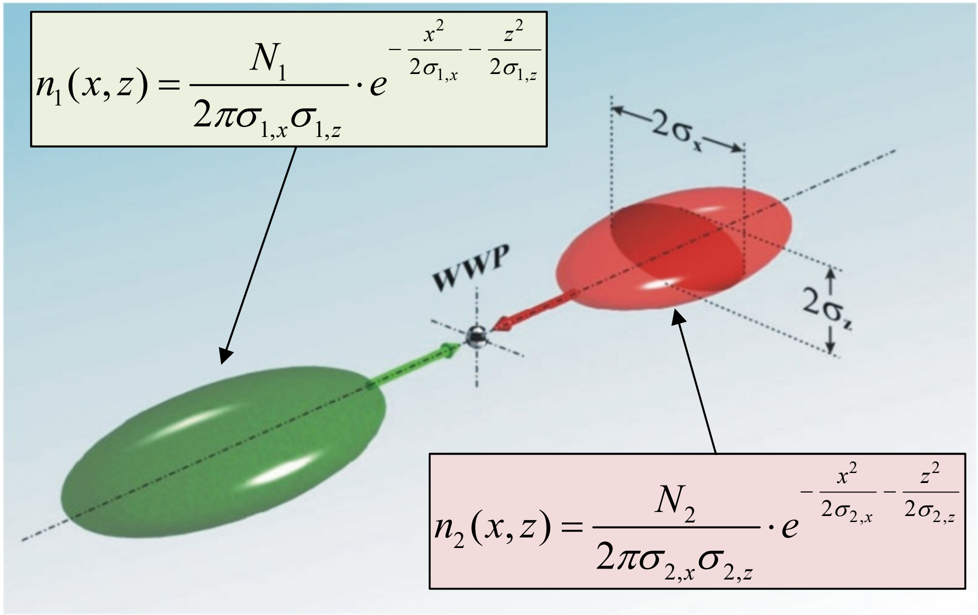
$$N_{b,b} = \sigma \cdot \iint n_1(x,z) \cdot n_2(x,z) \cdot dx\, dz$$

$$\Downarrow$$

e$^+$-e$^-$, p-p Collider:

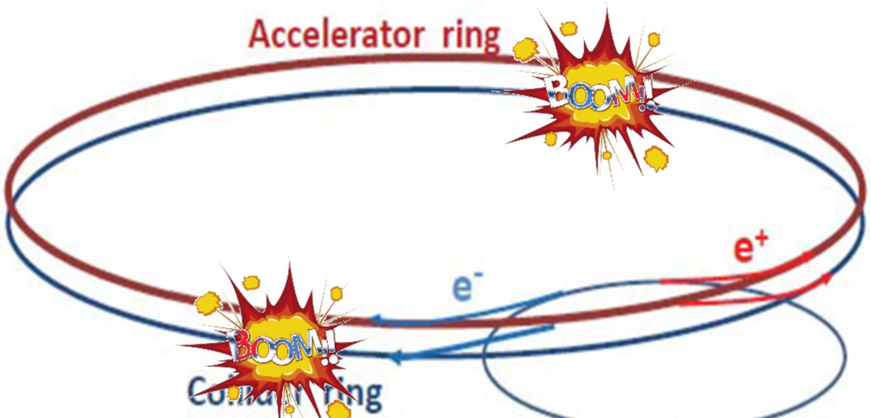
$$\sigma_1 = \sigma_2 = \sigma$$

$$\mathcal{L} = \frac{n_b \cdot f_{rev}}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_z}$$



Colliders

Circular



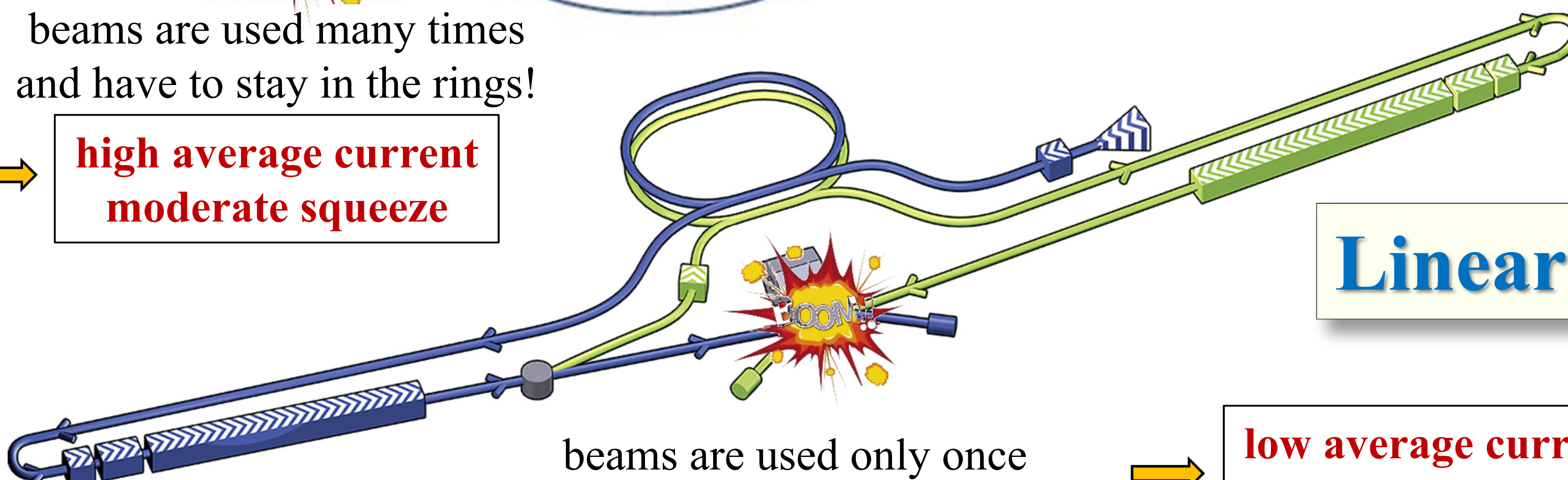
beams are used many times
and have to stay in the rings!

➡ **high average current**
moderate squeeze

Luminosity:

$$\mathcal{L} = \frac{n_b \cdot f_{rev}}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_z}$$

Linear



beams are used only once
and are dumped after collision!

➡ **low average current**
aggressive squeeze

Introduction Summary

Essence: What do we have to learn in the next hour?

- **How do we accelerate electrons (positrons) to ~TeV?**
  - ➢ **Crash course in RF acceleration:**
  - Cavities and their important parameters
  - Standing wave (sc) and travelling wave (nc) Linac structures

- **How can we achieve a maximum (acceptable) luminosity?**
  - ➢ **Crash course in beam dynamics in accelerators:**
  - How much can and should we squeeze? (→ final focus, damping rings, …)
  - What limits the intensity? (→ RF, beam-beam, instabilities, …)
  - ➢ **What else matters?** (beam-beam, beamstrahlung, wakefields, …)

- **What about polarized beams?**

➢ **Summary: Linear vs. Circular Collider – pros and cons**

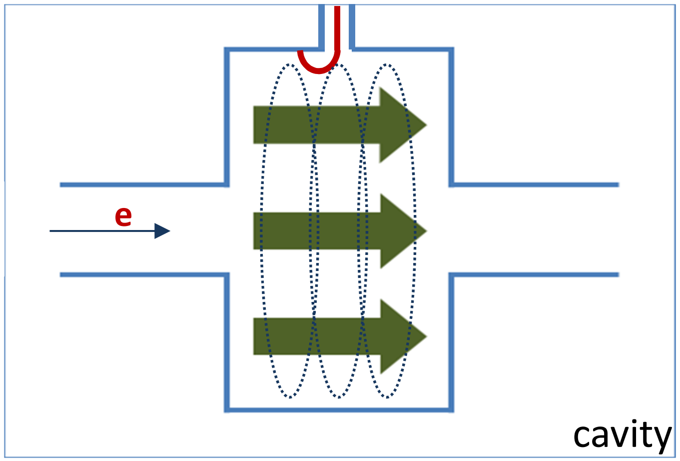
Acceleration

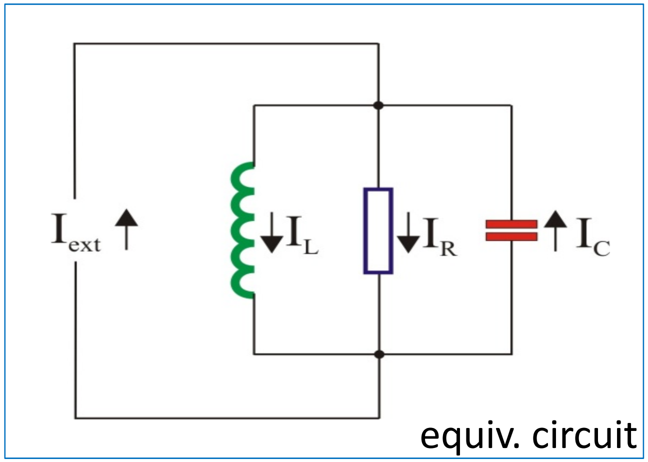
Linear Collider:

Circular Collider:

Cavities

General Idea: high accelerating field caused by resonance magnification





Parameters of interest:

- resonance frequency $\omega_0 = 1/\sqrt{LC}$ = determined by geometry
- quality factor $Q = \omega_0 RC = \dfrac{R}{\omega_0 L} = \dfrac{2\pi \cdot W_{stored}}{T_{RF} \cdot P_{walls}} = \omega_0 \tau_e$
- shunt impedance $R_S = R = Z(\omega_0)$ = resistance on resonance

$R_S/Q = \text{geom.}$

Accelerating voltage: $P_{walls} = \dfrac{U^2}{2R_S} \rightarrow$ requires $P_{RF} = \dfrac{U^2}{2R_S} + U \cdot I_{beam}$

Shunt Impedance

Determines unwanted power losses in cavity walls!

Typical values and scaling of R_S and Q (f_{res} = 1.3 GHz):

- **normal conducting cavities (copper, ~1 meter long resonator):**

$$R_S \approx 10^7\,\Omega, \quad Q \approx 10^4 \qquad R_S \sim \sqrt{f_{res}}, \quad Q \sim 1/\sqrt{f_{res}}$$

- **superconducting cavities (niobium, ~1 meter long resonator):**

$$R_S \approx 10^{13}\,\Omega, \quad Q \approx 10^{10} \qquad R_S \sim 1/f_{res}, \quad Q \sim 1/f_{res}^2$$

$$R_S/Q \sim f_{res}$$

Losses in superconducting cavities about factor 10^5 – 10^6 smaller!

Carnot efficiency (T_{Cav} = 2.2K): $\eta_{Carnot} = \dfrac{T_{Cav}}{T_{room} - T_{Cav}} \approx 0.7\%$

Overall cooling efficiency: $\eta \approx$ 0.1-0.2%, but R_S gain > 10^5!

Superconducting RF

But: Maximum accelerating field limited by H_{C2} of BCS theory to ≈ 54 MV/m!

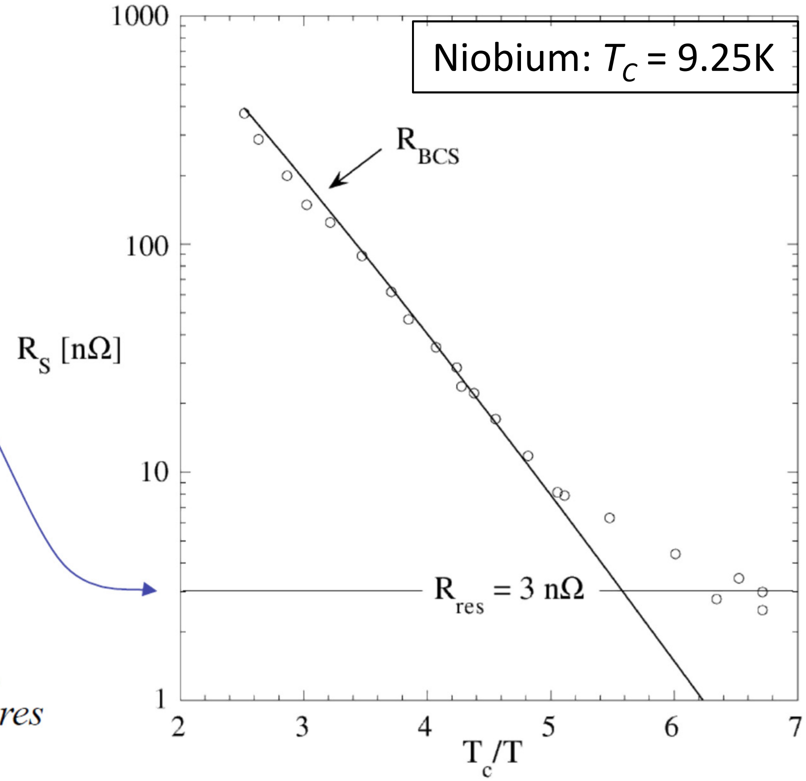
Choice of optimum frequency and temperature:

$$R_{BCS} \propto \frac{f^2}{T}\exp\left(-1.76T_c/T\right)$$

Two important parameters:

- residual resistivity R_{res}
- thermal conductivity

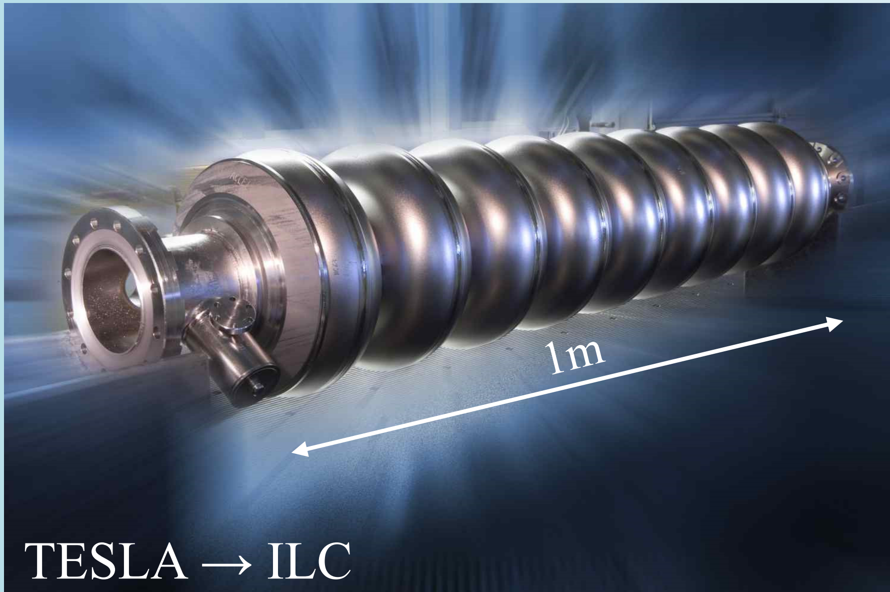
losses { $\propto$ surface area $\propto f^1$; $R_s \propto f^2$ when $R_{BCS} > R_{res}$ }

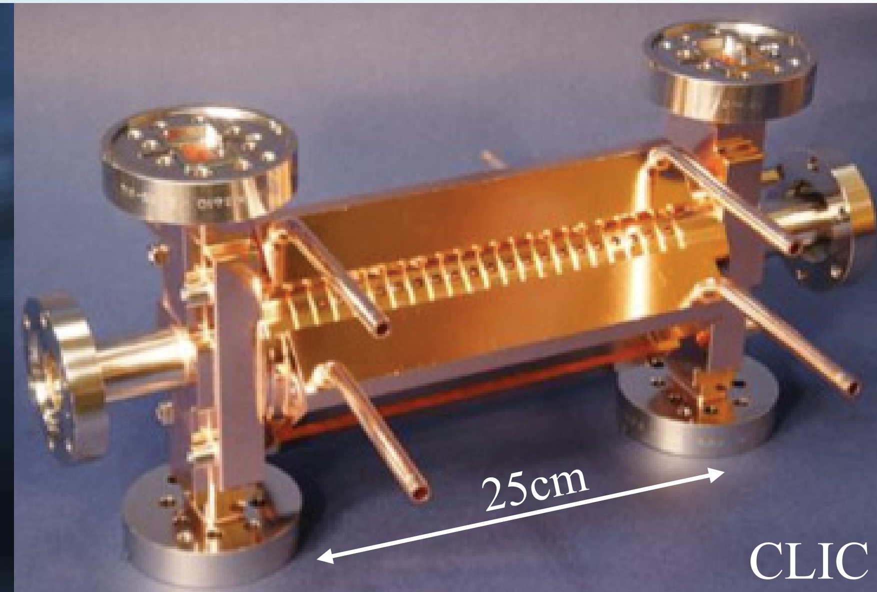


f_{TESLA} = 1.3 GHz

f > 3 GHz

Linear Collider: Acceleration





SW
$f = 1.3$ GHz

$$E_{\parallel} = \sqrt{2 \cdot r_S \cdot P/L}$$

$$E_{\parallel} = \sqrt{\frac{r_s}{Q} \cdot \frac{\omega}{v_g} \cdot P(s)}$$

TW
$f = 12$ GHz

Envisaged gradients:

$$E_{acc} = 31.5 \frac{\text{MV}}{\text{m}}$$

$$E_{acc} = 72(100) \frac{\text{MV}}{\text{m}}$$

Shunt Impedance and its Importance

RF power needed for generating the acc. field:

$$P_{RF} = \frac{U^2}{2R_S}$$

Let's assume 25cm and 1m long structures and $E_{\text{kin}} = 250$ GeV

a) n.c. ($E_{\text{acc}} = 72$ MV/m): $L_{\text{RF}} = 3.5$ km → 13889 structures

RF power $$P_{RF} = 13889 \cdot \frac{\left(7 \cdot 10^7\,\text{V/m}\right)^2}{2 \cdot 10^7\,\Omega} \approx 10^{11}\,\text{W}$$

b) s.c. ($E_{\text{acc}} = 30$ MV/m): $L_{\text{RF}} = 8.3$ km → 8333 structures

RF power $$P_{RF} = 8333 \cdot \frac{\left(3 \cdot 10^7\,\text{V/m}\right)^2}{2 \cdot 10^{13}\,\Omega} \approx 4 \cdot 10^5\,\text{W}, \quad \eta_{cryo} = 10^{-3}$$

P U L S E D

nc versus sc Linacs

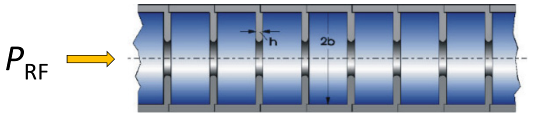
Normal Conducting Linac

Breakdown limits E_{max}!

