An Introduction to Particle Accelerators

Based on sample of slides by
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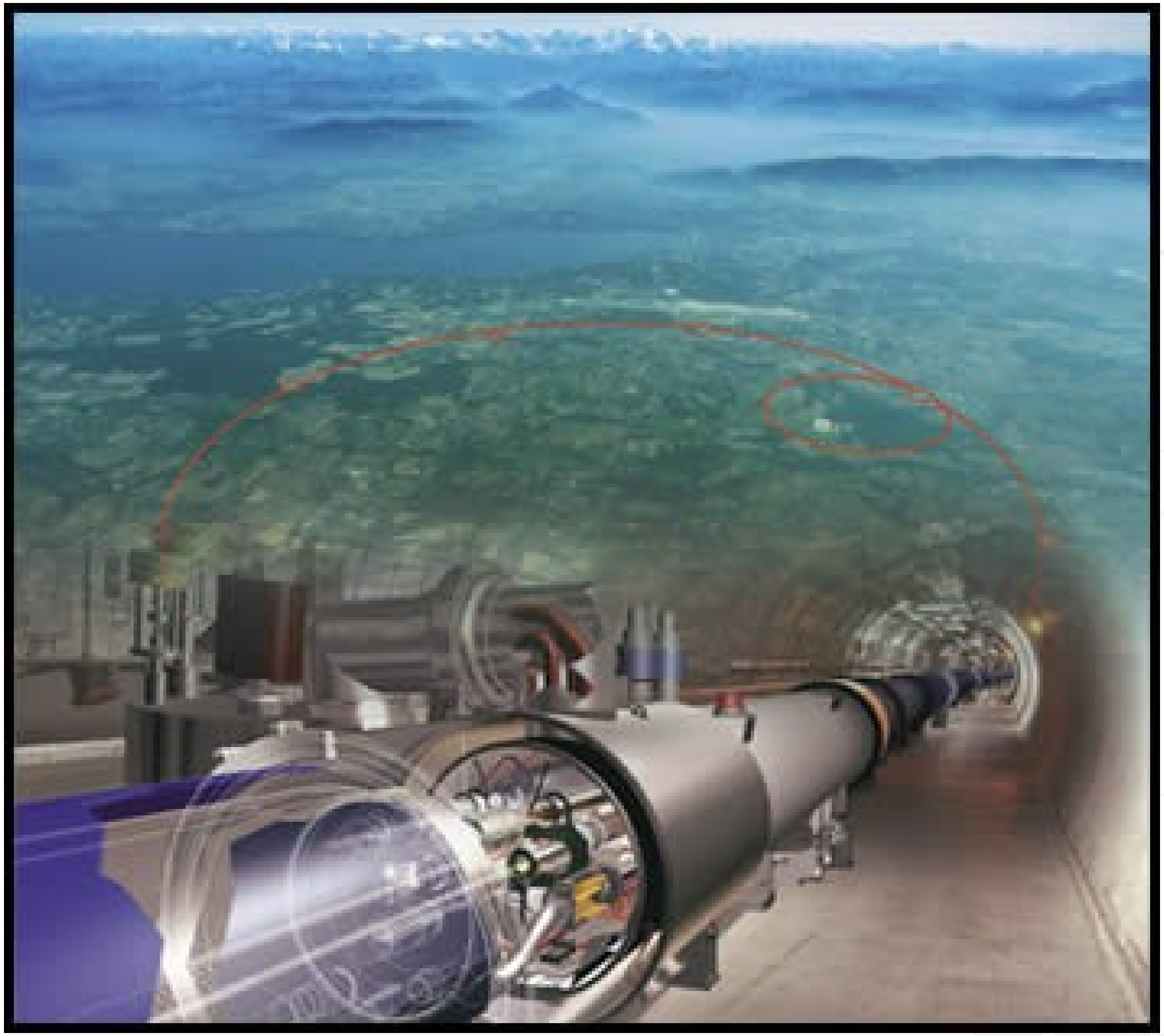
v1.32

Particle accelerators for HEP



- **LHC**: the world biggest accelerator, both in energy and size (as big as LEP)

Particle accelerators for HEP

The next *big* thing. After LHC, a Linear Collider of over 30 km length, will probably be needed

Others accelerators

- Historically: the main driving force of accelerator development was collision of particles for high-energy physics experiments

- However, today there are estimated to be around **25 000 particle accelerators in the world**, and only a fraction is used in HEP

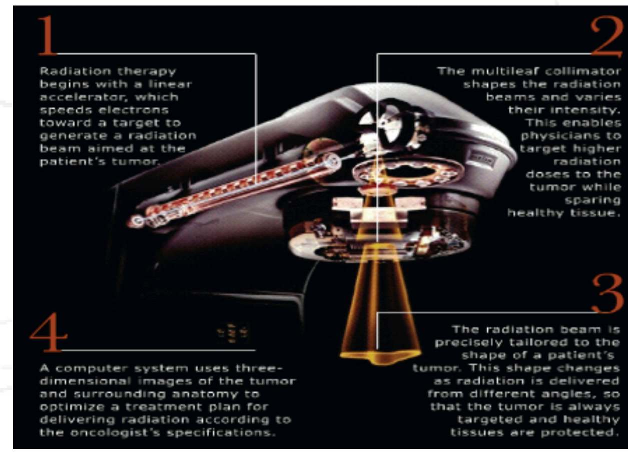
- Over half of them used in medicine

- Accelerator physics: a discipline in itself, growing field

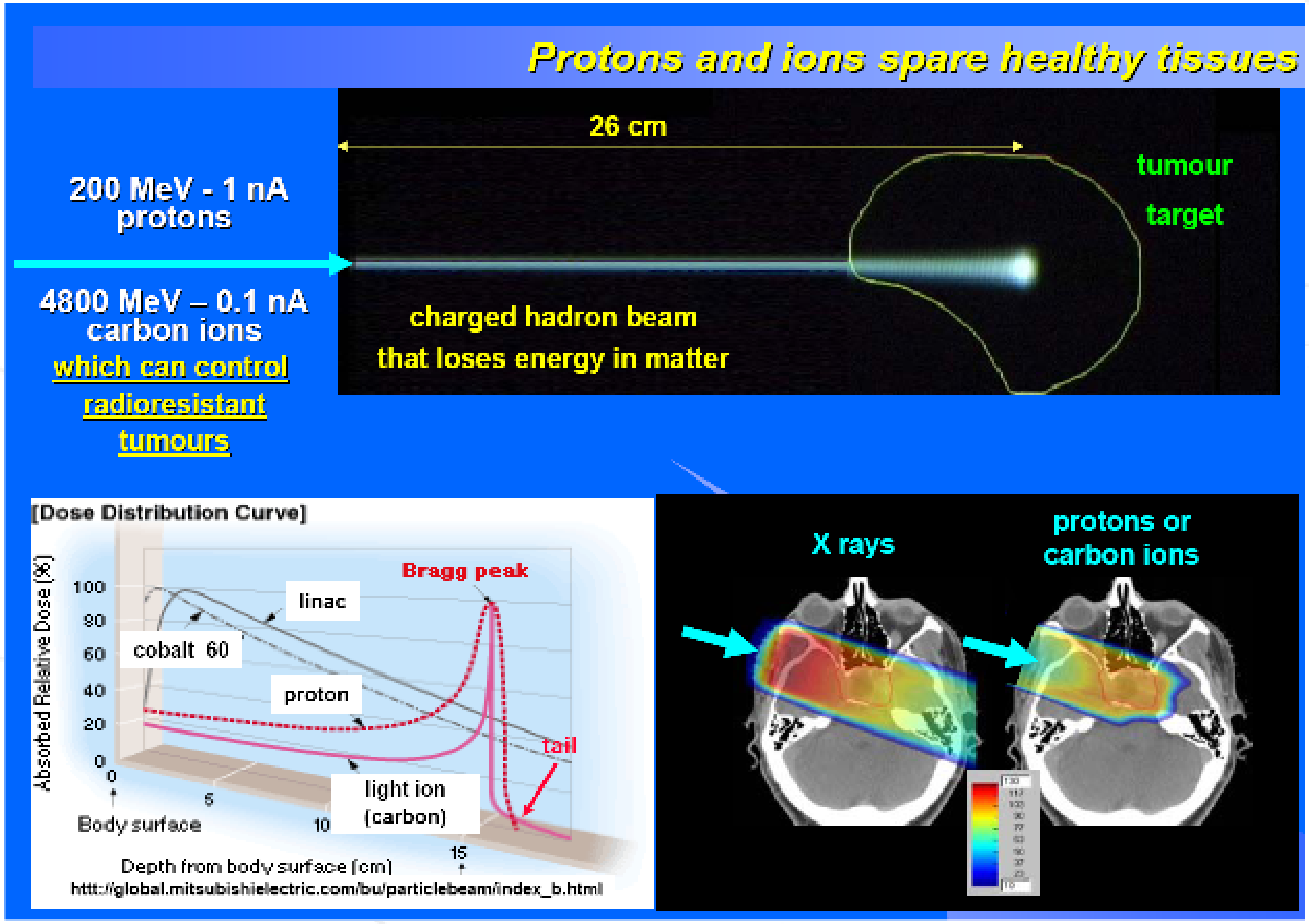
- Some examples:

Medical applications

- Therapy
  - The last decades: electron accelerators (converted to X-ray via a target) are used very successfully for cancer therapy)
  - Today's research: proton accelerators instead (hadron therapy): energy deposition can be controlled better, but huge technical challenges
- Imaging
  - Isotope production for PET scanners



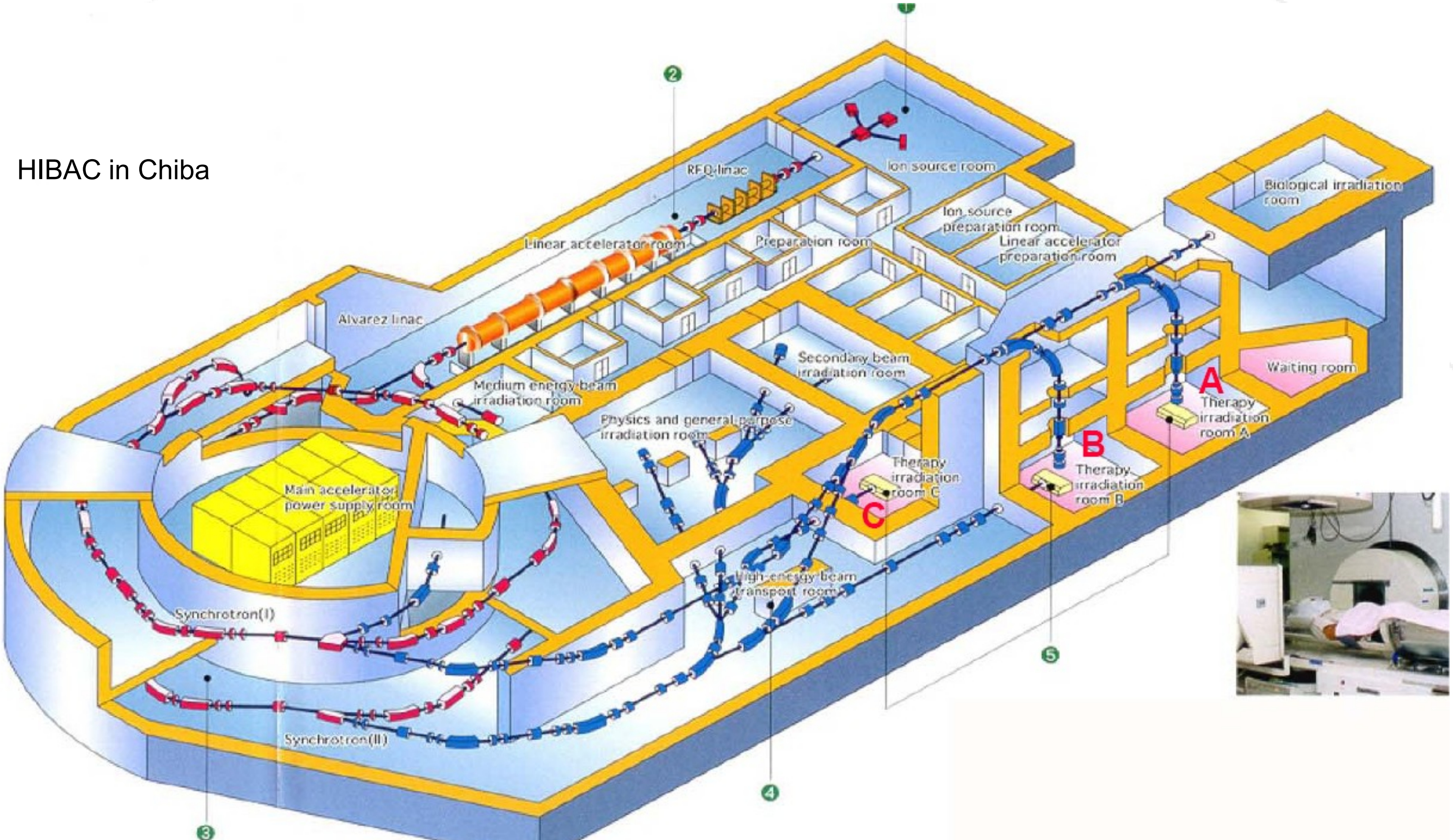
Advantages of proton / ion-therapy



(Slide borrowed from U. Amaldi)

Proton therapy accelerator centre

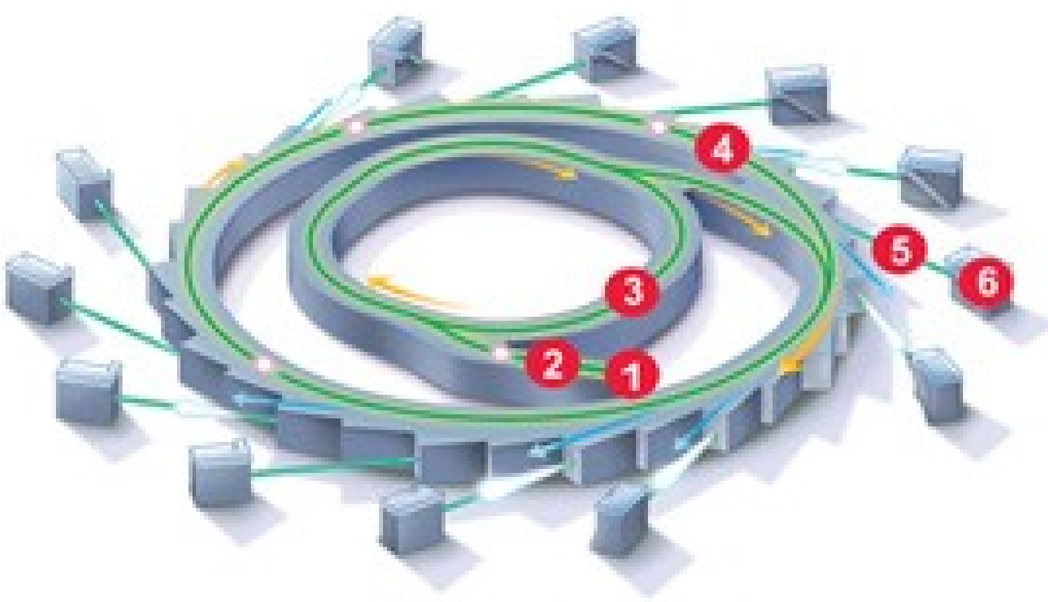
HIBAC in Chiba

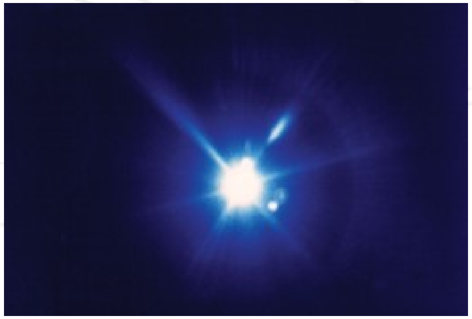


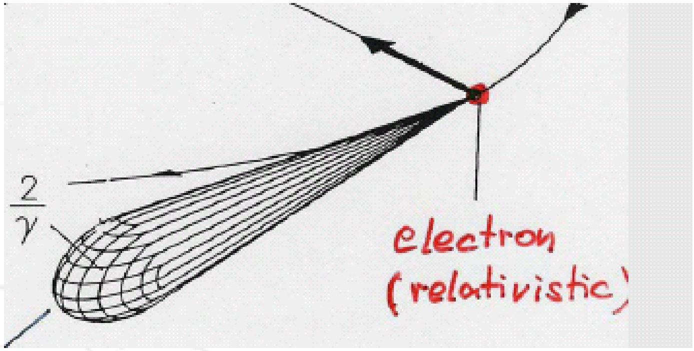
(Slide borrowed from U. Amaldi)