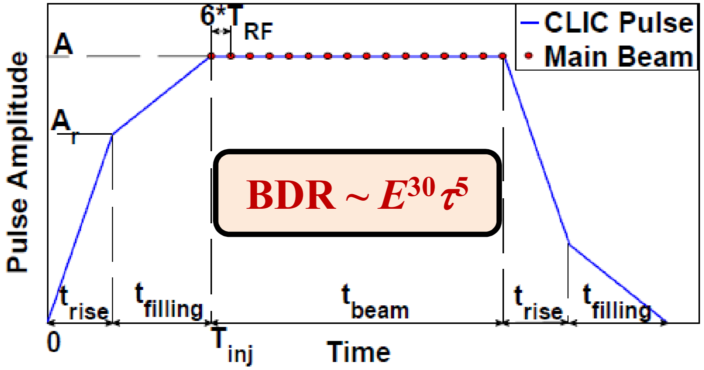
- short beam & RF pulses
- short filling times
- TW structures ($\tau_{fill} = v_g \cdot L$)
- "high" RF frequency (tolerances!)

CLIC @ CERN:

f_{RF} = 12 GHz, I_b = 1.2 A, t_b = 244 ns



CLIC PULSE SHAPE OPTIMIZATION



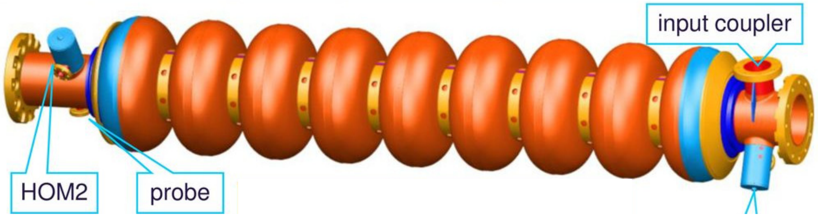
Superconducting Linac

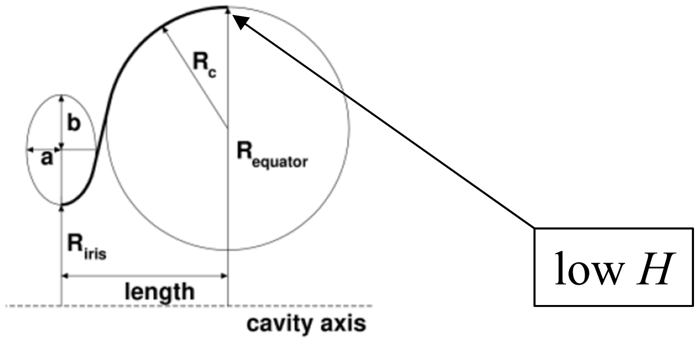
Supercritical field H_{C2} limits E_{max}!

- optimization for low H @ walls
- long RF pulses possible
- SW structures (↔ low losses)
- "low" RF frequency (size)

TELSA, FLASH, XFEL → ILC:

f_{RF} = 1.3 GHz, N_b = 10^{10}, t_b = 0.65ms





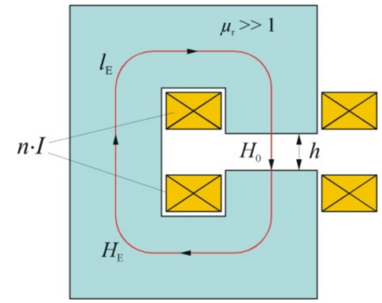
Collision
→ Luminosity

Magnets

Beam guidance:

dipole magnets

$$\frac{1}{R} = \kappa = \frac{e}{p} \cdot B_z, \quad B_z = const.$$

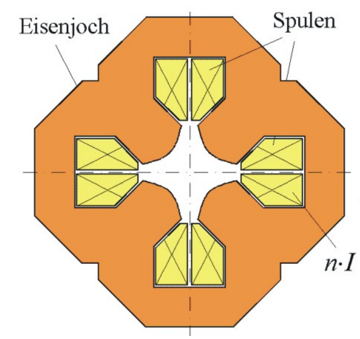


Beam focusing:

quadrupole magnets

=g

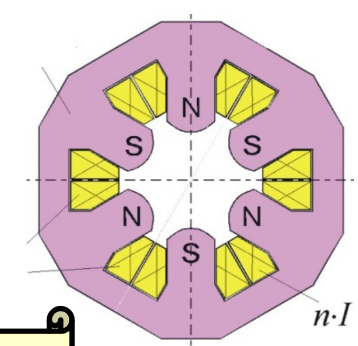
$$\frac{1}{f} = kL, \quad B_x = \frac{p}{e} k z, \quad B_z = \frac{p}{e} k x$$



Chromatic Correction:

sextupole magnets

$$B_x = \frac{p}{e} m x z, \quad B_z = \frac{p}{2e} m \left(x^2 - z^2\right)$$

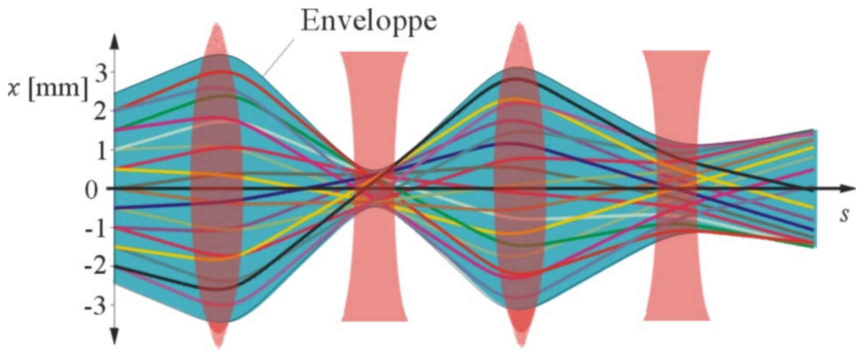


Properties defined by pole profiles

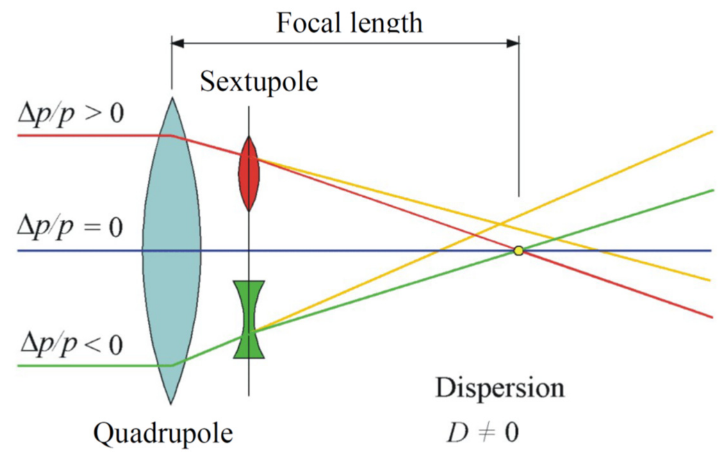
$B \leq 2$ T

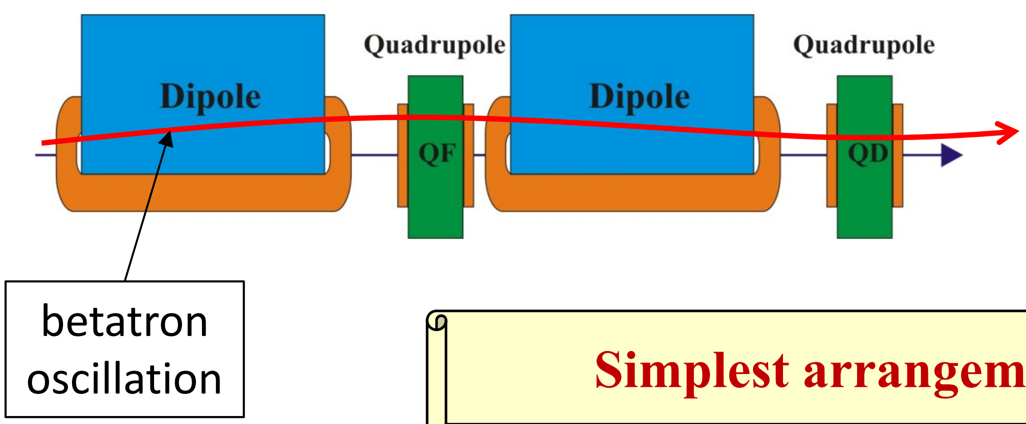
Strong (AG) Focusing:

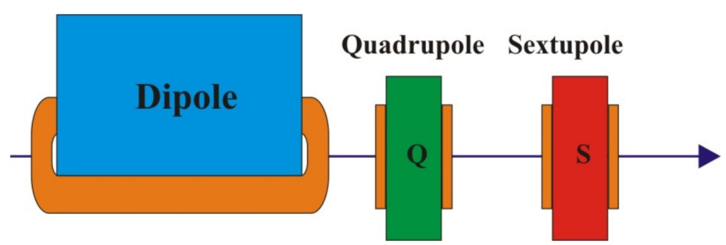
Strong Focusing:



Chromatic Correction:







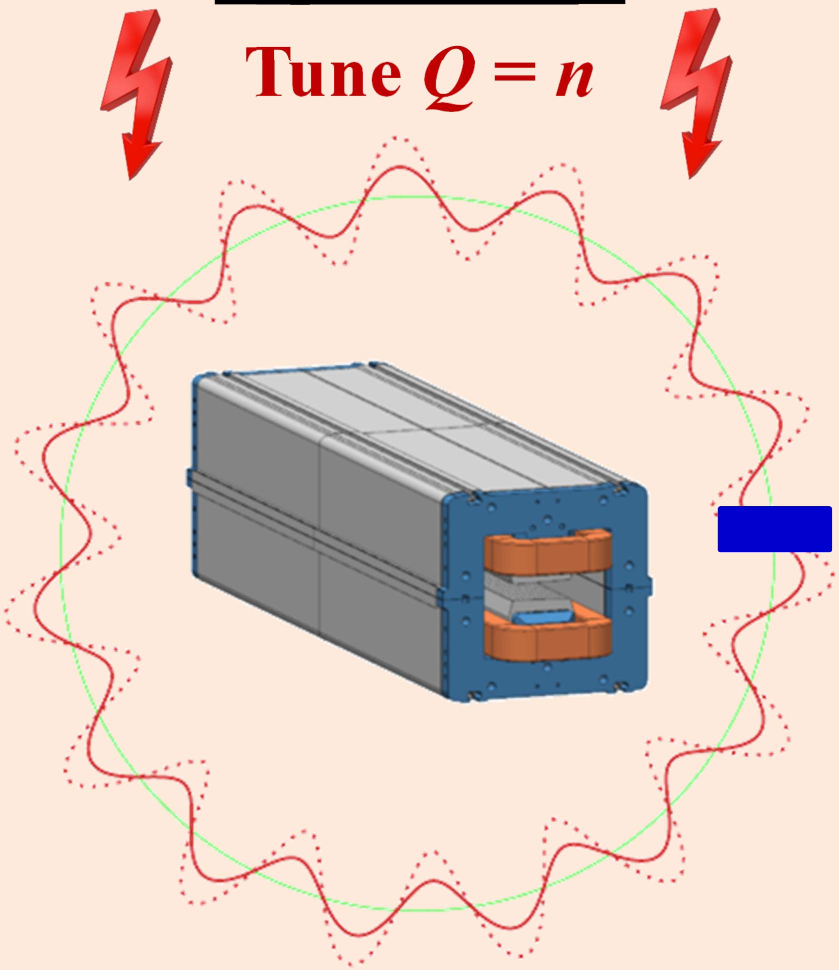
Simplest arrangement: FODO

Optical Resonances

Tune Q = # betatron oscillations per turn

Dipole Error

Tune $Q = n$



Quadrupole Error

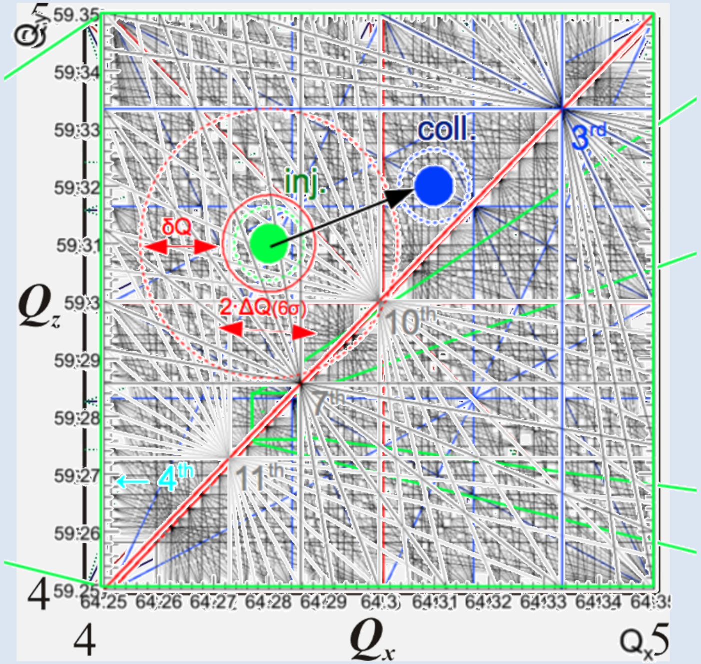
Tune $Q = n/2$

Tune and Optical Resonances:

Optical Resonances:

$$m \cdot Q_x + l \cdot Q_y = n$$

Tune Diagram:



Circular Accelerators:

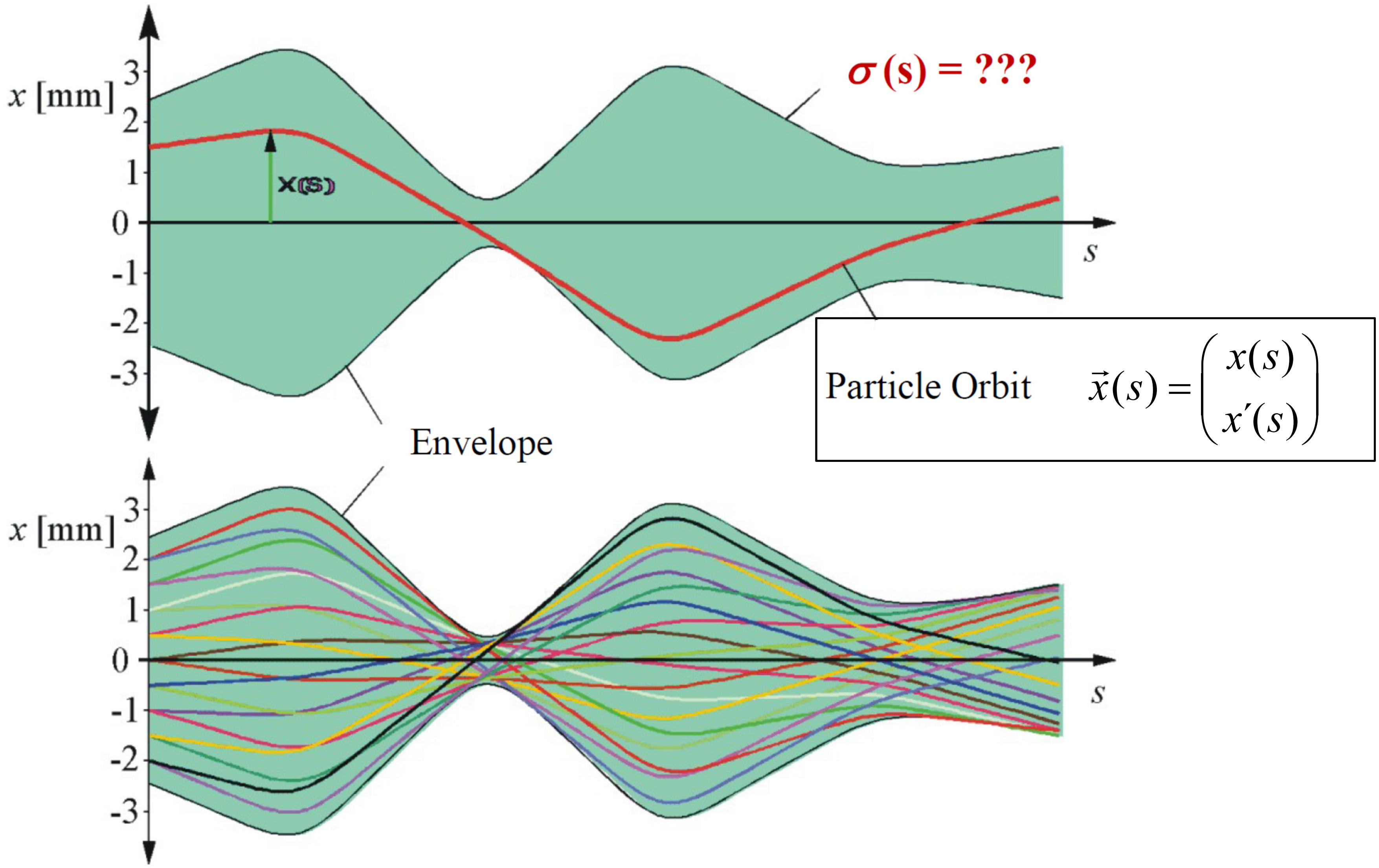
- Beam-Beam Interaction
- Space Charge Forces
- Beam-Wall Interaction
- Capture of Ions / Electrons

Tune Spread!

Intensity Limitation!

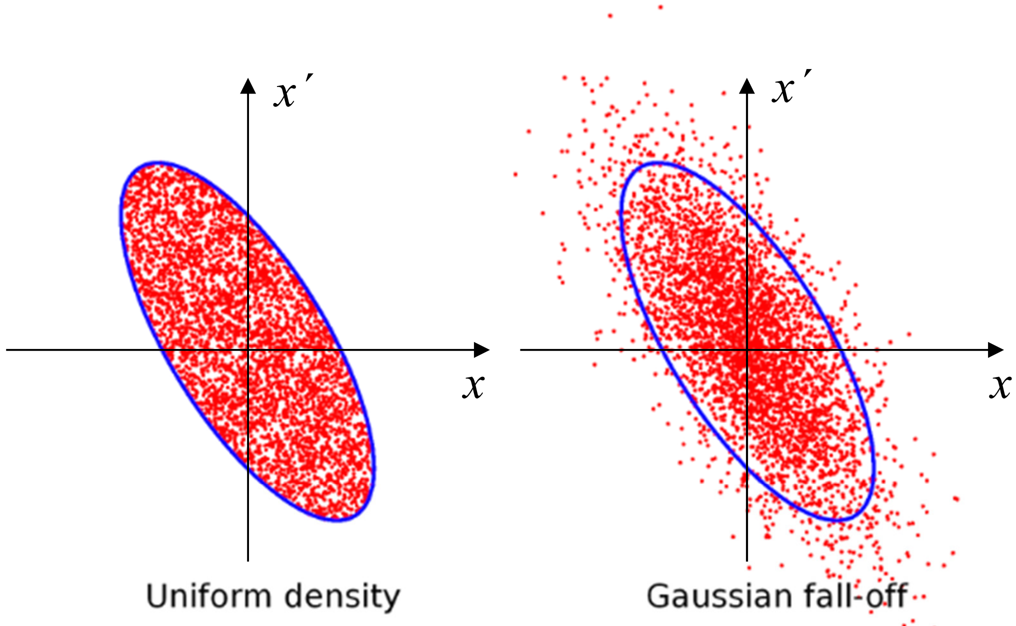
Doesn't affect a Linear Accelerator

Particle Trajectories ↔ Beam



Beam Emittance

Each particle is represented by a point (x, x') in phase space!