Synchrotron Light Sources

- the last two decades, enormous increase in the use of synchrony radiation, emitted from particle accelerators
- Can produce very intense light (radiation), at a wide range of frequencies (visible or not)
- Useful in a wide range of scientific applications

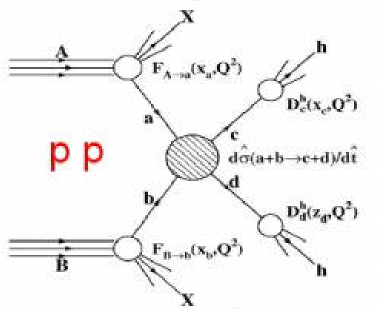




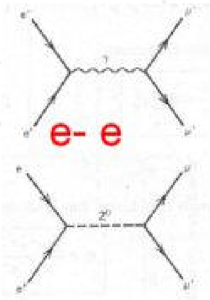


Main parameters: particle type

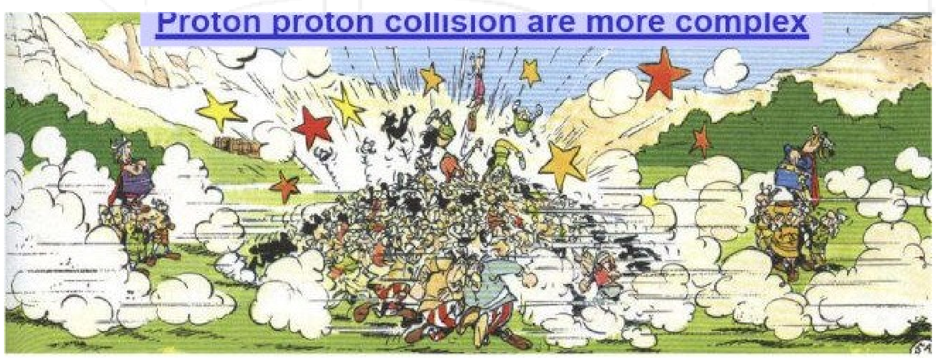
- Hadron collisions: compound particles
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - ***Hadron collisions $\Rightarrow$ large discovery range***



- Lepton collisions: elementary particles
  - Collision process known
  - Well defined energy
  - ***Lepton collisions $\Rightarrow$ precision measurement***



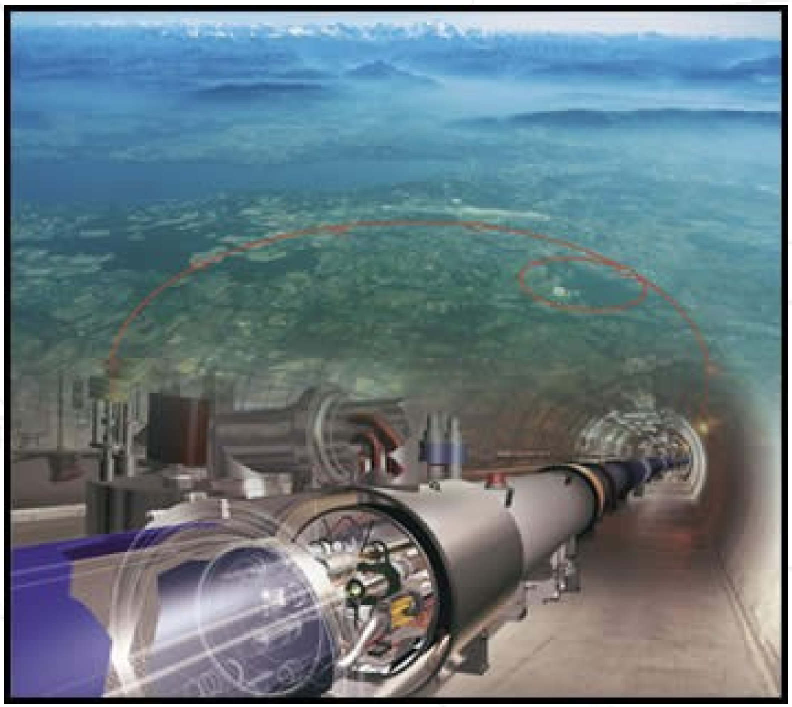
"If you know what to look for, collide leptons, if not collide hadrons"



Main parameters: particle type

Discovery

Precision



SppS / LHC

LEP / LC

Main parameters: particle energy

- New physics can be found at larger unprobed energies
- Energy for particle creation: centre-of-mass energy, E_{CM}
- Assume particles in beams with parameters m, E, E >> mc^2
  - Particle beam on fixed target: $\mathrm{E}_{\mathrm{CM}} = \sqrt{mE}$
  - Colliding particle beams: $\mathrm{E}_{\mathrm{CM}} = 2E$
- $\Rightarrow$ Colliding beams much more efficient

Main parameters: luminosity

- High energy is not enough !

- Cross-sections for interesting processes are very small (~ pb = 10^{-36} cm²) !
  - $\sigma(gg \rightarrow H)$ = 23 pb [at $s^2_{pp} = (14\ \text{TeV})^2$, $m_H = 150\ \text{GeV}/c^2$]

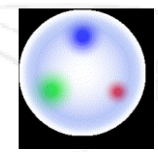
$$R = \mathcal{L}\sigma$$

  - We need $\mathcal{L} \gg 10^{30}\ \text{cm}^{-2}\text{s}^{-1}$ in order to observe a significant amount of interesting processes!

- $\mathcal{L}$ [$\text{cm}^{-2}\text{s}^{-1}$] for "bunched colliding beams" depends on
  - number of particles per bunch (n_1, n_2)
  - bunch transverse size at the interaction point (σ_x, σ_y)
  - bunch collision rate (f)

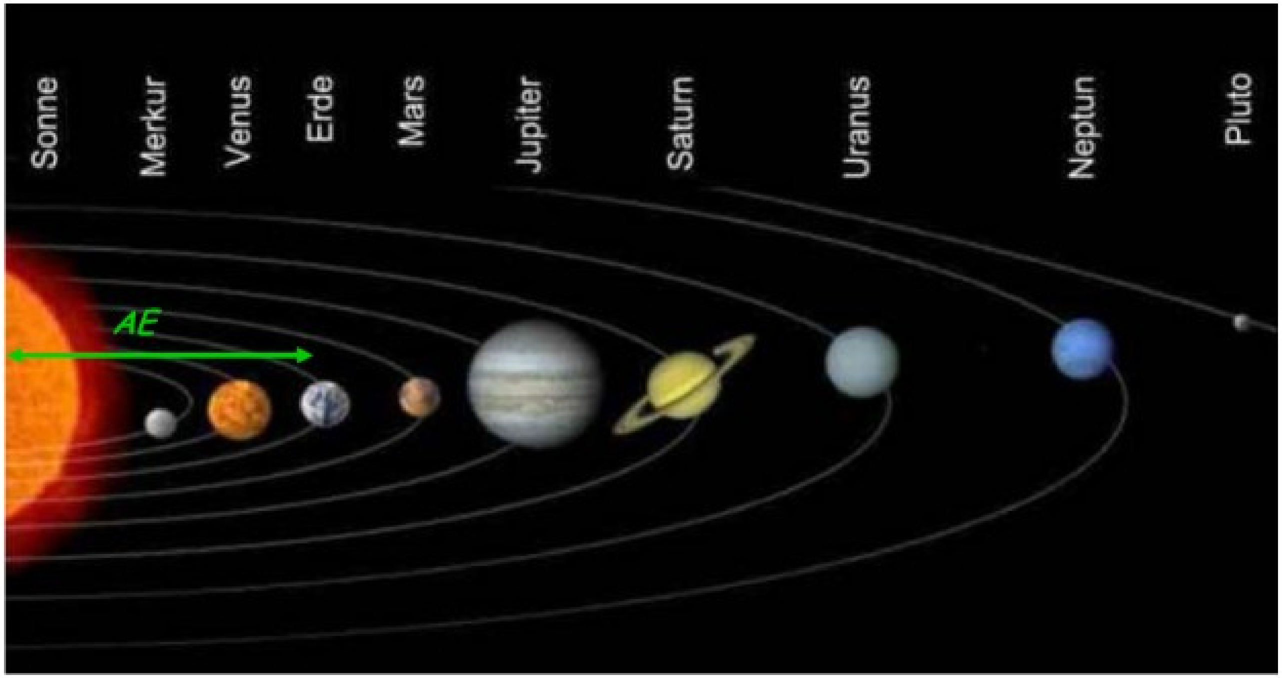
$$\mathcal{L} = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

Main parameters: LEP and LHC

	LEP	LHC
Particle type(s)	**e^+** and **e^-** 	**p,** ions (**Pb, Au**) 
Collision energy (E_{cm})	**209 GeV** (max)	p: **14 TeV** at p (~ 2-3 TeV mass reach, depending on physics) Pb: 1150 TeV
Luminosity ($\mathcal{L}$)	Peak: **10^{32} cm^{-2}s^{-1}** Daily avg last years: 10^{31} cm^{-2}s^{-1} Integrated: ~ 1000 pb^{-1} (per experiment)	Peak: **10^{34} cm^{-2}s^{-1}** (IP1 / IP5)

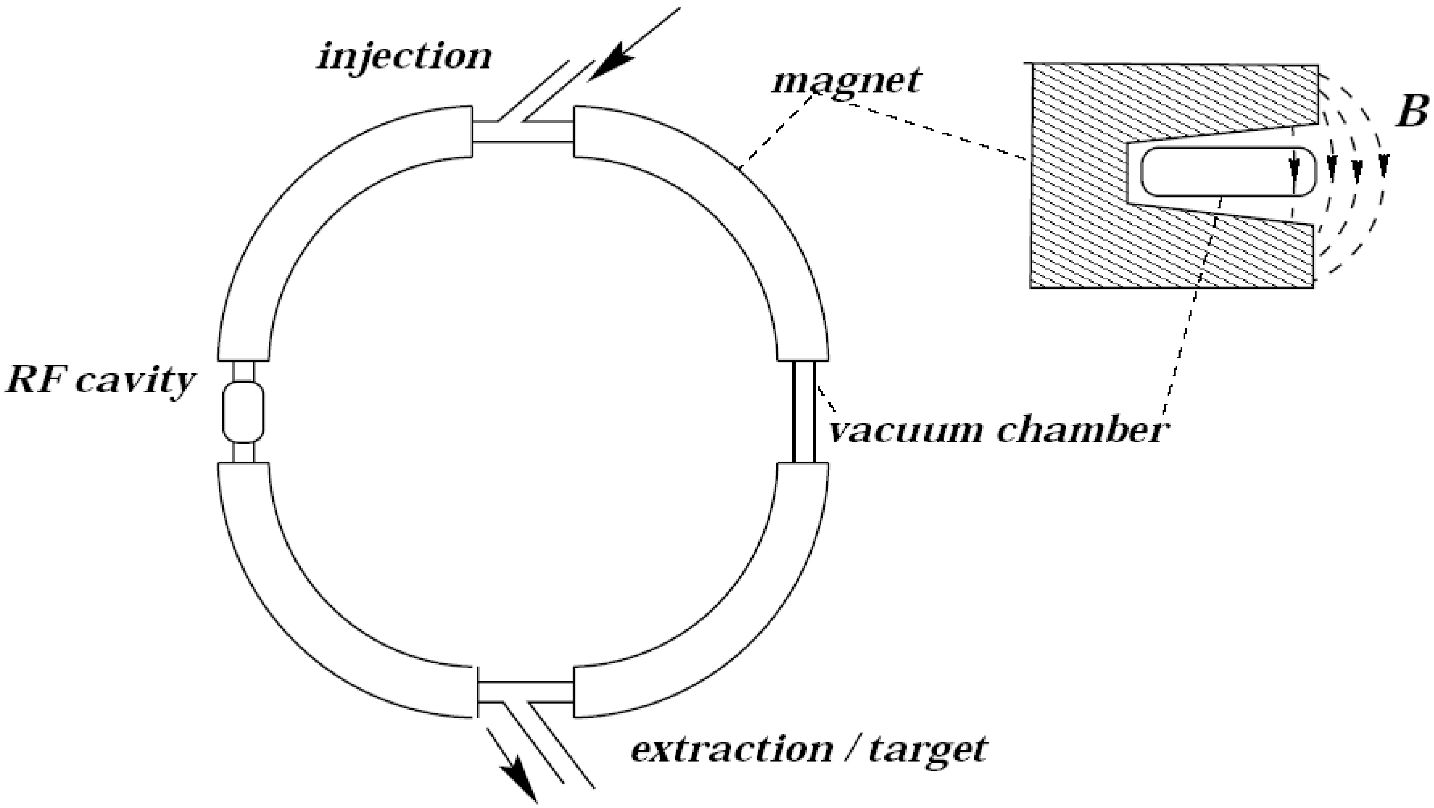
Capabilities of particle accelerators

- A modern HEP particle accelerator can accelerate particles, keeping them within millimeters of a defined reference trajectory, and transport them over a distance of several times the size of the solar system



HOW?

An accelerator



- Structures in which the particles will move
- Structures to accelerate the particles
- Structures to steer the particles
- Structures to measure the particles

Lorentz equation

- The two main tasks of an accelerator
  - Increase the particle energy
  - Change the particle direction (follow a given trajectory, focusing)

- Lorentz equation:

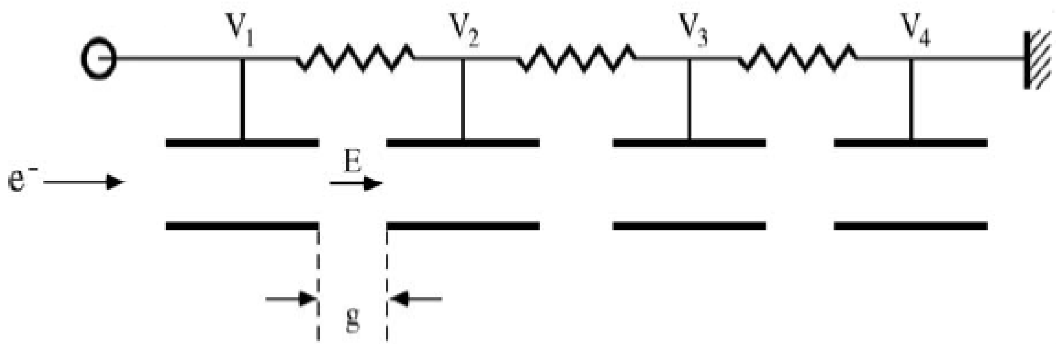
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = q\vec{E} + q\vec{v} \times \vec{B} = \vec{F}_E + \vec{F}_B$$

- $F_B \perp v \Rightarrow F_B$ does no work on the particle
  - ***Only F_E can increase the particle energy***

- F_E or F_B for deflection? $v \approx c \Rightarrow$ Magnetic field of 1 T (feasible) same bending power as en electric field of $3 \cdot 10^8$ V/m (NOT feasible)
  - ***F_B is by far the most effective in order to change the particle direction***

Acceleration techniques: DC field

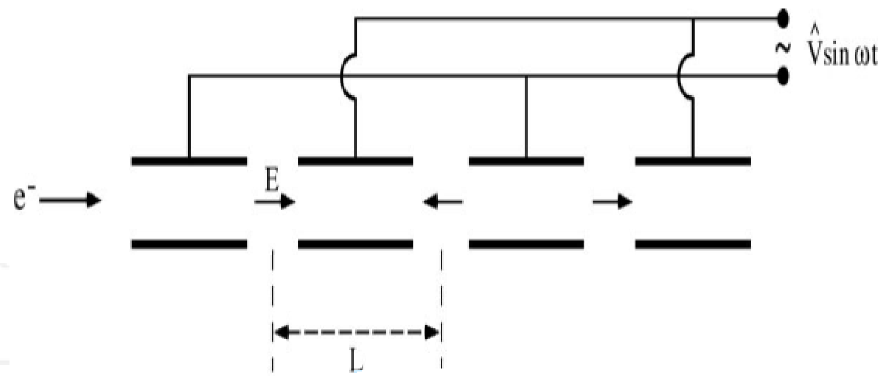
- The simplest acceleration method: DC voltage
- Energy kick: $\Delta E = qV$
- Can accelerate particles over many gaps: electrostatic accelerator



- Problem: breakdown voltage at ~10MV
- DC field still used at start of injector chain