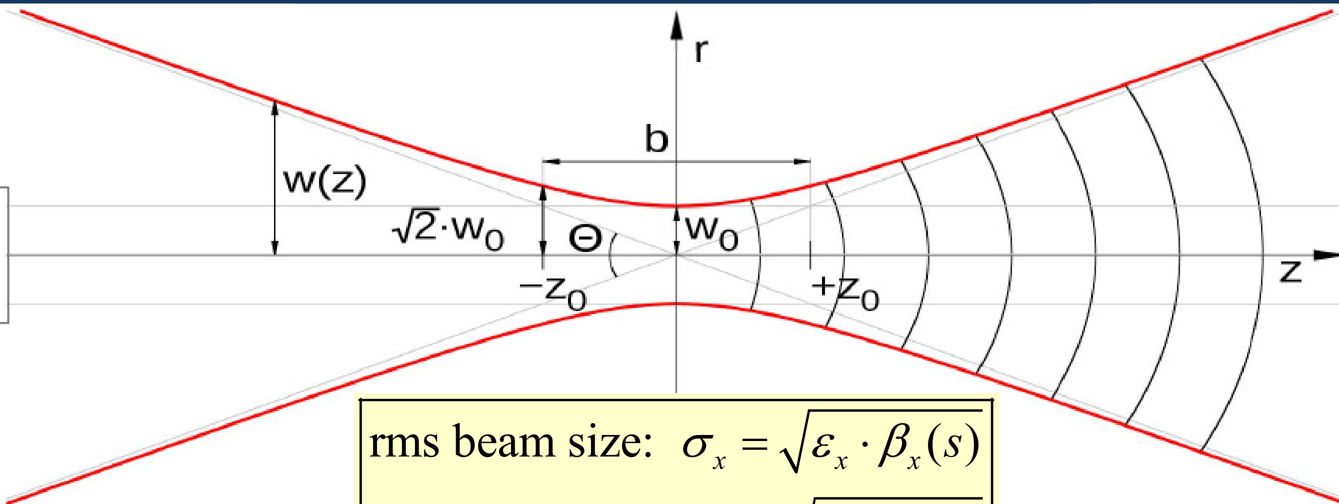
Emittance ε_x = rms area in phase space / π

Liouville: area in phase space remains constant → emittance ε = konst.

Take care: $x' = \frac{\mathrm{d}x}{\mathrm{d}s} = \frac{\mathrm{d}x}{\mathrm{d}t}\frac{\mathrm{d}t}{\mathrm{d}s} = \frac{v_x}{\beta c} = \frac{1}{\beta\gamma}\frac{p_x}{m_0}$ → norm. emittance $\boxed{\varepsilon_n = \beta\gamma\varepsilon = \text{konst.}}$

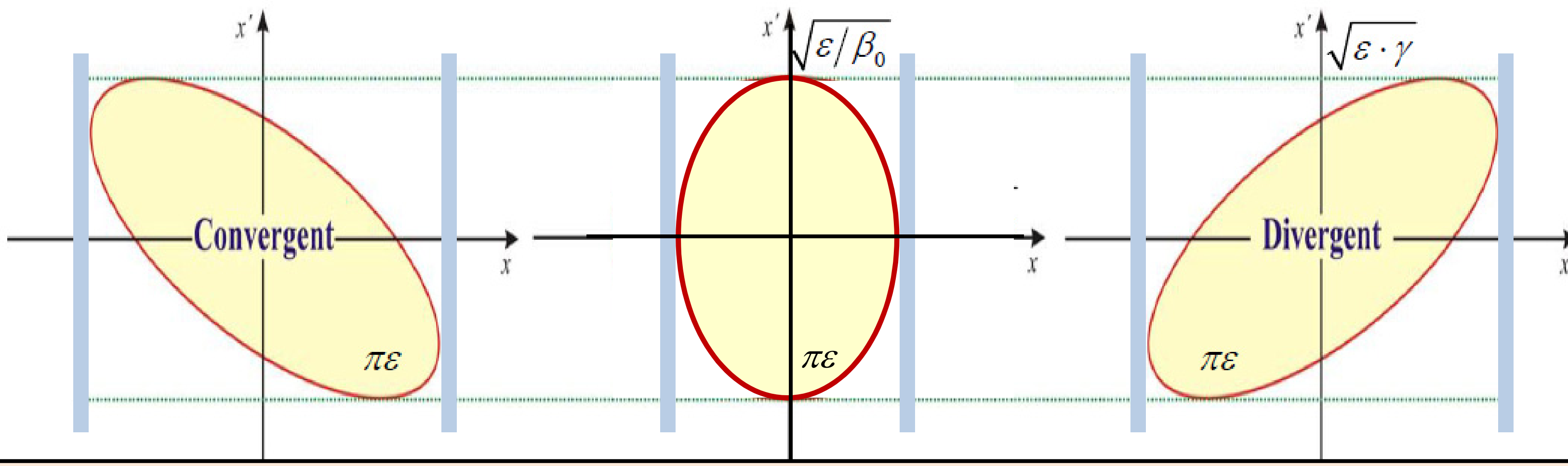
Beam Optics

beam near focal plane



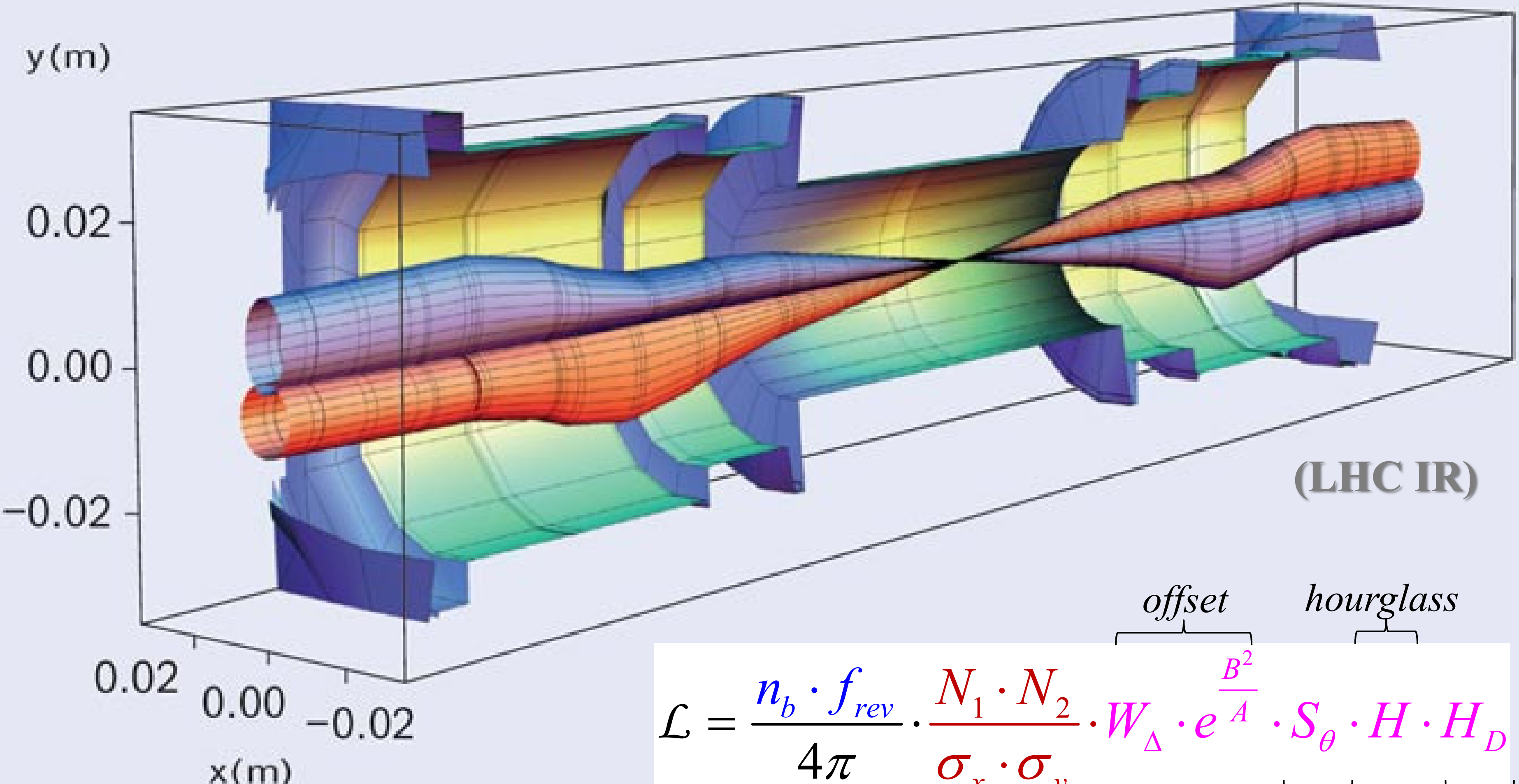
rms beam size: $\sigma_x = \sqrt{\varepsilon_x \cdot \beta_x(s)}$

rms beam div.: $\sigma_{x'} = \sqrt{\varepsilon_x \cdot \gamma_x(s)}$



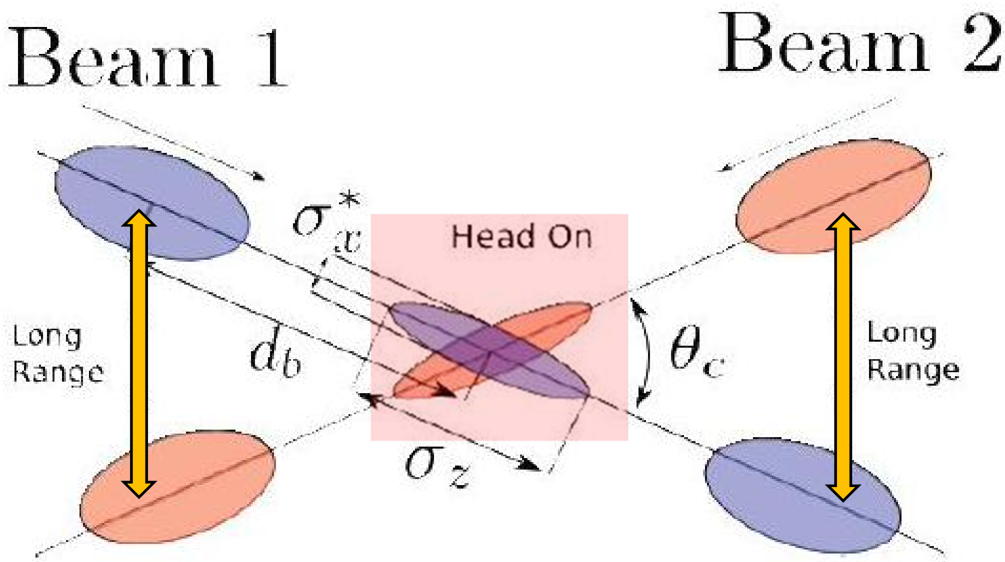
Beam size is determined by emittance ε and (lokal) beta function $\beta(s)$!

Luminosity Optimization



$$\mathcal{L} = \frac{n_b \cdot f_{rev}}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_y} \cdot \overbrace{W_\Delta \cdot e^{\frac{B^2}{A}}}^{offset} \cdot \underbrace{S_\theta}_{\text{crossing angle}} \cdot \overbrace{H}^{hourglass} \cdot \underbrace{H_D}_{\text{disrup-tion}}$$

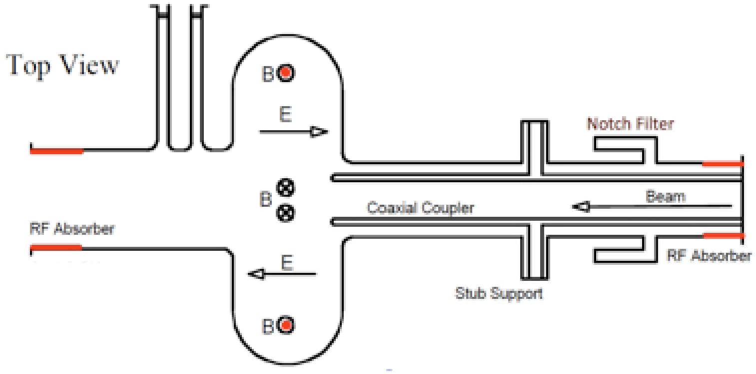
Beam Crossing

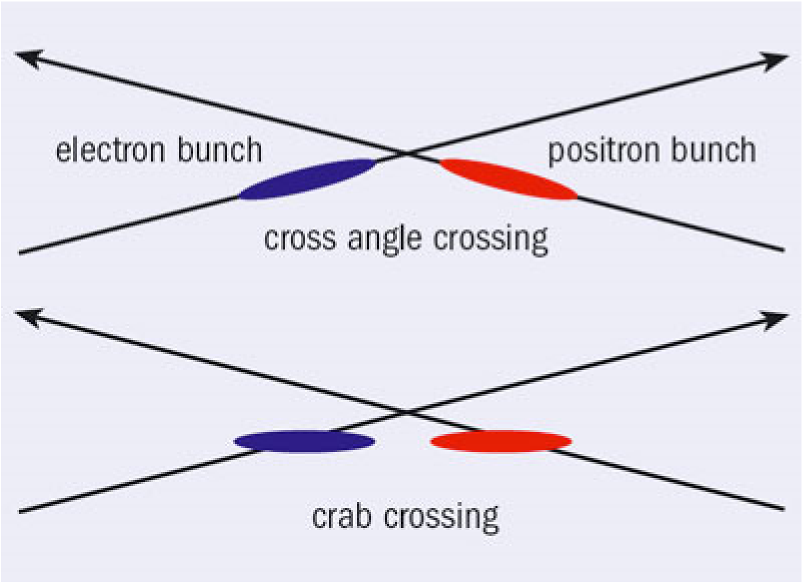


- Sufficient beam separation
- Small crossing angle
- Long bunch separation
- …

$$\mathcal{L} = \frac{n_b \cdot f_{rev}}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_y} \cdot S_\theta$$

One option: **Crab-Cavities:**

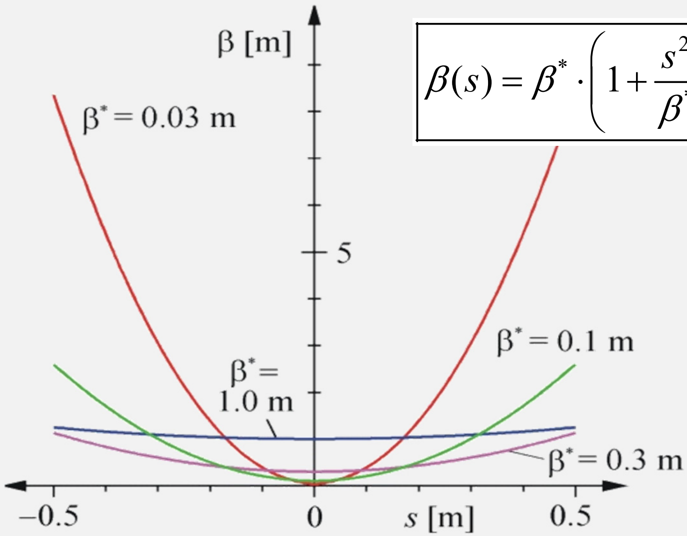




"Beta Squeeze"

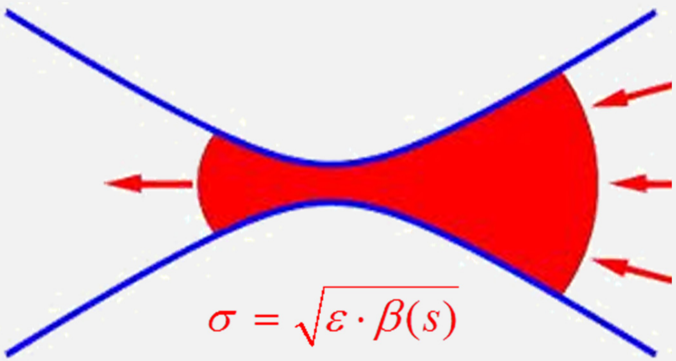
$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y} \cdot \beta_{x,y}}$$

Beam Broadening:



$$\beta(s) = \beta^* \cdot \left(1 + \frac{s^2}{\beta^{*2}}\right)$$

Hourglass Effect:

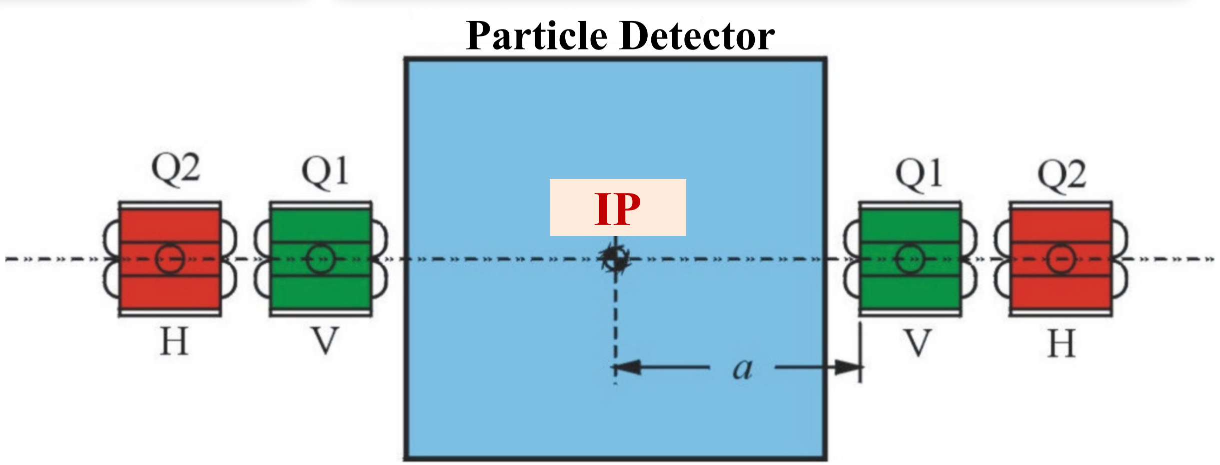


$$\sigma = \sqrt{\varepsilon \cdot \beta(s)}$$

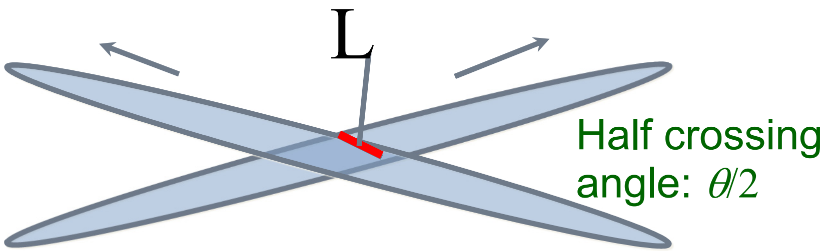
Short Bunches!