Acceleration techniques: RF field

- Oscillating RF (radio-frequency) field



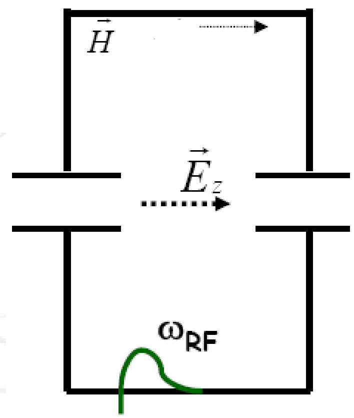
- "Widerøe accelerator", after the pioneering work of the Norwegian Rolf Widerøe (brother of the aviator Viggo Widerøe)

- Particle must sees the field only when the field is in the accelerating direction
  - Requires the synchronism condition to hold: $T_{particle} = ½T_{RF}$ $$L = (1/2)vT$$

- Problem: high power loss due to radiation

Acceleration techniques: RF cavities

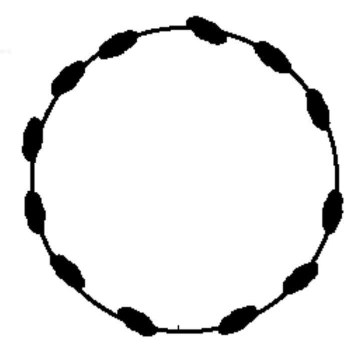
- Electromagnetic power is stored in a resonant volume instead of being radiated



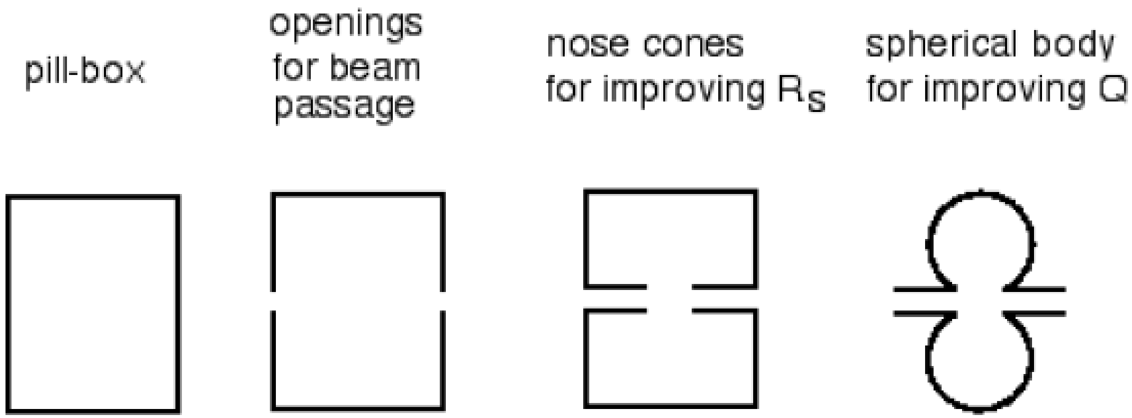
- RF power feed into cavity, originating from RF power generators, like Klystrons

- RF power oscillating (from magnetic to electric energy), at the desired frequency

- RF cavities requires **bunched beams** (as opposed to coasting beams)
  - particles located in bunches separated in space

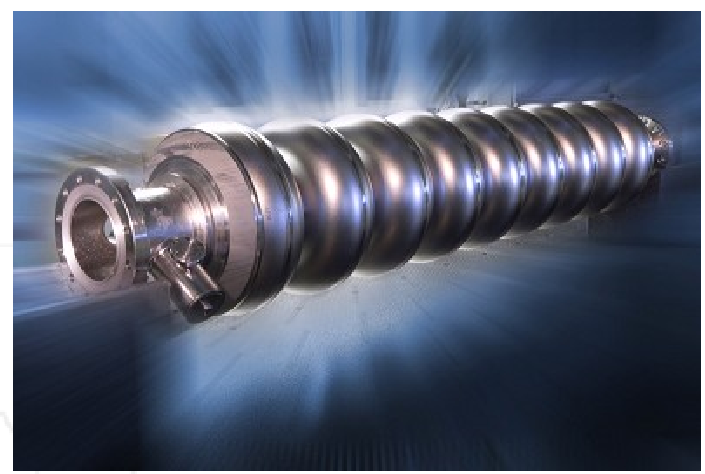


From pill-box to real cavities



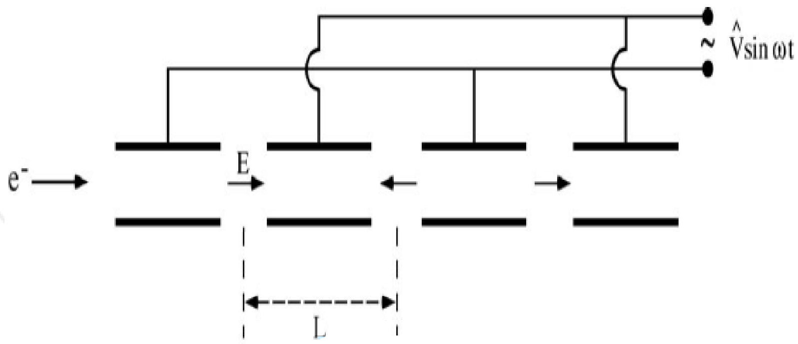
(from A. Chao)

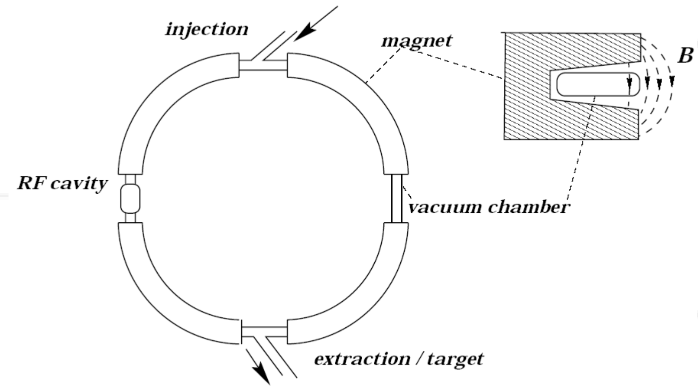
LHC cavity module



ILC cavity

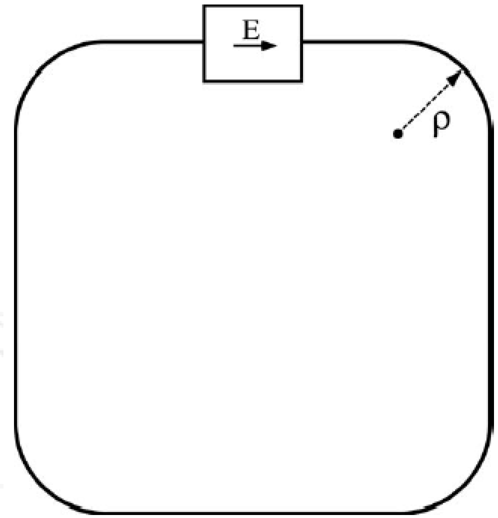
Why circular accelerators?





- Technological limit on the electrical field in an RF cavity (breakdown)
- Gives a limited ΔE per distance
- $\Rightarrow$ Circular accelerators, in order to re-use the same RF cavity
- This requires a bending field F_B in order to follow a circular trajectory (later slide)

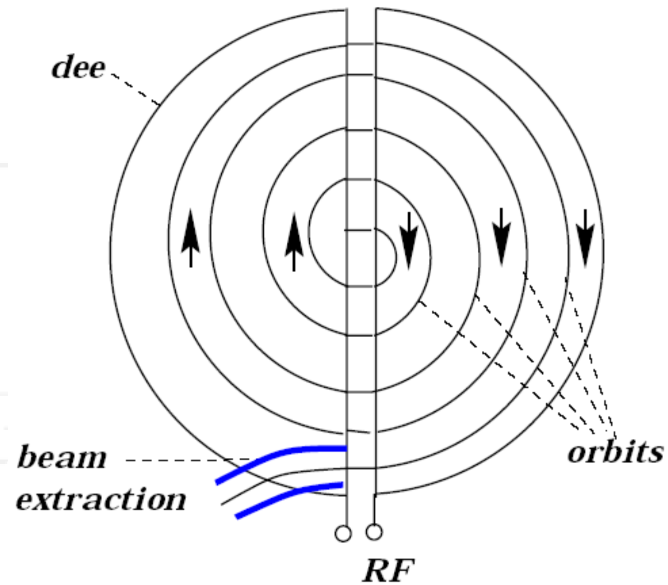
The synchrotron



- Acceleration is performed by RF cavities
- (Piecewise) circular motion is ensured by a guide field F_B
- F_B : Bending magnets with a homogenous field
- In the arc section: $F_B = m\frac{v^2}{\rho} \Rightarrow \frac{1}{\rho} = \frac{qB}{p} \Leftrightarrow \frac{1}{\rho}[m^{-1}] \approx 0.3\frac{B[T]}{p[GeV/c]}$
- RF frequency must stay locked to the revolution frequency of a particle (later slide)
- Almost all present day particle accelerators are synchrotrons