$$\sigma_s \approx \beta^*$$

$$\mathcal{L} = \frac{f_{rev} n_b}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_y} \cdot H$$

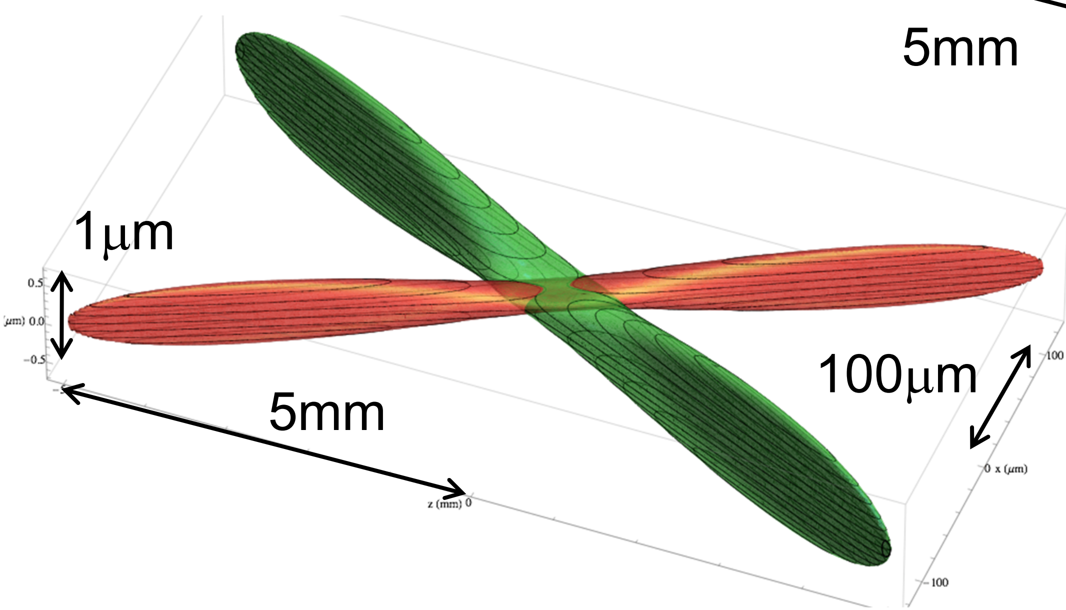


Approach: strong vertical squeeze

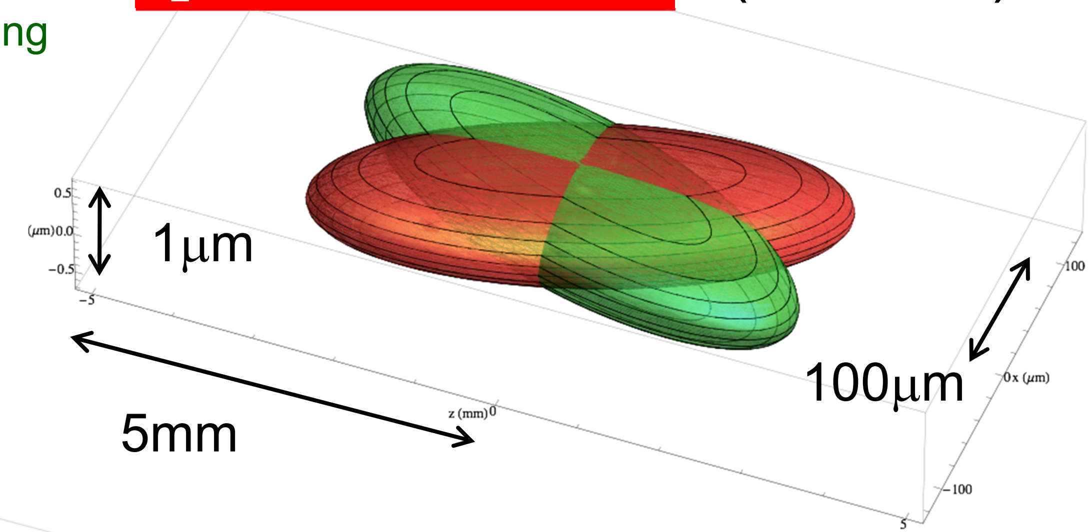


Hourglass condition: $\beta_y^* \geq L = \sigma_x/\theta$

SuperKEKB



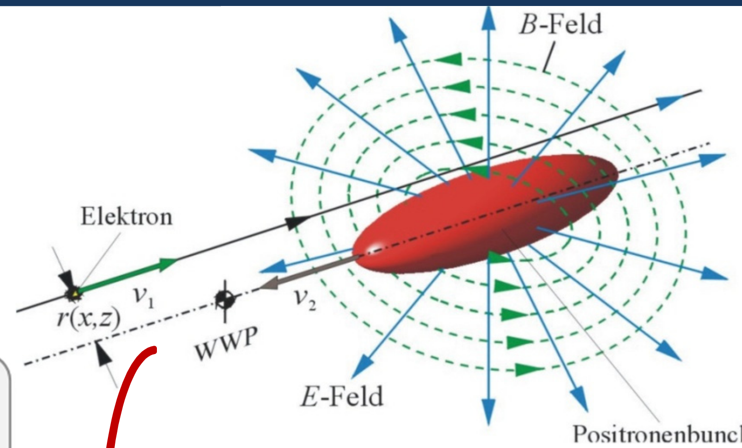
present KEKB (w/o crab)

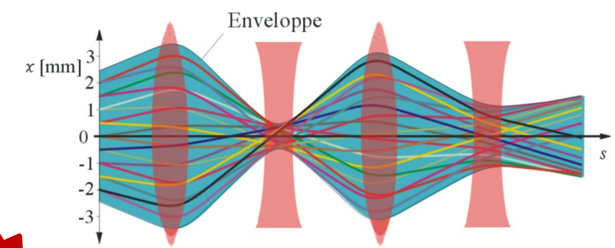


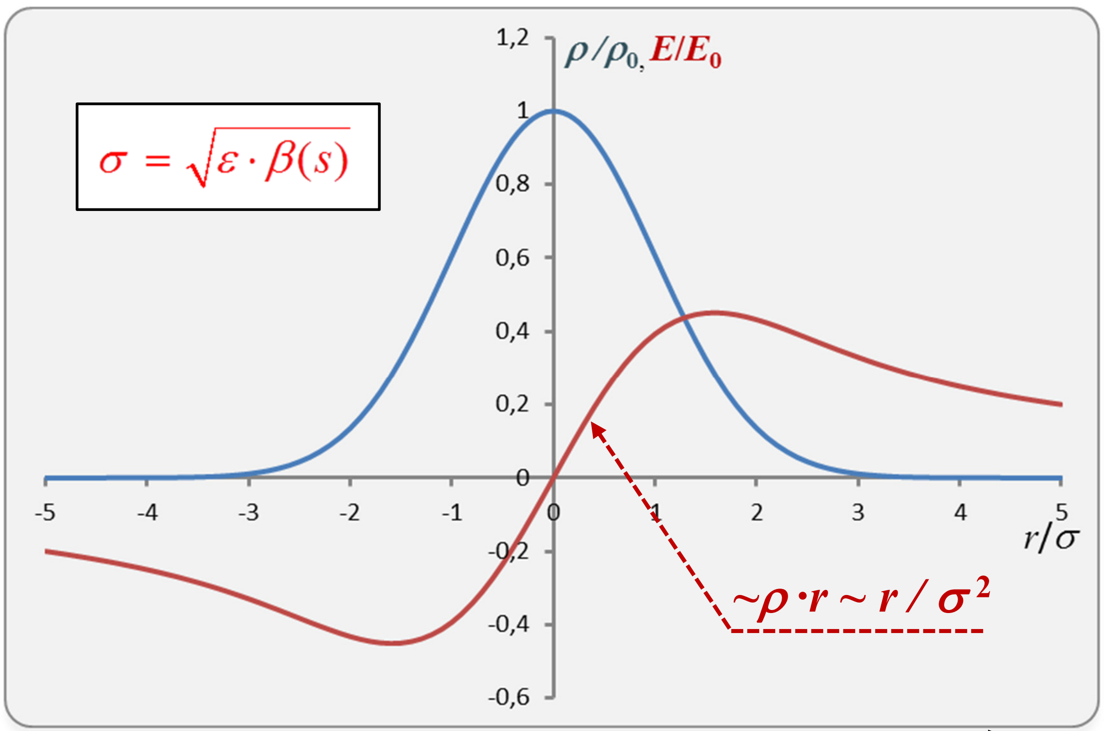
→ ***Nano Beams***

Beam-Beam Effects ↔ $\mathcal{L} = \frac{f_{rev} n_b}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_z} \cdots$

Additional Focusing or Defocusing in the Interaction Region







Sets limit on emittance in head-on collisions!

Beam-Beam Parameters:

$$\xi_{x,y} = \frac{r_e N}{2\pi\gamma_r} \frac{\beta^*_{x,y}}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)}$$

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}}$$

Storage Rings

Important Relations:

a) **Luminosity**

$$\mathcal{L} = \frac{n_b \cdot f_{rev}}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_y} \cdot S_\theta \cdot H$$

b) **Beam-Beam Parameters**

$$\xi_{x,y} = \frac{r_e N}{2\pi\gamma_r} \frac{\beta^*_{x,y}}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)}$$

→ **Rewrite Luminosity Formula ($\xi_y > \xi_x$)**

$$\mathcal{L} = \frac{\gamma_r}{2er_e} \cdot \left(1 + \frac{\sigma^*_y}{\sigma^*_x}\right) \cdot \frac{I_{beam} \cdot \xi_y}{\beta^*_y} \cdot S_\theta \cdot H$$

Lorentz factor

Beam current

Beam-beam parameter

Aspect ratio at IP

Vertical beta function at IP

Hourglass effect: $\beta^*_y \geq \sigma_x / \theta$

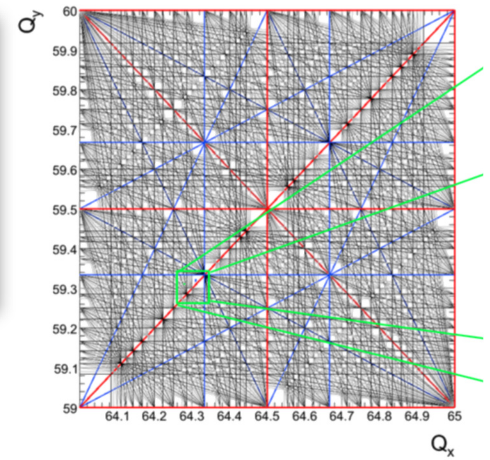
(small ε_x)

Beam-Beam Parameters

$$\xi_{x,y} = \frac{r_e N}{2\pi\gamma_r} \frac{\beta^*_{x,y}}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)}, \qquad \sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}}$$

Circular Colliders: $\xi_{x,y} < 0.05$ typ.

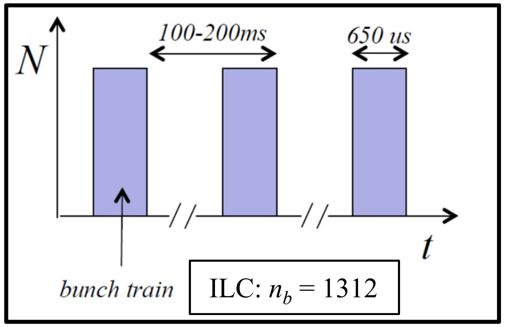
Linear Colliders: $\xi_x = 0.54,\ \xi_y = 1.44$ (ILC)



$$\mathcal{L} = \frac{\gamma_r}{2er_e} \cdot \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \cdot \frac{I_{beam} \cdot \xi_y}{\beta_y^*} \cdot S_\theta \cdot H$$

But:

Time structure of linear / circular colliders are different:



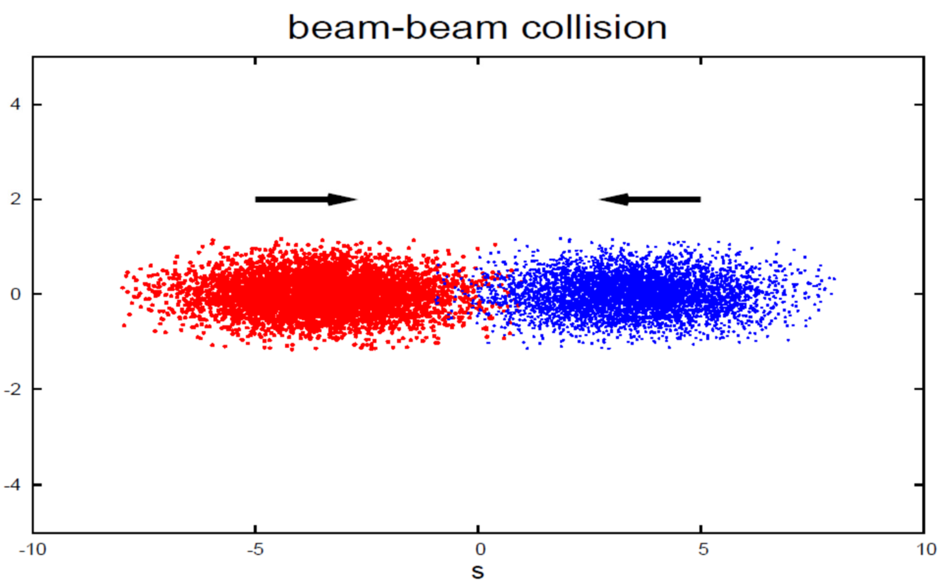
Comparison FCC-ee (@Higgs) ↔ ILC:

- SR: $I_{beam} = f_{rev} n_b q N = 3000 \cdot 393 \cdot q \cdot 1.5 \cdot 10^{11} = 29\,\text{mA}$
- LC: $I_{beam} = f_{rep} n_b q N = 5 \cdot 1312 \cdot q \cdot 1 \cdot 10^{10} = 11\,\mu\text{A}$

Linear Colliders

$\xi_y > 1$:

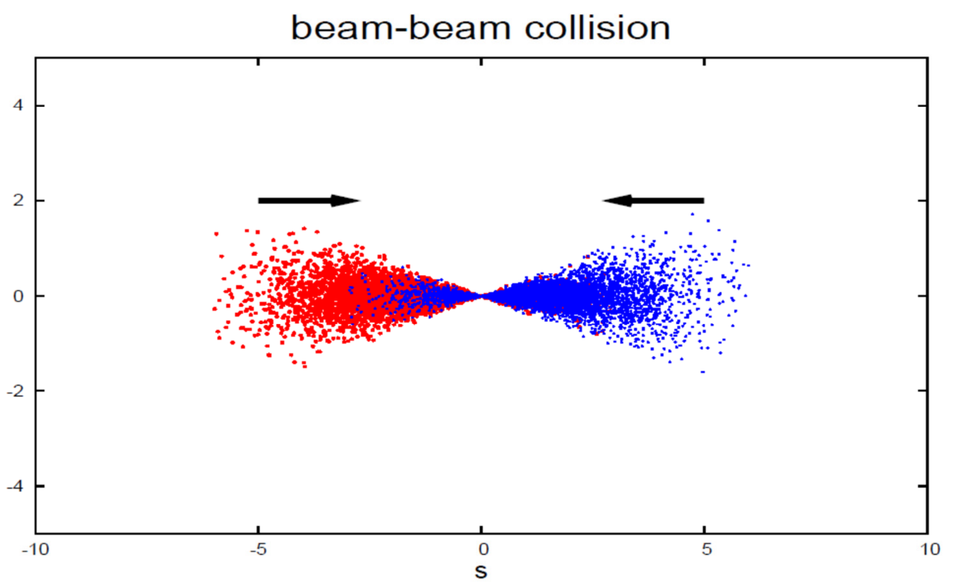
Pinch effect - disruption



Linear Colliders

$\xi_y > 1$:

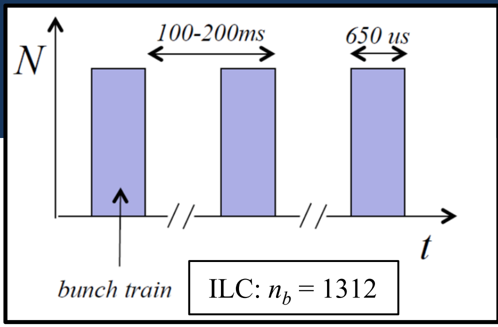
Pinch effect - disruption

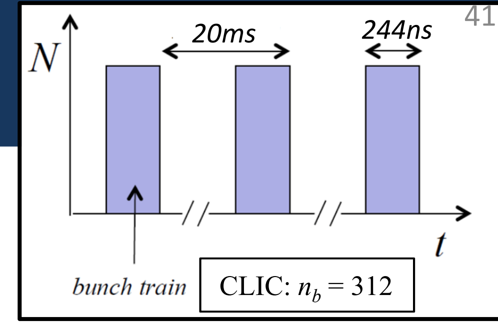


- Additional focusing by opposing beams

Enhancement Factor H_D

Linear Collider





Important Relations:

a) **Luminosity**

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

b) **RF to beam power efficiency**

$$P_{beams} = f_{rep} n_b N \cdot E_{cm} = \eta_{RF} \cdot P_{RF}$$

→ **Rewrite Luminosity Formula**

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

Beam-beam effects:

- beamstrahlung
- disruption

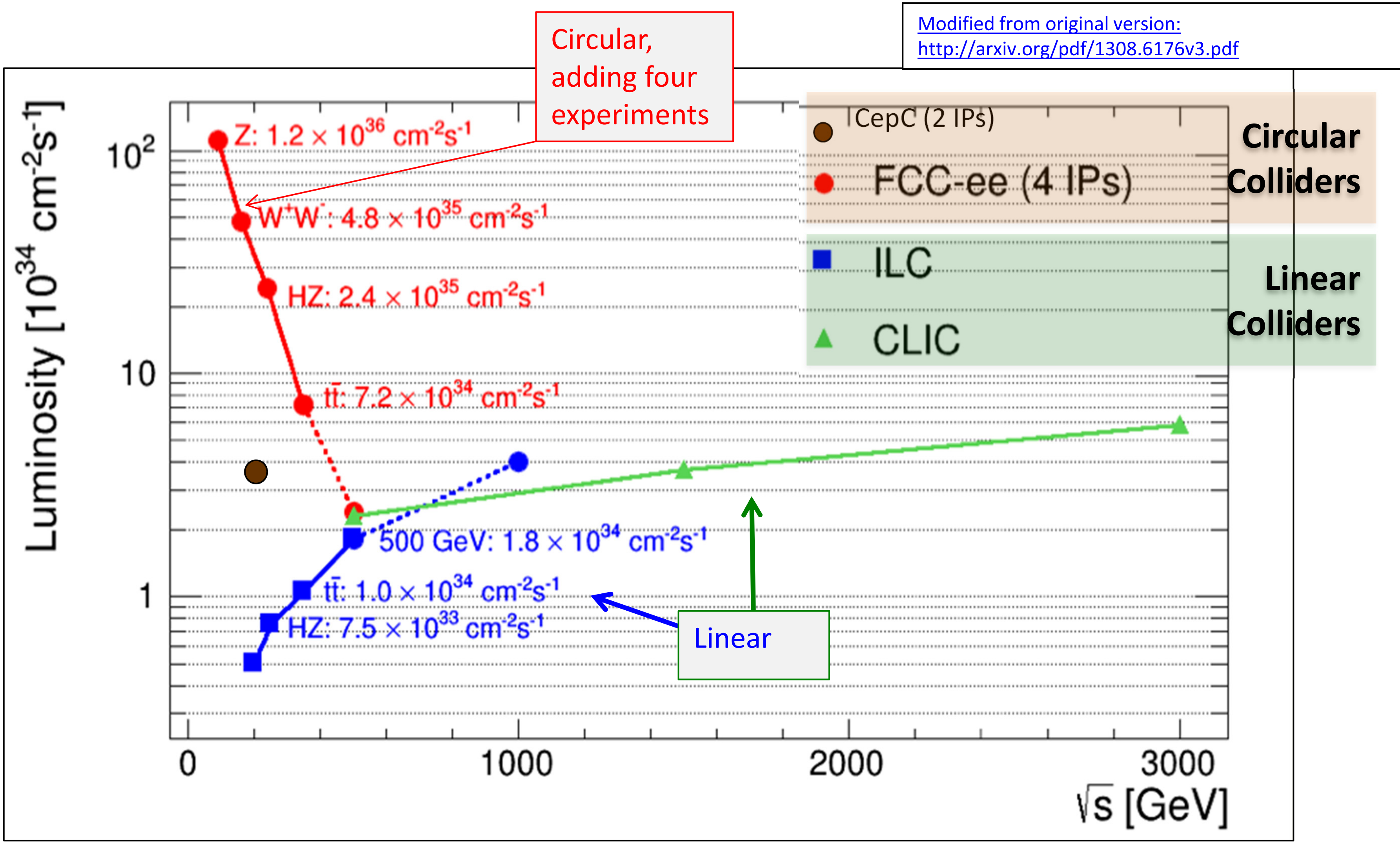
Choice of linac technology:

- efficiency
- available power

Strong final focus:

- Optical aberrations
- Stability issues and tolerances

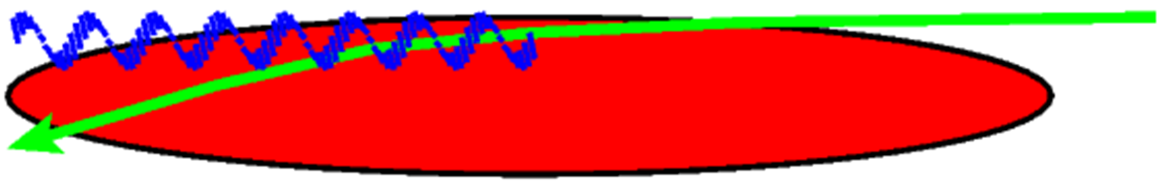
Circular vs. Linear Collider



F. Gianotti

Beamstrahlung

Particles are deflected in magnetic field of colliding bunch:



Peak field: $B_{max} = \frac{2E_{\perp,max}}{c} = \frac{eN}{2\pi\varepsilon_0 c\sigma_x\sigma_s}$ = up to 1000 Tesla!

Classical treatment of synchrotron radiation: $\Delta E \sim \frac{\gamma^4}{R^2} \sim \gamma^2 B^2$

- **particles with high energy loss will be lost**
- **short beam life time**

} Storage rings

- **impact on luminosity and actual collision energy**

Beamstrahlung $\rightarrow \mathcal{L}$

RMS energy loss for weak beamstrahlung:

$$\delta_{BS} \approx 0.86 \frac{e r_e^3}{2 m_0 c^2} \cdot \frac{E_{cm}}{\sigma_s} \cdot \frac{N^2}{\left(\sigma_x + \sigma_y\right)^2} \propto \frac{E_{cm}}{\sigma_s} \cdot \frac{N^2}{\sigma_x^2}$$

- **use flat beams ($\sigma_x >> \sigma_y$) but keep $\sigma_x + \sigma_y$ large to reduce δ_{BS}**

a) **Luminosity**

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

b) **Vertical rms beam size**

$$\sigma_y = \sqrt{\frac{\varepsilon_{n,y} \beta_y}{\gamma_r}}$$

$\rightarrow$ Again Rewrite Luminosity Formula ($\delta_{BS} \approx$ few %)

$$\mathcal{L} \propto \frac{\eta_{RF} P_{RF}}{4\pi E_{cm}} \cdot \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} \cdot \underbrace{\sqrt{\frac{\sigma_s}{\beta_y}} \cdot H}_{\text{hourglass: } \beta_y \approx \sigma_s} \cdot H_D \propto \frac{\eta_{RF} P_{RF}}{4\pi E_{cm}} \cdot \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} \cdot H_D$$

damping rings!

Luminosity: Beamstrahlung Limit

$$\mathcal{L} \propto \frac{\rho P_{SR}}{E^{13/3}} \left(\frac{\xi_y \eta^2}{\varepsilon_{g,y}} \right)^{1/3}$$

Circular ↔ Linear

$$\mathcal{L} \propto \frac{\eta_{RF} P_{RF}}{4\pi E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D$$

P_{SR} : syn.rad.power

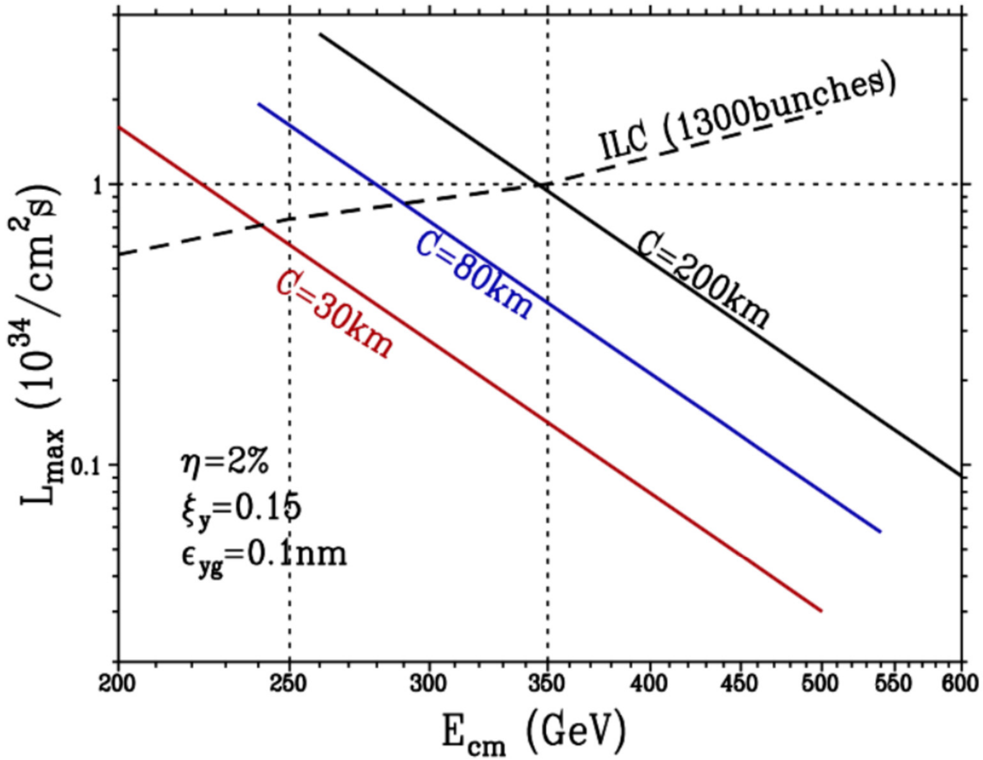
ρ : bending radius

ξ_y : tune-shift

$\varepsilon_{g,y}$: geometric emit.

?????

example with
- η=2%
- ξ_y=0.15
- ε_{gy}=0.1nm



K. Yokoya, KEK

Beam Emittance

a) Adiabatic Damping

$$\varepsilon = \frac{1}{\beta\gamma}\varepsilon_n \overset{E_{kin}=250\,\mathrm{GeV}}{=} 2\cdot 10^{-6}\,\varepsilon_n$$

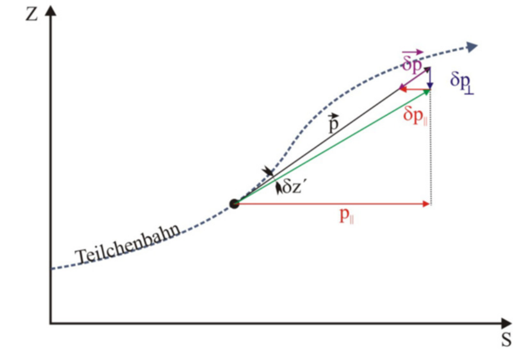
in particular not sufficient for positrons!

b) Radiative Damping
equilibrium emittance in storage rings
only dependent on the magnetic lattice
→ low emittance lattice (suppress dispersion)

Damping rings required for Linear Collider!

e^+ - e^- in Storage Rings

Equilibrium Emittance ↔ "Radiation" Damping

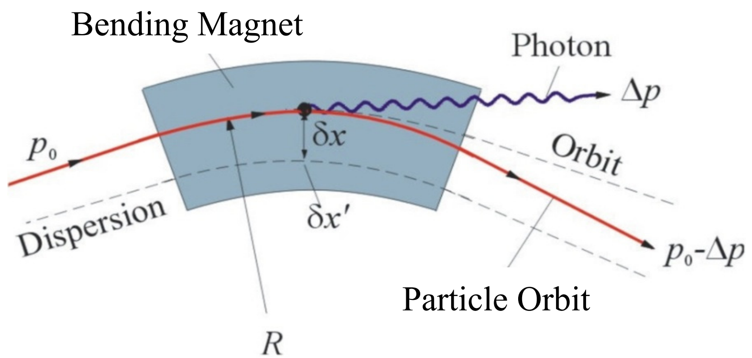


2 Effects!

Cooling:

- photon emission → recoil (long. and transverse)
- acceleration restores long. momentum

→ **Net reduction of transv. momentum: damping!**



Heating:

- photon emission in dispersive sections
- shift of ideal dispersion orbit by δx, $\delta x'$

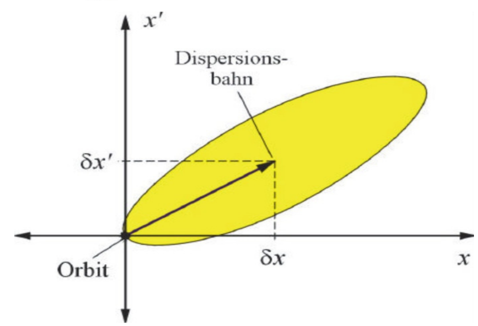
→ **Excitation of betatron oscillations: heating!**

Equilibrium Emittance:

- Cooling = Heating

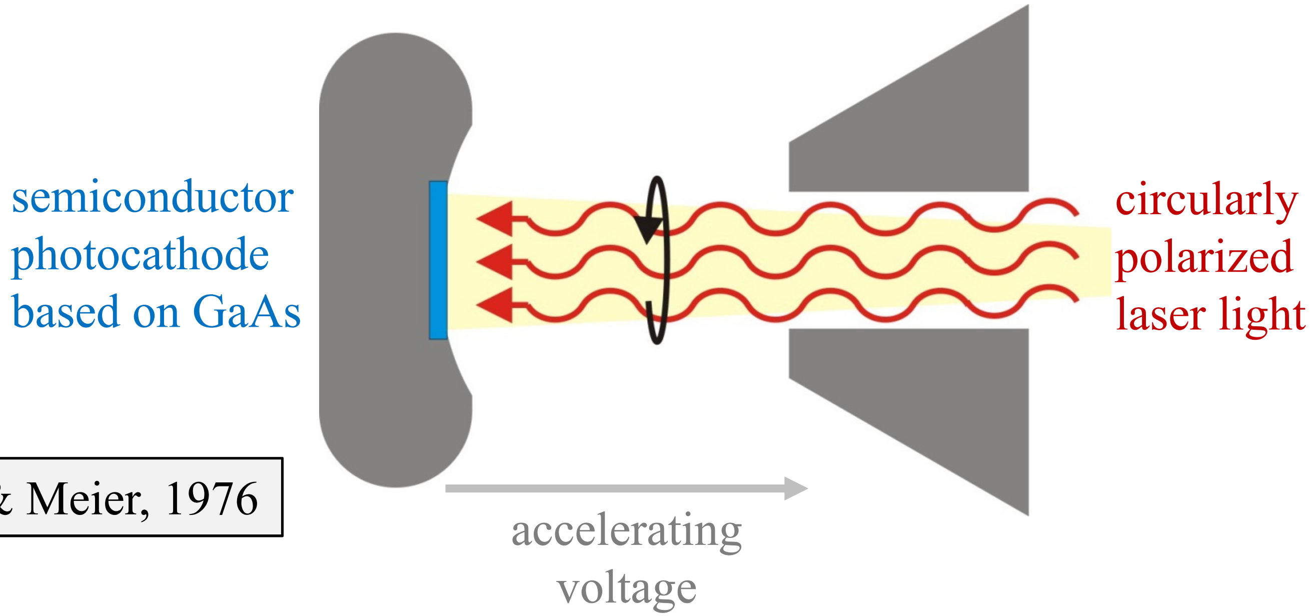
Dispersion!

$$\varepsilon_x = \frac{55}{32\sqrt{3}} \cdot \frac{\hbar c \gamma^2}{J_x m_0 c^2} \cdot \frac{\left\langle \frac{1}{R^3} \cdot \mathcal{H}(s) \right\rangle}{\left\langle \frac{1}{R^2} \right\rangle}$$



Polarized Electrons

Functional Principle:



Achieved at:

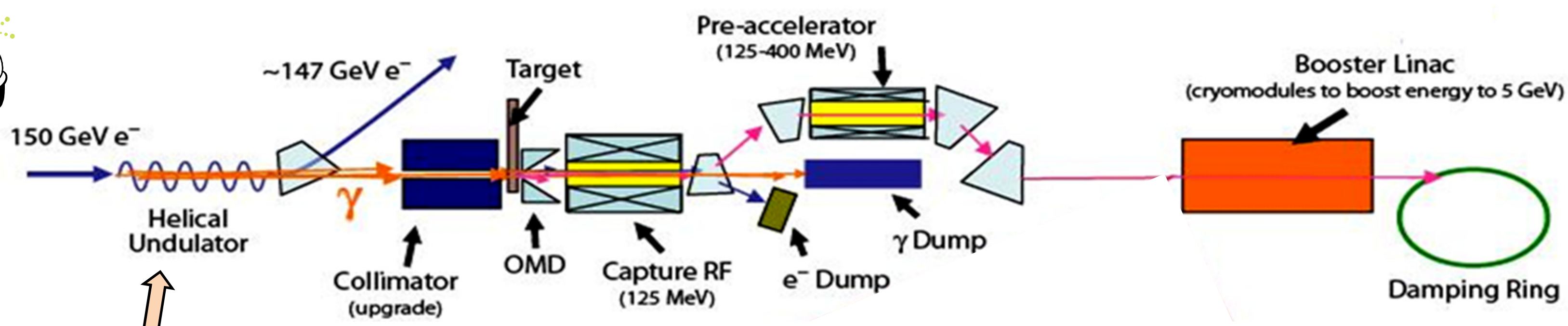
- SLAC
- MIT Bates
- AmPs
- **CEBAF**
- **Bonn**
- **Mainz**
- **Darmstadt**