Digression: other accelerator types

- Cyclotron:
  - constant B field
  - constant RF field in the gap increases energy
  - radius increases proportionally to energy
  - limit: relativistic energy, RF phase out of synch
  - In some respects simpler than the synchrotron, and often used as medical accelerators



- Synchro-cyclotron
  - Cyclotron with varying RF phase

- Betatron
  - Acceleration induced by time-varying magnetic field

- ***The synchrotron will be the only type discussed in this course***

Frequency dependence on energy

- In order to see the effect of a too low/high ΔE, we need to study the relation between the change in energy and the change in the revolution frequency (η: "slip factor")

$$\eta = \frac{df_r / f_r}{dp / p}$$

- Two effects:

1. Higher energy $\Rightarrow$ higher speed (except ultra-relativistic)

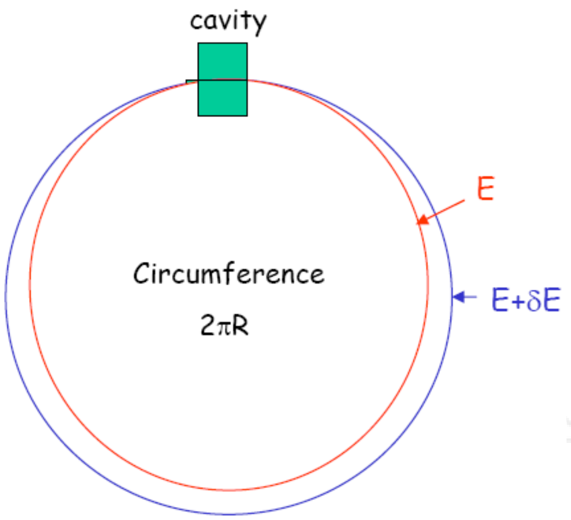
$$f_r = \frac{\beta c}{2\pi R}$$

2. Higher energy $\Rightarrow$ larger orbit "Momentum compaction"

Momentum compaction

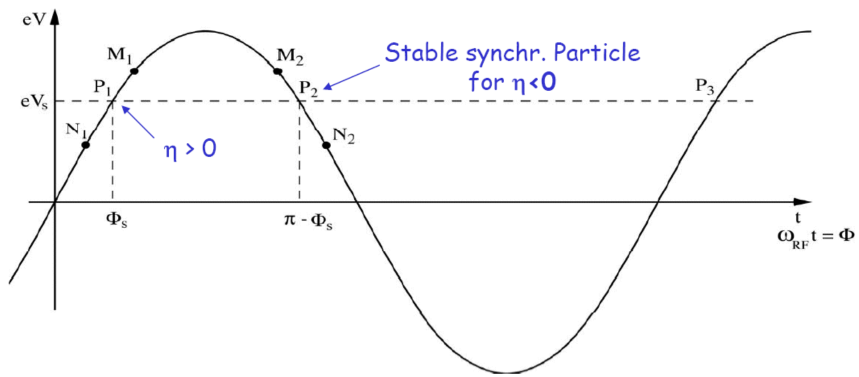
- Increase in energy/mass will lead to a larger orbit

$$F_B = m\frac{v^2}{\rho} \Rightarrow \frac{1}{\rho} = \frac{qB}{p} \Leftrightarrow \frac{1}{\rho}[m^{-1}] \approx 0.3\frac{B[T]}{p[GeV/c]}$$



Phase stability

- $\eta>0$: velocity increase dominates, f_r increases

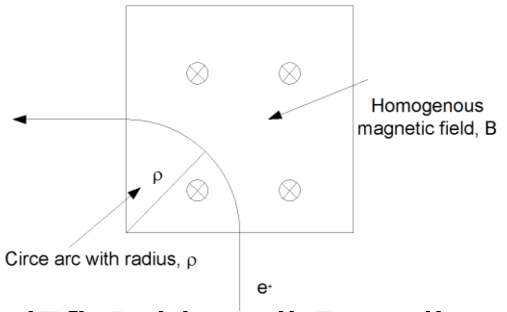


- Synchronous particle stable for $0º<\phi_s<90º$
  - A particle N_1 arriving early with $\phi= \phi_s-\delta$ will get a lower energy kick, and arrive relatively later next pass
  - A particle M_1 arriving late with $\phi= \phi_s+\delta$ will get a higher energy kick, and arrive relatively earlier next pass

- $\eta<0$: stability for $90º<\phi_s<180º$

- $\eta=0$ is called **transition**. When the synchrotron reaching this energy, the RF phase needs to be switched rapidly from ϕ_s to $180-\phi_s$

Bending field



- Circular accelerators: deflecting forces are needed

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_E + \vec{F}_B$$

- Circular accelerators: piecewise circular orbits with a defined bending radius ρ
  - Straight sections are needed for e.g. particle detectors
  - In circular arc sections the magnetic field must provide the desired bending radius:

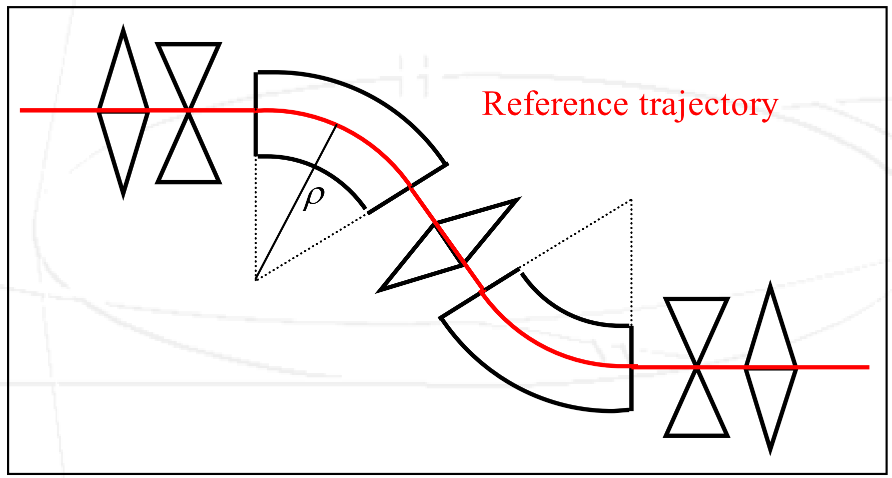
$$\frac{1}{\rho} = \frac{eB}{p}$$

- For a constant particle energy we need a constant B field ⇒ dipole magnets with homogenous field

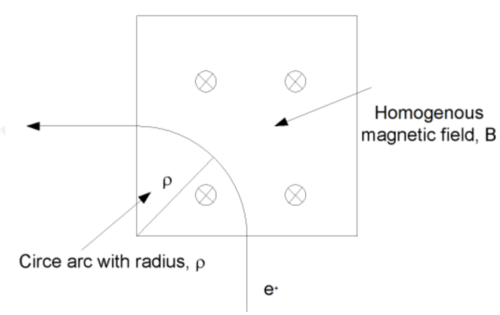
- In a synchrotron, the bending radius,$1/\rho = eB/p$, is kept constant during acceleration (last section)

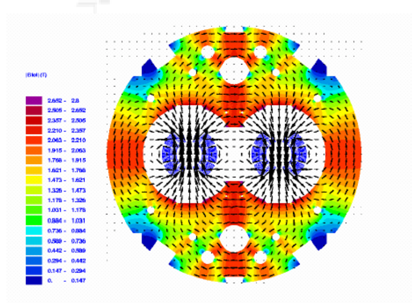
The reference trajectory

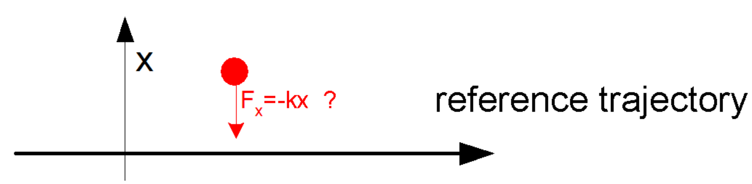
- We need to steer and focus the beam, keeping all particles close to the reference orbit