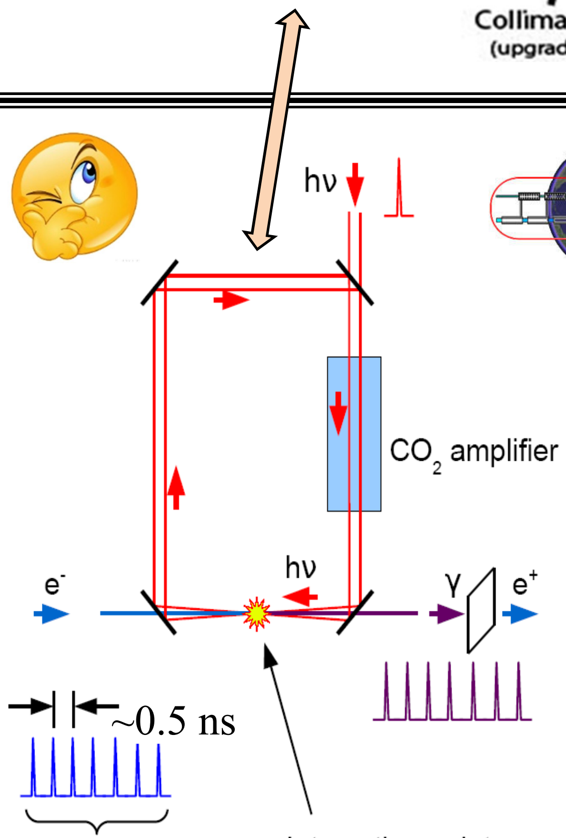
Pierce & Meier, 1976

Photoelectron emission from GaAs

polarization transfer from laser photons to emitted electrons

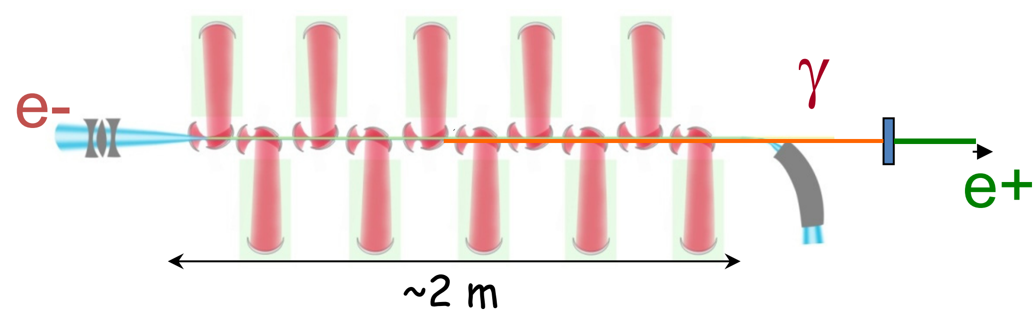
ILC Positron Source Layout





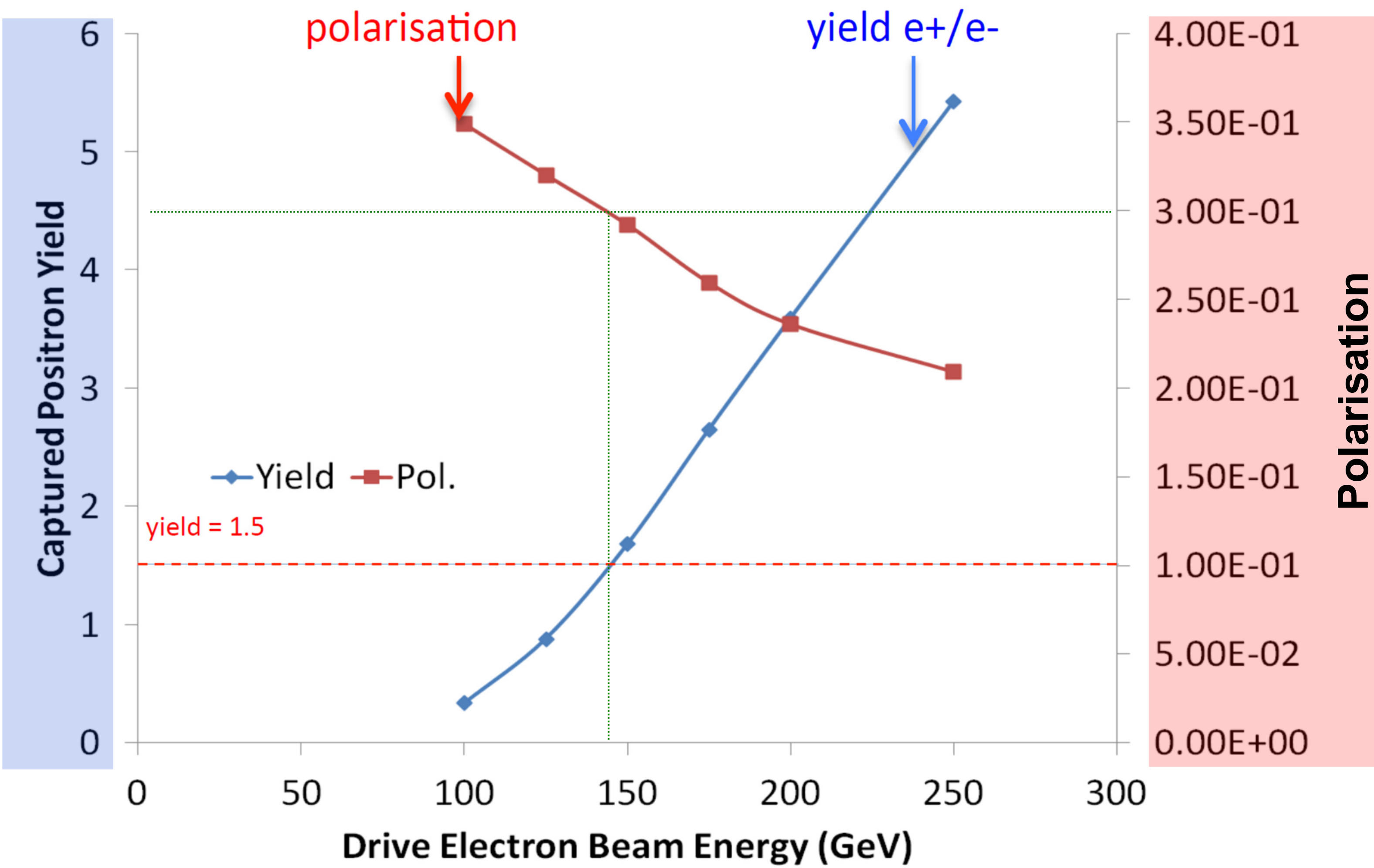
CLIC Compton Linac

- Compton backscattering inside a CO_2 laser amplifier cavity
- Production of 1 photon per electron (demonstrated at BNL)

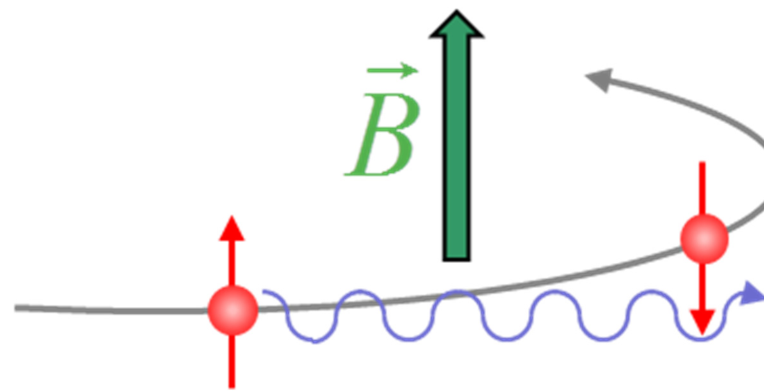


- 10 consecutive Compton IPs to accumulate γ flux

Polarized Positrons @ ILC



Self Polarization in Storage Rings

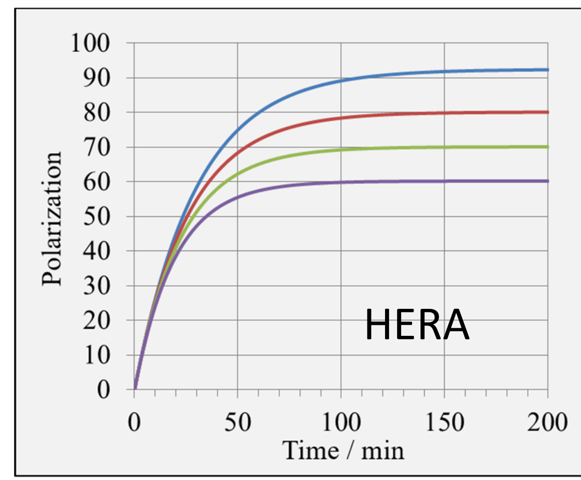


Transition Rates :

- no spin flip: $w_{\uparrow\uparrow}$, $w_{\downarrow\downarrow}$
- with spin flip: $w_{\uparrow\downarrow}$, $w_{\downarrow\uparrow}$

Probability of a spin-flip transition:

$$\frac{w_{\uparrow\downarrow}+w_{\downarrow\uparrow}}{\left(w_{\uparrow\uparrow}+w_{\downarrow\downarrow}\right)+\left(w_{\uparrow\downarrow}+w_{\downarrow\uparrow}\right)}=\frac{1}{3}\cdot\left(\frac{\hbar\omega_c}{E}\right)^2<10^{-10}$$ = very small, but:



The beam will get polarized in a while due to $w_{\uparrow\downarrow} > w_{\downarrow\uparrow}$!

Sokolov-Ternov-Effect: $P(t)=P_{ST}\left(1-e^{-t/\tau_P}\right)$

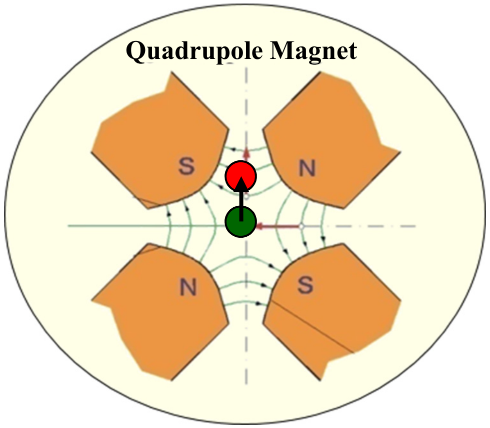
P_{ST}: 92.4%

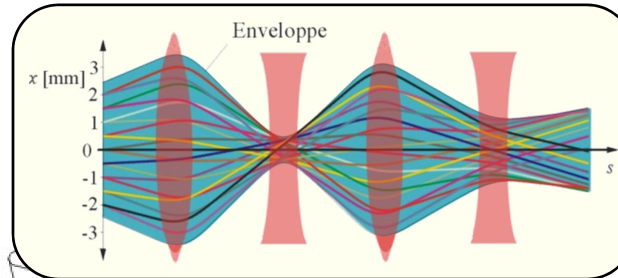
Rise time: $\tau_P=\left(\frac{8}{5\sqrt{3}}\frac{c\lambda_c r_e}{2\pi}\frac{\gamma^5}{R^3}\right)^{-1}$

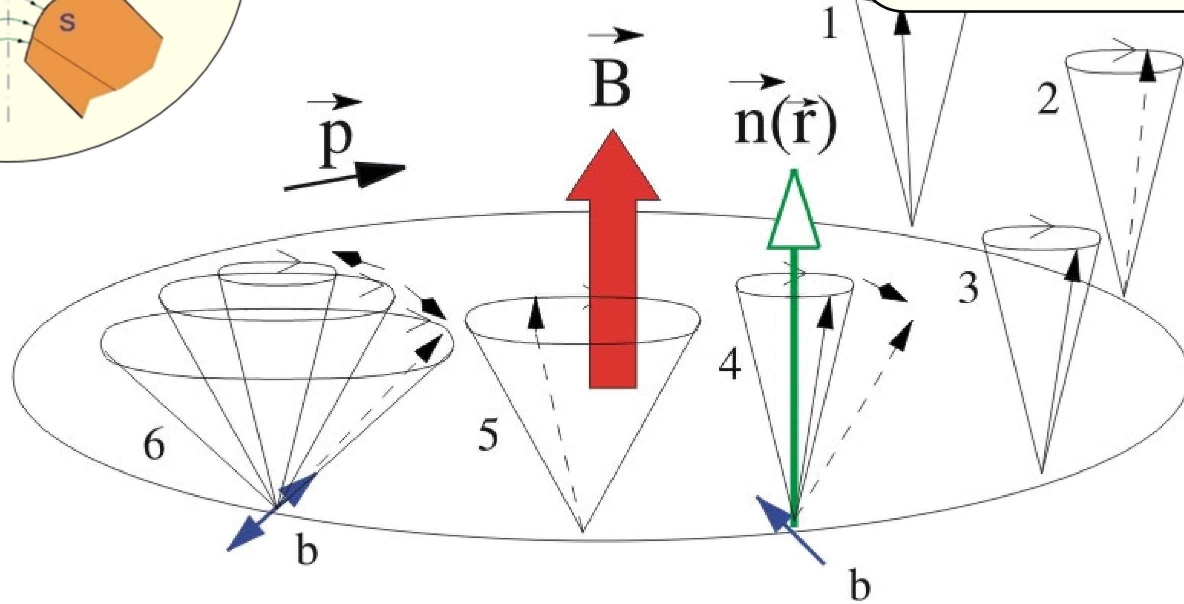
Depolarizing effects: $P_\infty=P_{ST}\frac{\tau_{depol}}{\tau_P+\tau_{depol}}$ and $\frac{1}{\tau}=\frac{1}{\tau_P}+\frac{1}{\tau_{depol}}$

But not @ > 100GeV!

Depolarizing Resonances







Imperfection Resonance: $\gamma \cdot a = n, \quad n \in Z$

Intrinsic Resonance: $\gamma \cdot a = n \cdot P \pm Q_z, \quad n \in Z$

Circular ↔ Linear Collider

Can both achieve $\mathcal{L} > 10^{34}$ cm^{-2}

Circular Collider

Beam Emittance:

Radiative Equilibrium!
→ low emittance lattice
("well-known" from SR sources)

Beam Polarization:

Self polarization ("moderate" E_{beam})
reduced by depol. resonances
not enough for HEP requirements
but
can help to precisely determine E_{beam}

works up to ~ 350 GeV

Linear Collider

Beam Emittance:

Adiabatic Damping!
not sufficient to reduce initial values
→ additional damping rings required

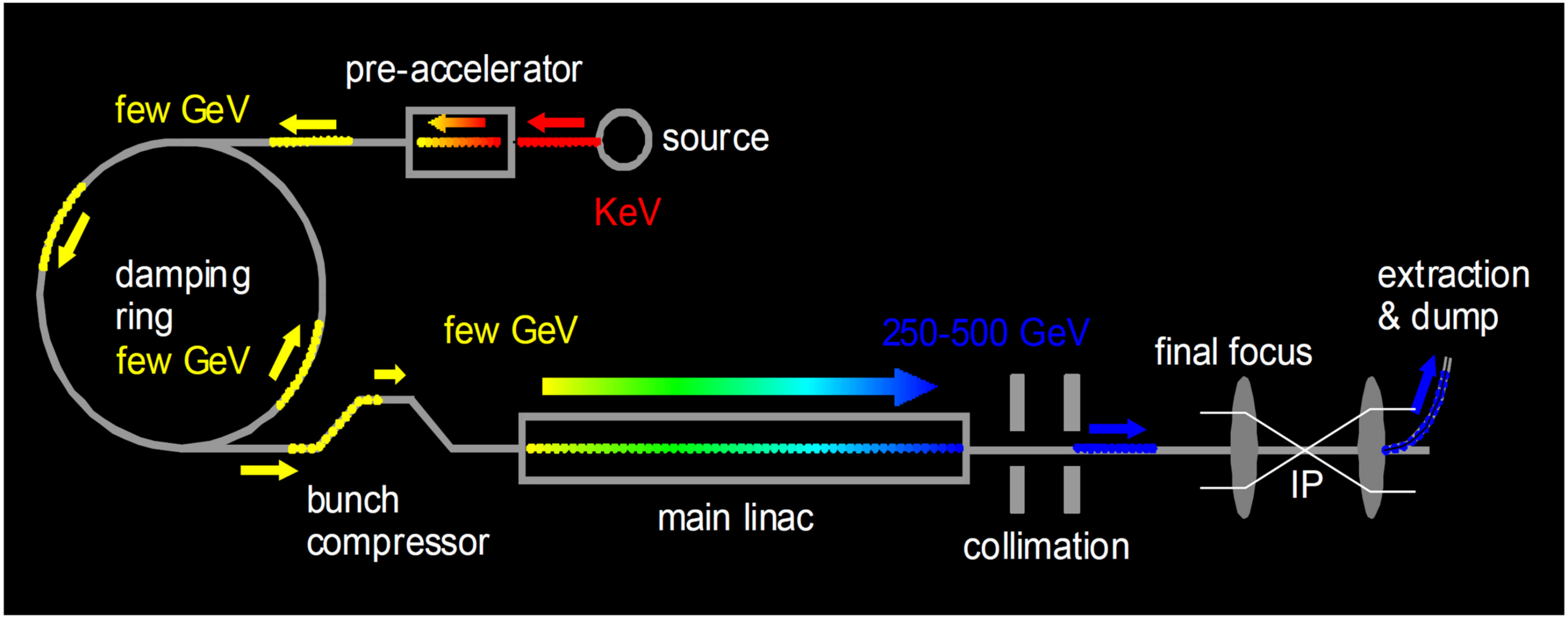
Beam Polarization:

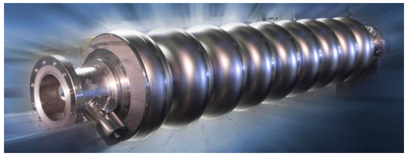
Acceleration of polarized beams
electrons: photoemission from GaAs
positrons: from pol. MeV-photons
aiming at:
$P(e^-) = 80\%$, $P(e^+) = 30\%$

works up to ~ 1 (3) TeV

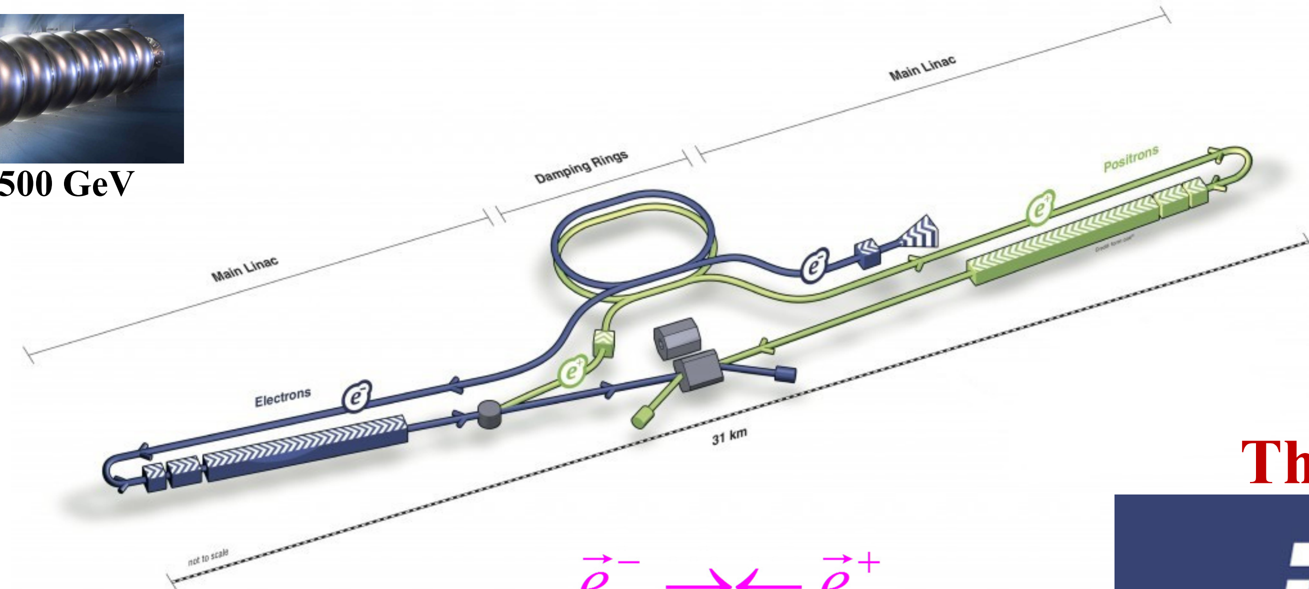
Linear Colliders

The 'Generic' Linear Collider (1/2)