Dipole magnets to steer **Focus?**







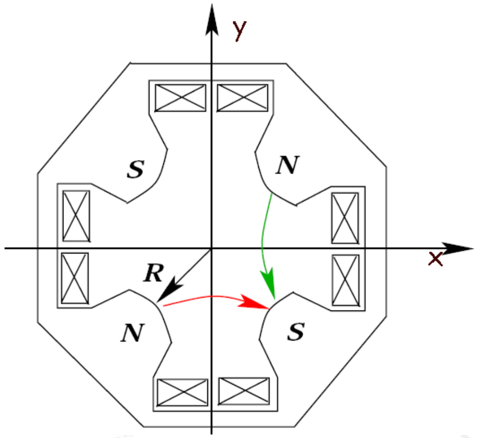
homogenous field **or** **cosθ distribution**

Focusing field: quadrupoles

- Quadrupole magnets gives linear field in x and y:

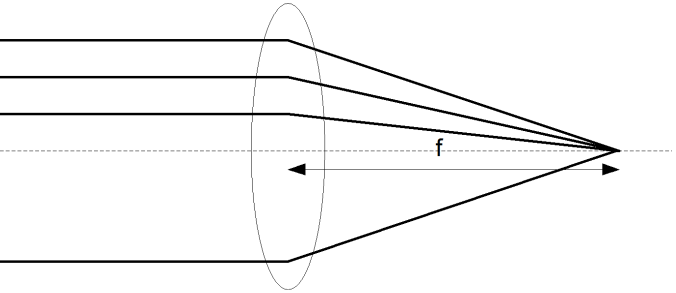
  $B_x = -gy$

  $B_y = -gx$

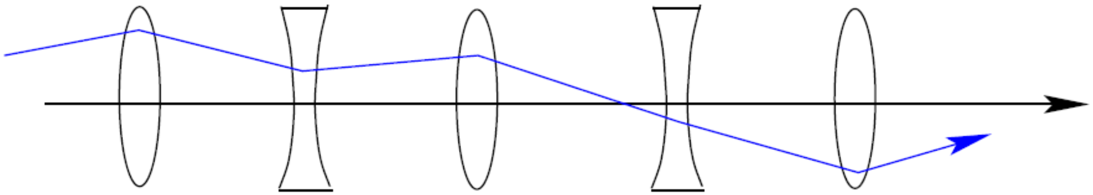


- However, forces are focusing in one plane and *defocusing* in the orthogonal plane: $F_x = -qvgx$ (focusing)

  $F_y = qvgy$ (defocusing)



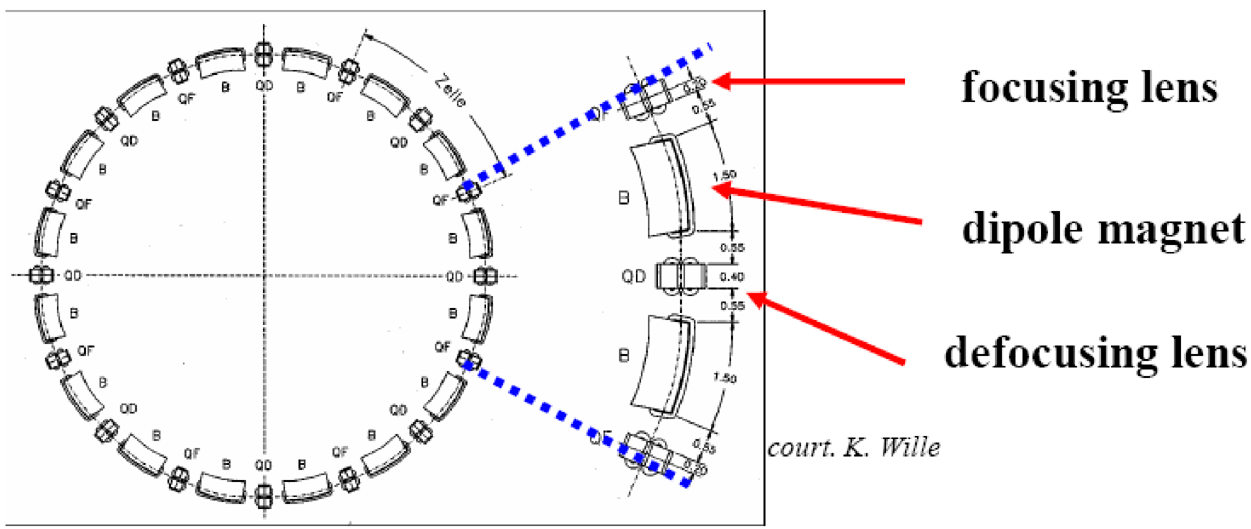
Alternating gradient scheme, leading to **betatron oscillations**



The Lattice

- An accelerator is composed of bending magnets, focusing magnets and non-linear magnets (later)

- The ensemble of magnets in the accelerator constitutes the "accelerator lattice"



Example: lattice components

The transverse beam size

- A very important parameter
  - Vacuum chamber
  - Interaction point and luminosity

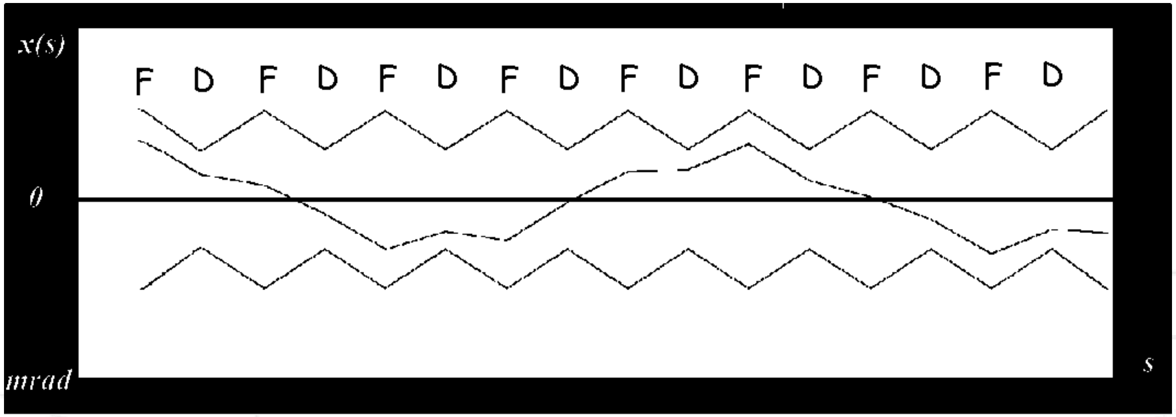
- The transverse beam size is given by the envelope of the particles:

$$E(s) = \sqrt{\varepsilon\beta(s)}$$

Beam quality

Lattice

The beta function, β

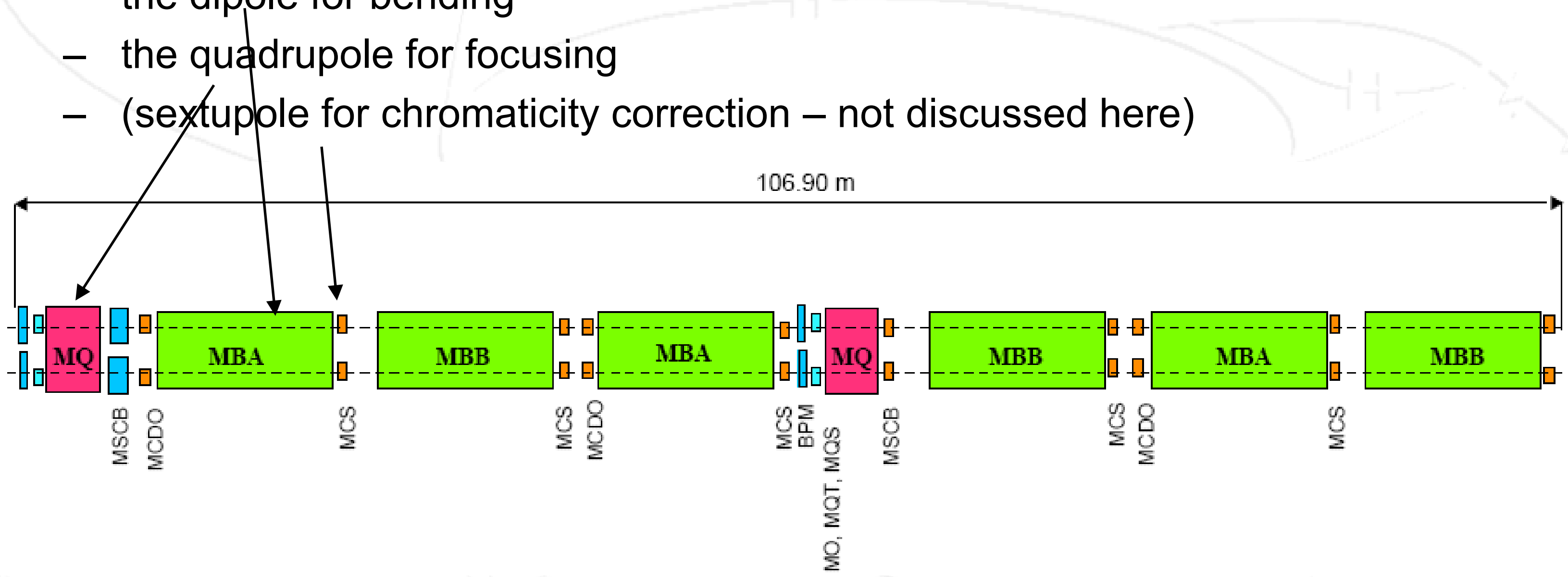


- NB: Even if beta function is periodic, the particle motion itself is in general *not* periodic (after one revolution the initial condition ϕ_0 is altered)