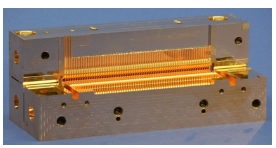


Layout at 500 GeV

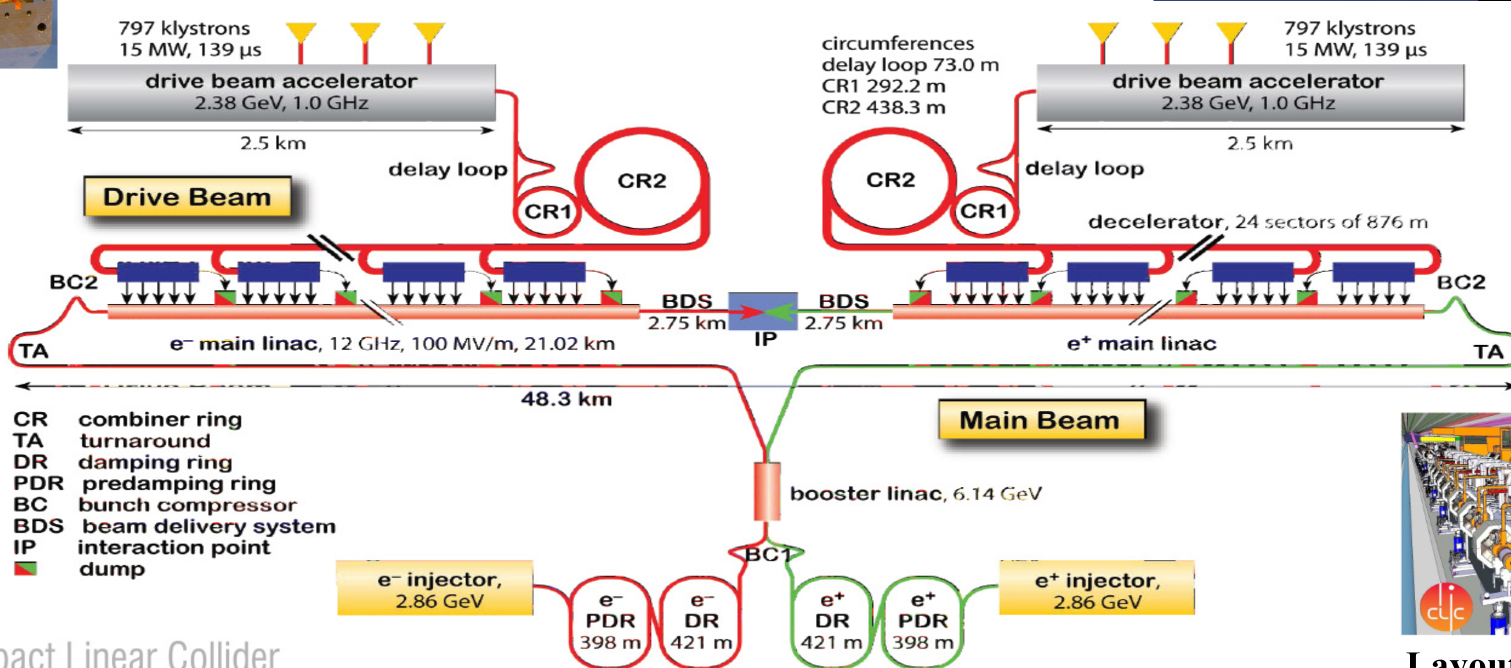


$\vec{e}^{\,-} \rightarrow\leftarrow \vec{e}^{\,+}$

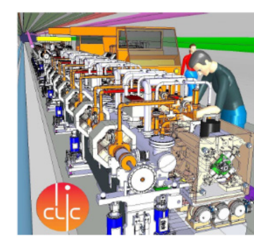
The "*Rivals*":



was "almost" dead – but not completely …

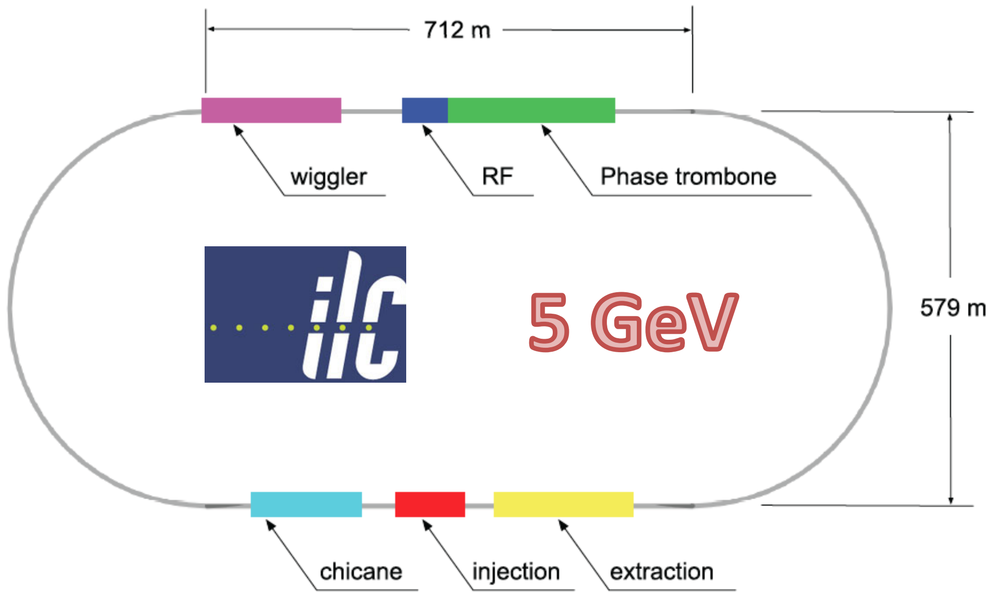


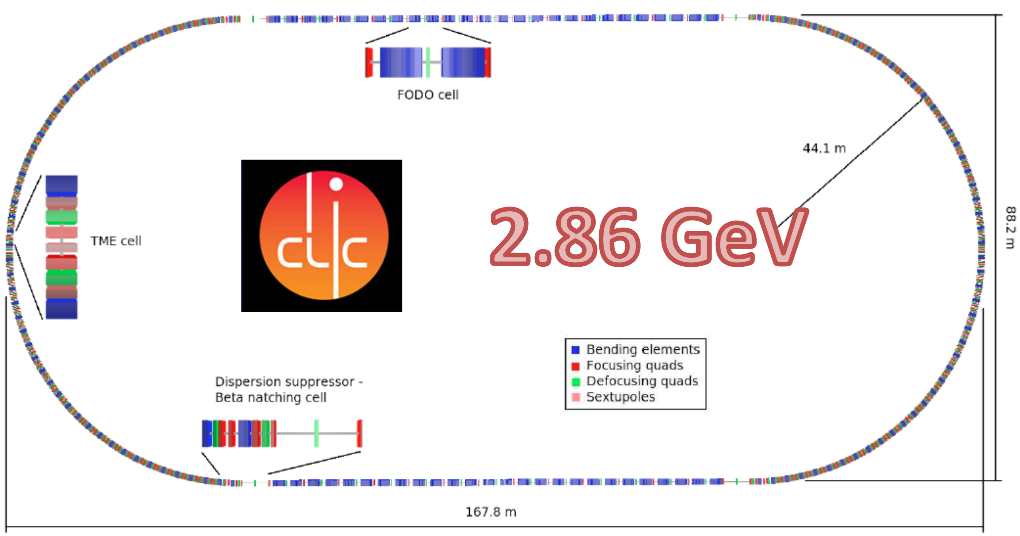
Compact Linear Collider



Layout at 3 TeV

Damping Rings



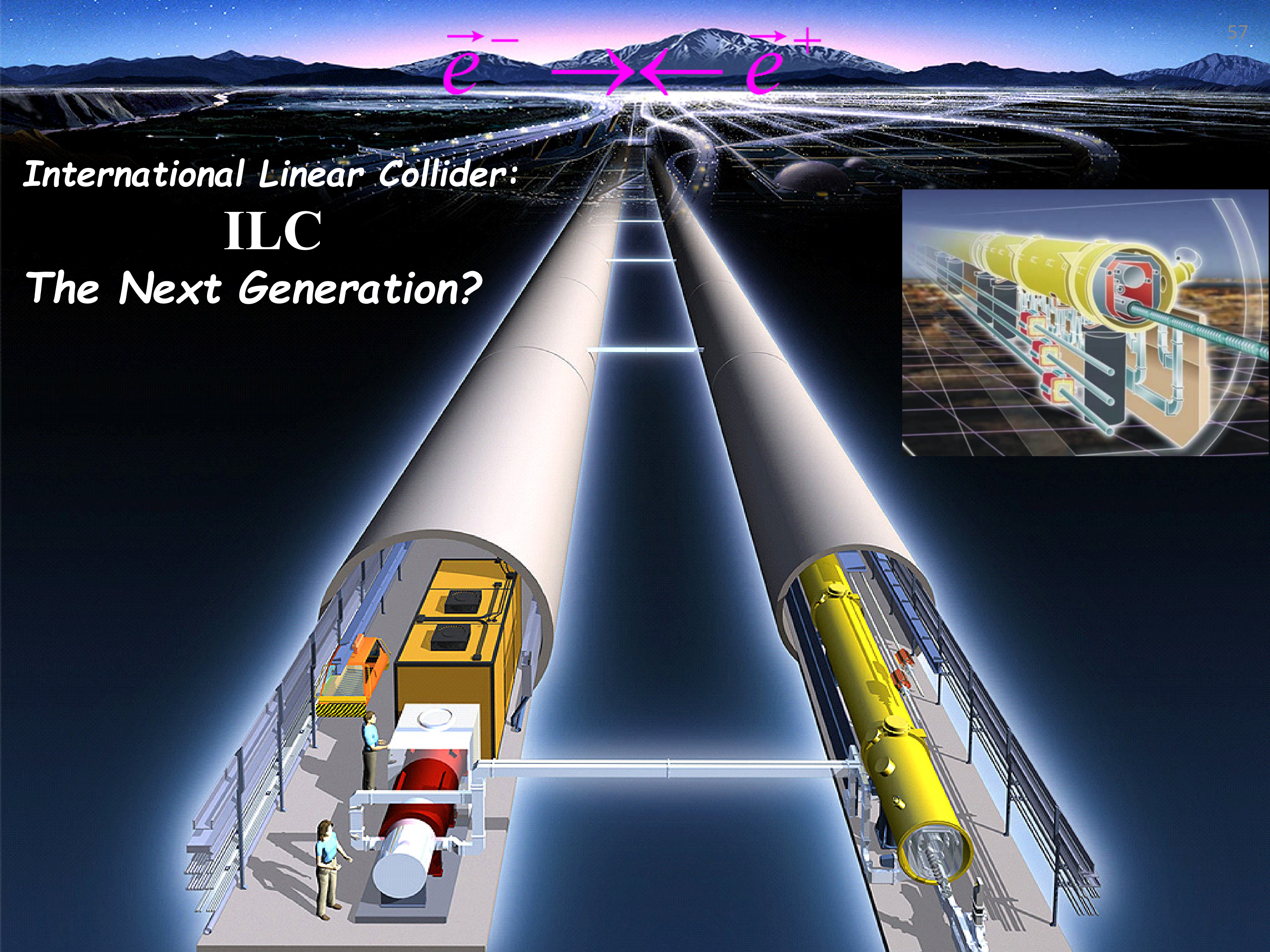


Parameters	CLIC	ILC
Particles per bunch	4×10^{9}	2×10^{10}
Machine repetition rate [Hz]	50	5
Linac RF pulse length [μs]	0.156	1600
Bunch spacing in linac/DR [ns]	0.5/1	554/6
Particles per machine pulse	1.3×10^{12}	5.3×10^{13}
Injected normalized emittance (e^{+}) [μm.rad]	7000	8
Injected rms energy spread [%]	±4.5	±0.75
H/V Extracted normalized emittances [nm]	500/5	5000/20
Extracted rms bunch length [mm]	1.8	6
Extracted rms energy spread [%]	0.1	0.15

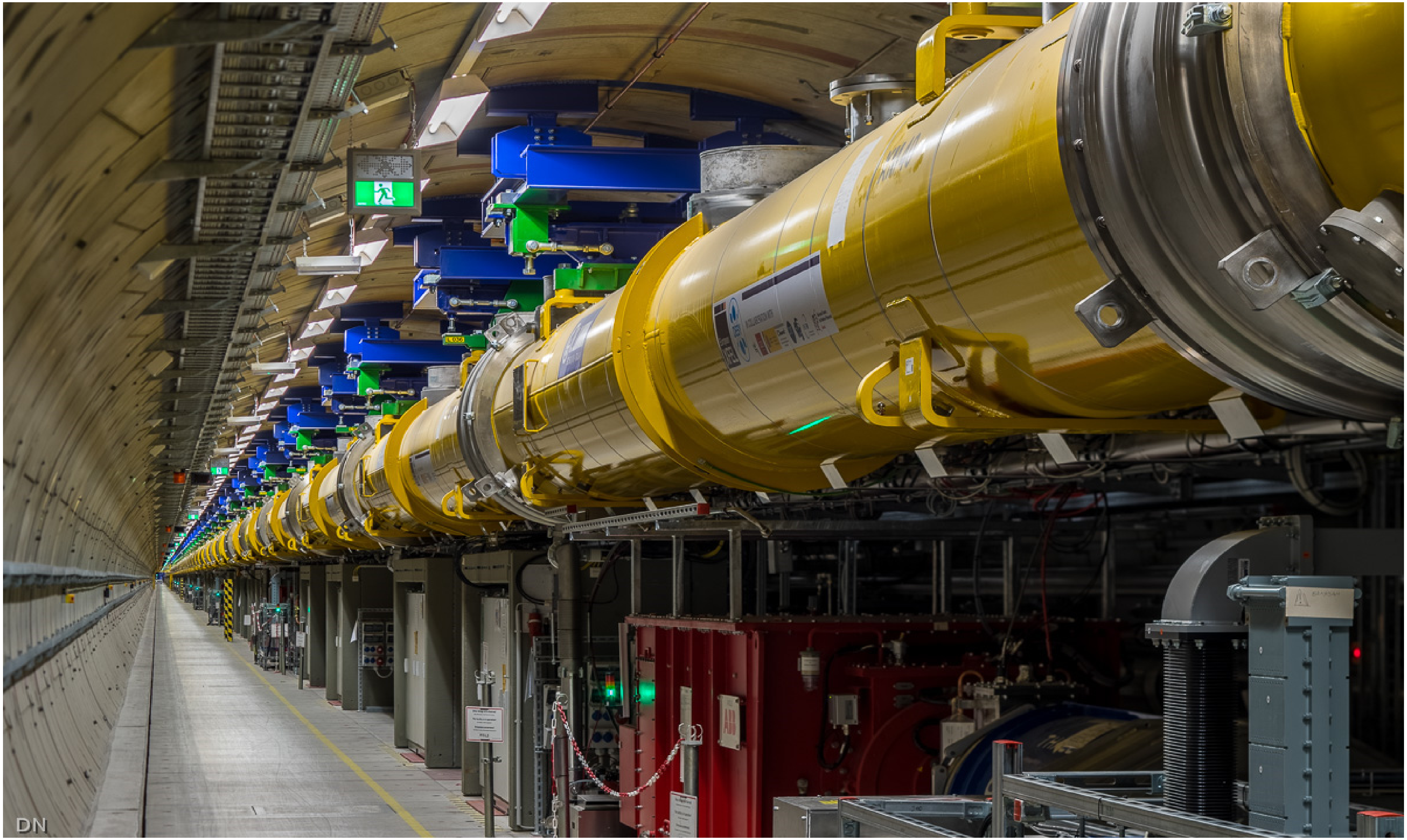
International Linear Collider:

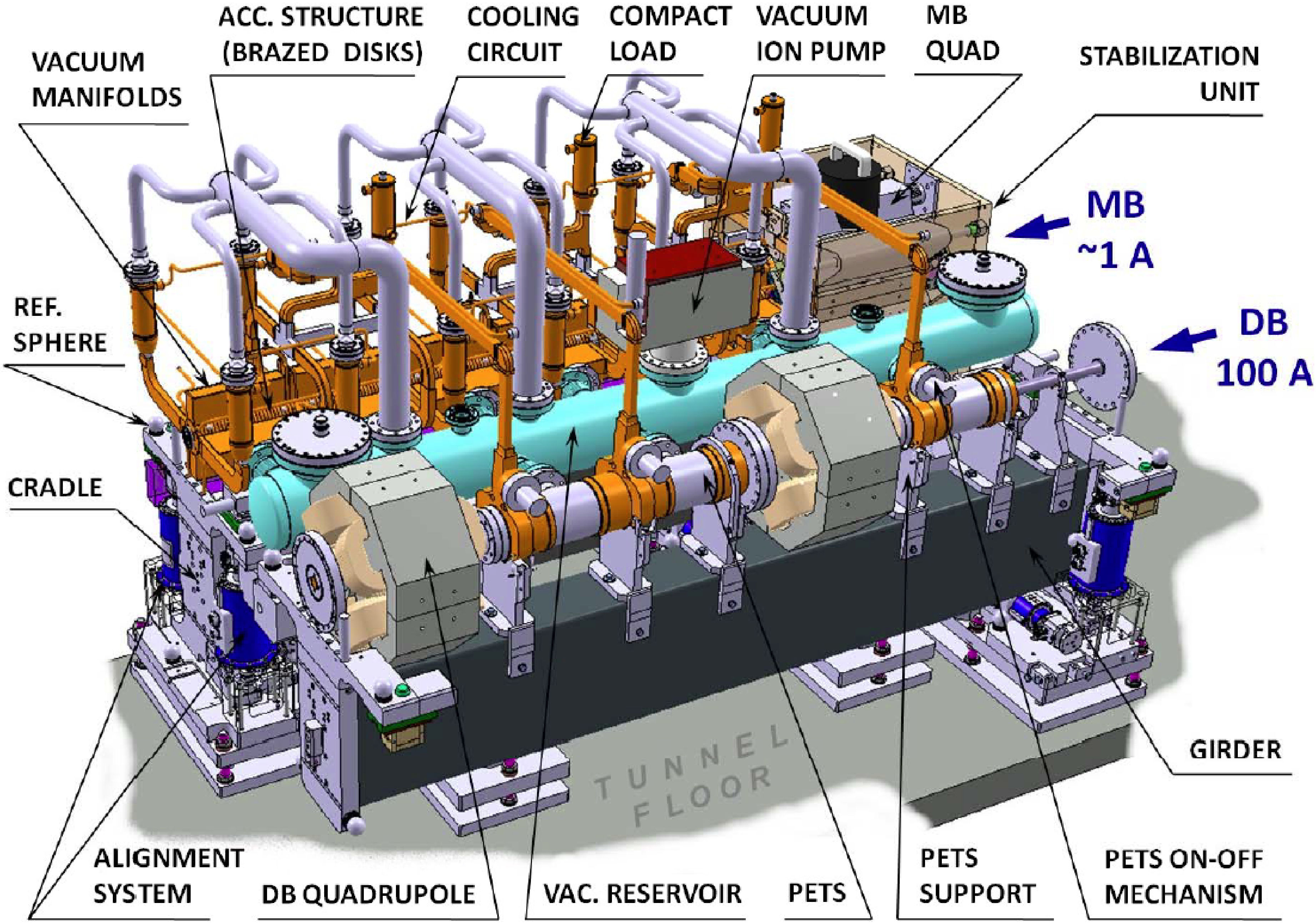
ILC

The Next Generation?



ca. 1 kilometer “cold” LINAC




VACUUM MANIFOLDS
ACC. STRUCTURE (BRAZED DISKS)
COOLING CIRCUIT
COMPACT LOAD
VACUUM ION PUMP
MB QUAD
STABILIZATION UNIT
MB ~1 A
DB 100 A
REF. SPHERE
CRADLE
TUNNEL FLOOR
GIRDER
ALIGNMENT SYSTEM
DB QUADRUPOLE
VAC. RESERVOIR
PETS
PETS SUPPORT
PETS ON-OFF MECHANISM

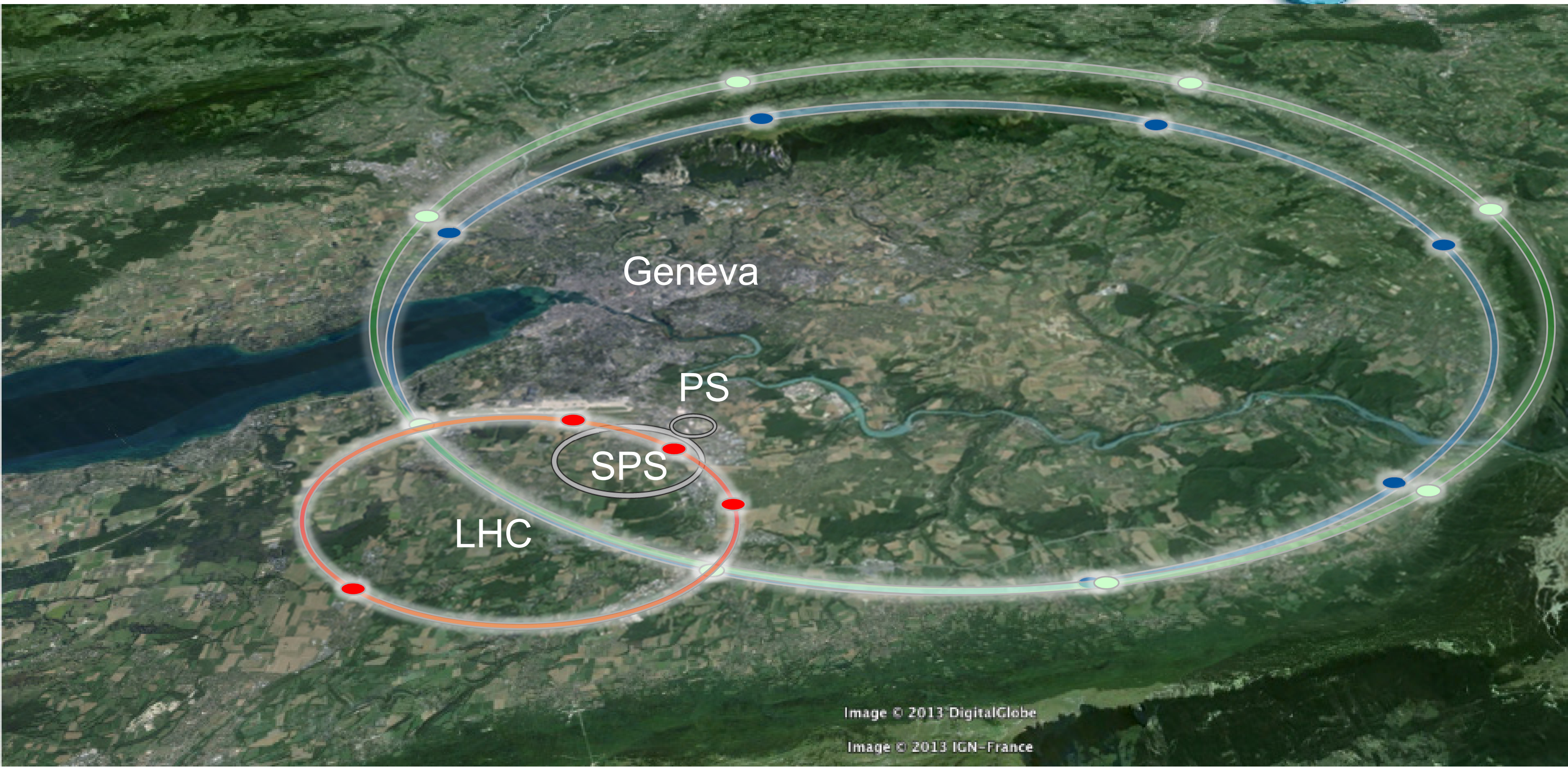
0.5 / 3 TeV Parameters

		ILC	CLIC
Physics	Max. E_{cm}	500 GeV	3 TeV
	Luminosity	1.8×10^{34} $cm^{-2}s^{-1}$	2.0×10^{34} $cm^{-2}s^{-1}$
	Polarisation (e-/e+)	80% / 30%	none
	δ_{BS}	4.5%	29%
Beam (interaction point)	σ_x / σ_y	574 nm / 6 nm	45 nm / 1 nm
	σ_z	300 μm	44 μm
	$\gamma\varepsilon_x$ / $\gamma\varepsilon_y$	10 μm / 35 nm	660 μm / 20 μm
	β_x / β_y	11 mm / 0.48 mm	6.9 mm / 0.068 mm
	bunch charge	2×10^{10}	0.6 nC
…structure)	Number of bunches / pulse	1312	312
	Bunch spacing	554 ns	0.5 ns
	Pulse current	5.8 mA	1.2 A
	Beam pulse length	727 μs	156 ns
	Pulse repetition rate	5 Hz	50 Hz
Accelerator (general)	Average beam power	10.5 MW (total)	14 MW
	Total AC power	163 MW	415 MW
	(linacs AC power	107 MW)	2 x 63.9 MW (drive beam)

tiny emittances
nano-beams at IP
strong beam-beam

High-power high-current
beams. Short / long bunch
trains. SRF / NC RF

Beyond the LHC: the FCC's



LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	3000 tons LTS	9000 tons LTS	6000 tons Nb_3Sn
0.2 tons HTS	700 tons HTS	2000 tons HTS	3000 tons Nb-Ti

FCC Study (Future Circular Colliders)

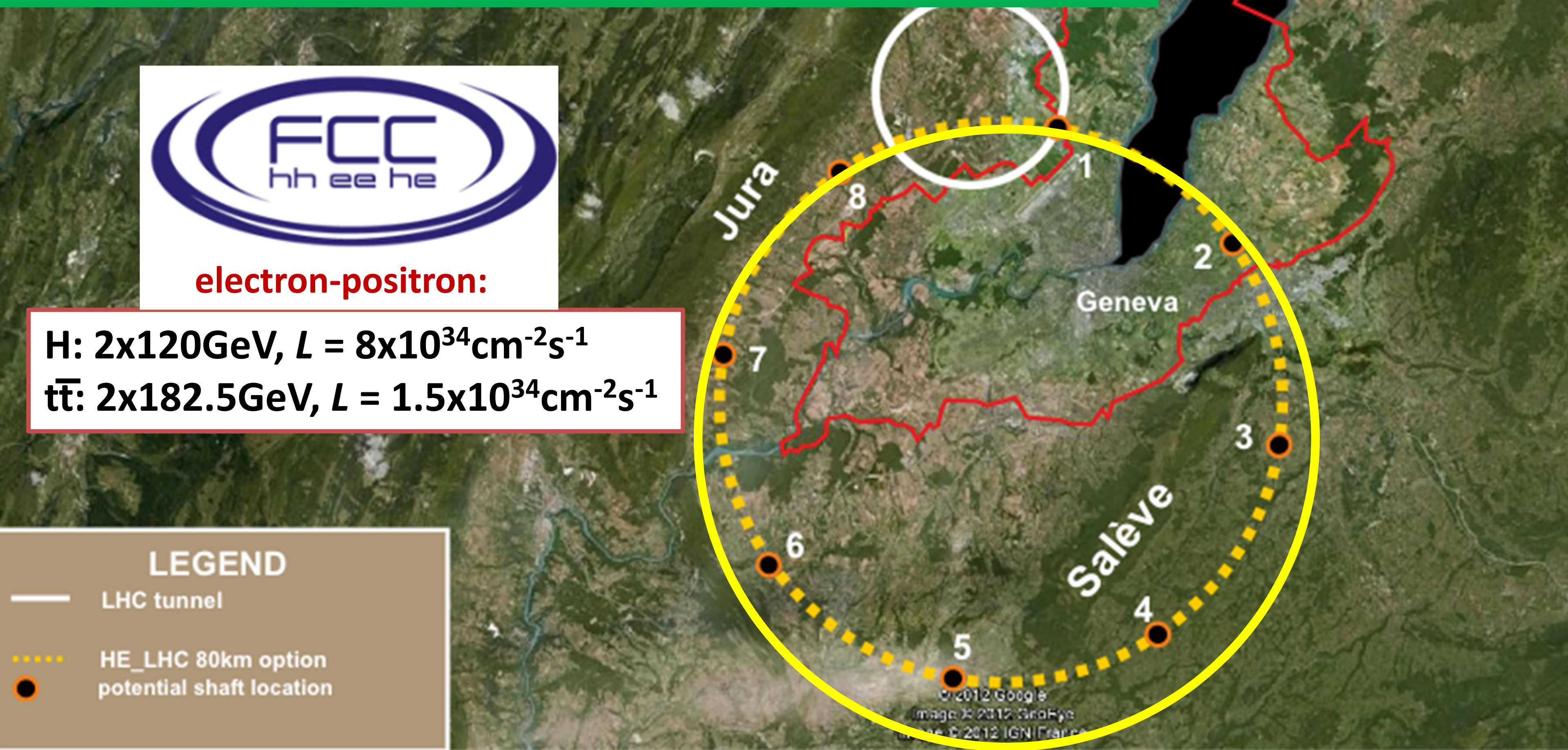
CDR and cost review for the next ESU (2018)

- 80-100 km tunnel infrastructure in Geneva area
- design driven by pp-collider requirements
- with possibility of e+-e- (FCC-ee) and p-e (FCC-he)
- CERN-hosted study performed in international collaboration

electron-positron:

H: 2x120GeV, L = 8x10^{34}cm^{-2}s^{-1}

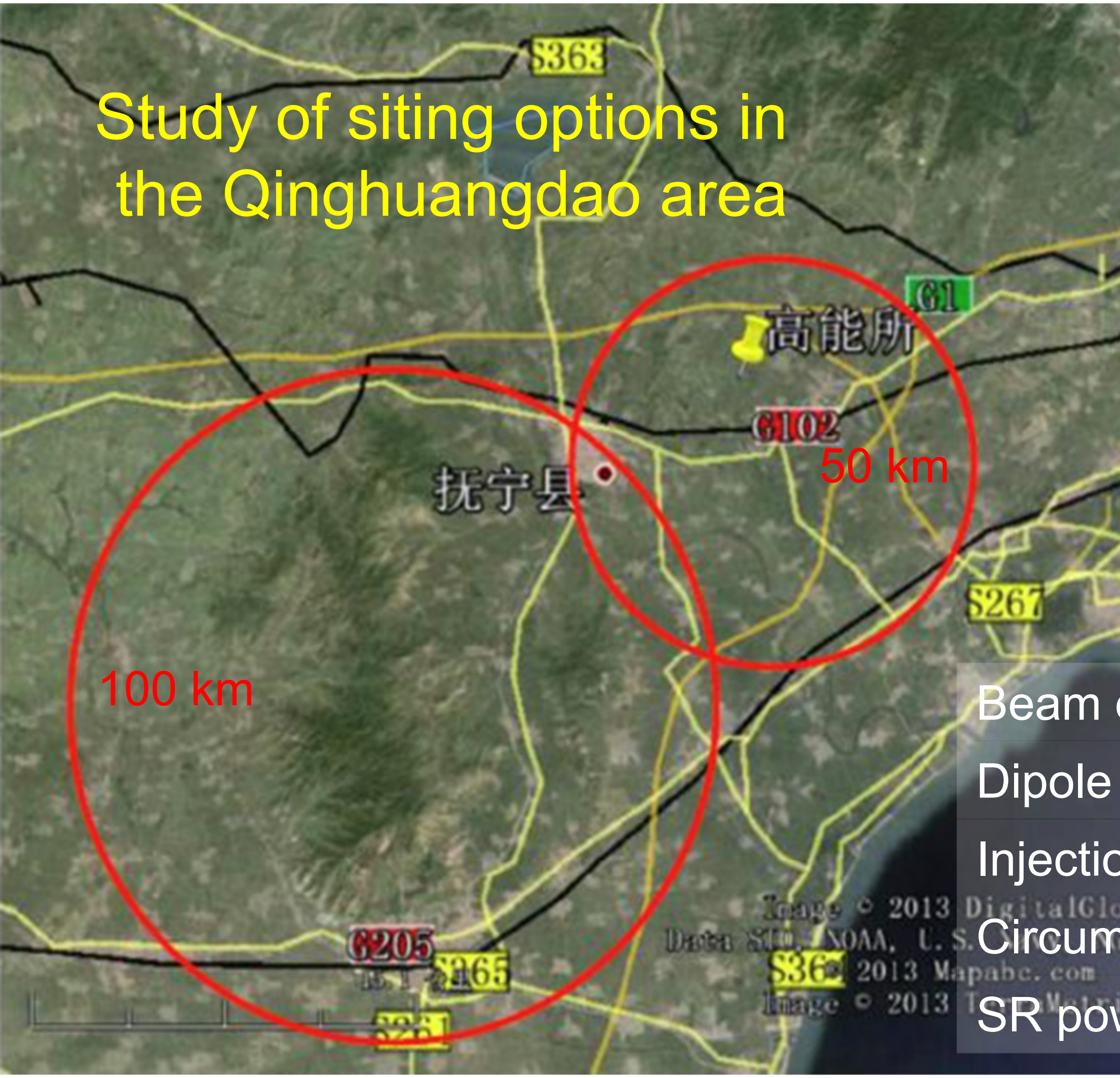
$t\bar{t}$: 2x182.5GeV, L = 1.5x10^{34}cm^{-2}s^{-1}

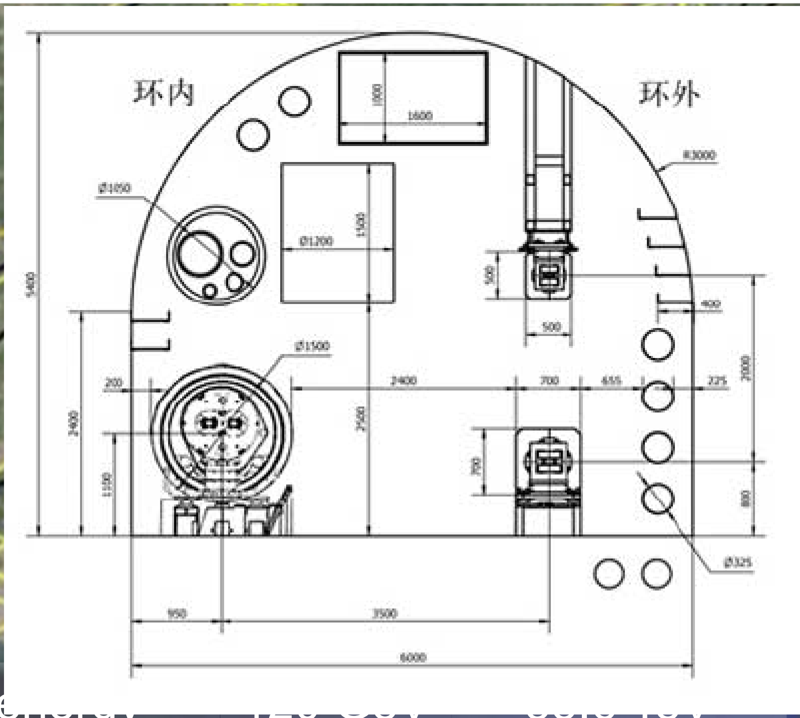


parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.45
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.99
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0350)
longitudinal damping time [ms]	414	77	23	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.93
RF acceptance [%]	1.9	1.9	2.3	4.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.39 / 1.60
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
luminosity [10^{34} $cm^{-2}s^{-1}$]	**230**	**32**	**8**	**1.5**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.094 / 0.150
luminosity lifetime [min]	70	50	42	44
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	10
actual lifetime by BS (“weak”) [min]	> 200	20	20	25

CEPC-SppC

中国科学院高能物理研究所
Institute of High Energy Physics





Beam energy	120 GeV	35.6 TeV
Dipole field		20 T
Injection energy		2.1 TeV (1.2 T)
Circumference	54.374 km	
SR power/beam	51.7 MW	2.1 MW

From: A. Apyan, et al., "CEPC-SPPC Preliminary Conceptual Design Report", IHEP-CEPCPP-DR-2015-01, IHEP-AC-2015-012015.

LCWS MiniSchool

e^+ - e^- Colliders

Summary:

Different Electron-Positron Collider Approaches

Linear Colliders:

- **sc: high η_{RF}, long pulses and bunch spacing, reduced sensitivity to tolerances (wakefields), upgradable, lower acc. gradients**
- **nc: ultimate acc. gradients, upgradable, low η_{RF}, short pulses and bunch spacing, highly sensitive to tolerances**

Circular Colliders:

- **reach about the same luminosity values, good time structure, limited by synchrotron radiation, not upgradable, no beam polarization**