- The beta function should be kept at minimum, β^*, at interaction points to maximize the luminosity

Conclusion: transverse dynamics

- We have now studied the transverse optics of a circular accelerator and we have had a look at the optics elements,
  - the dipole for bending
  - the quadrupole for focusing
  - (sextupole for chromaticity correction – not discussed here)



- All optic elements (+ more) are needed in a high performance accelerator, like the LHC

Intermezzo
Norske storheter innen akseleratorfysikk

Rolf Wideröe

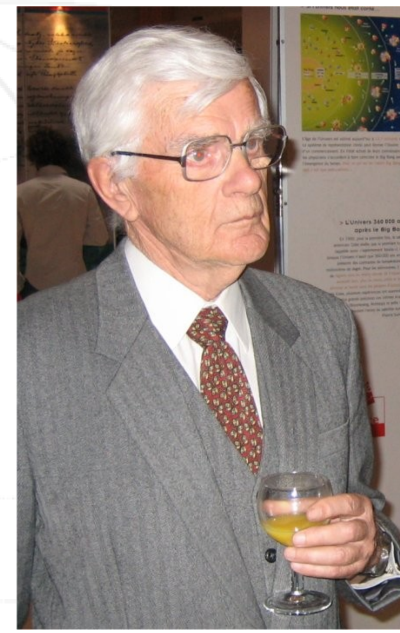
Pioneer både for betatronprinsippet og for lineære akseleratorer

Odd Dahl

Leder av CERN PS prosjektet (en viktig del av LHC-komplekset den dag i dag)

Bjørn Wiik

Professor og direktør ved Europas nest største akseleratorsenter (DESY i Hamburg)



Kjell Johnsen

Involvert i en rekke CERN-prosjekter, leder av ISR og CERN's gruppe for akseleratorforskning

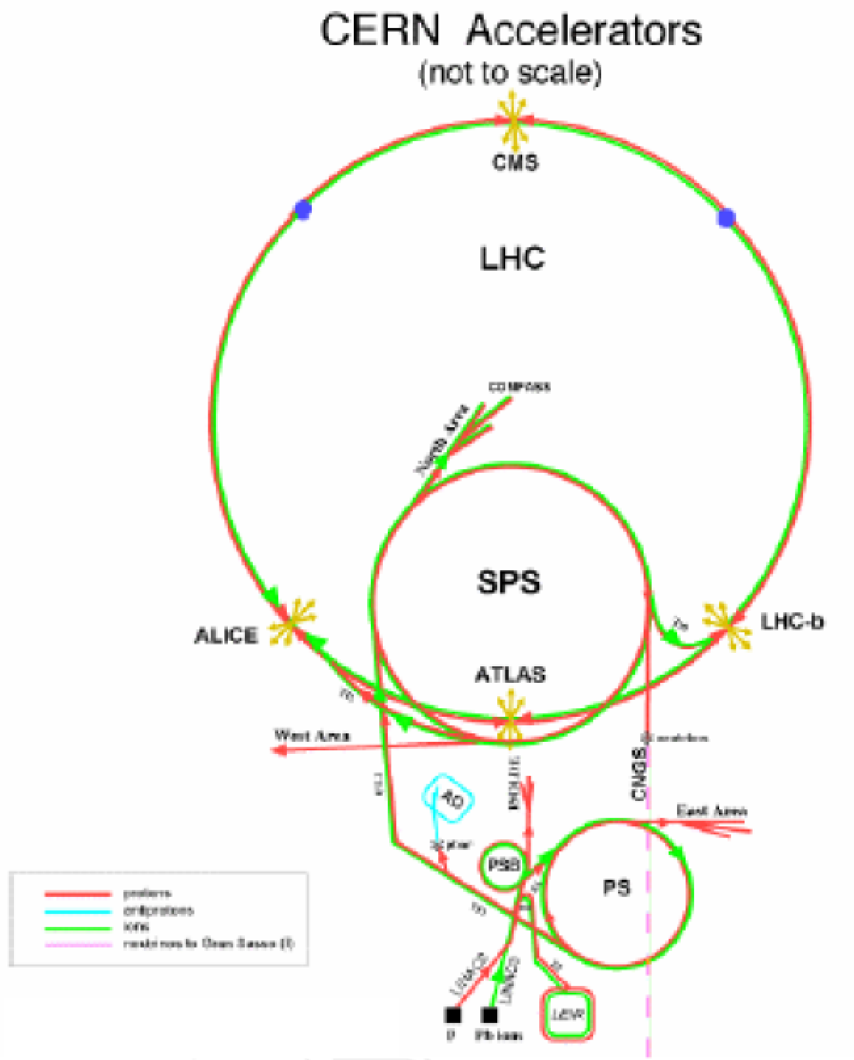
LHC

LHC: wrt. to earlier slides

- ***proton-proton collisions***
  $\Rightarrow$ ***two vacuum chambers***, with ***opposite bending field***
- ***RF cavities***
  $\Rightarrow$ ***bunched beams***
- ***Synchrotron*** with ***alternating-gradient focusing***
- ***Superconducting lattice magnets*** and ***superconducting RF cavities***
- Regular ***FODO arc-section*** with ***sextupoles*** for chromaticity correction
- Proton chosen as particle type due to **low synchrotron radiation**
- Magnetic **field-strength limiting factor** for particle energy

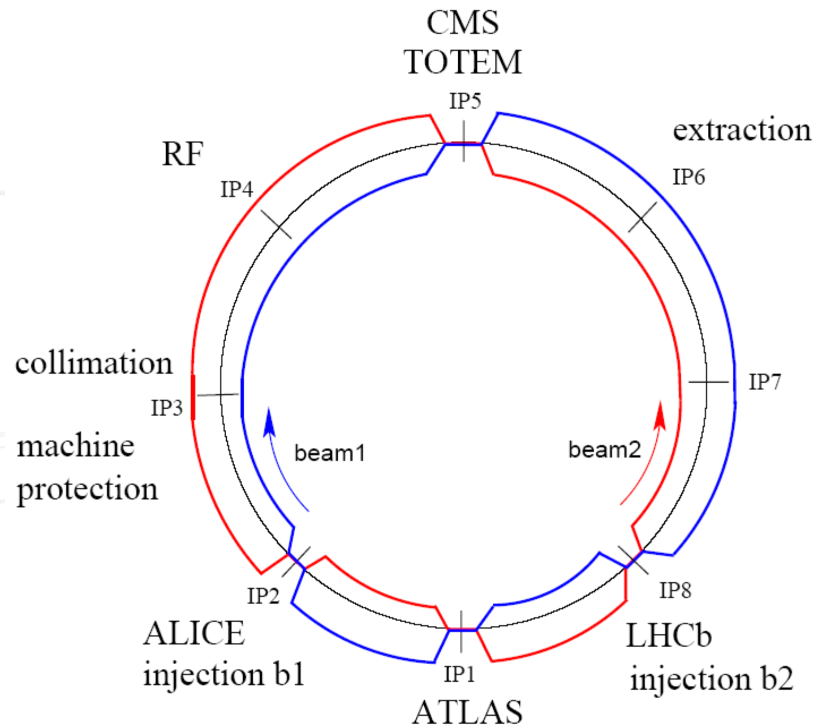
LHC injector system

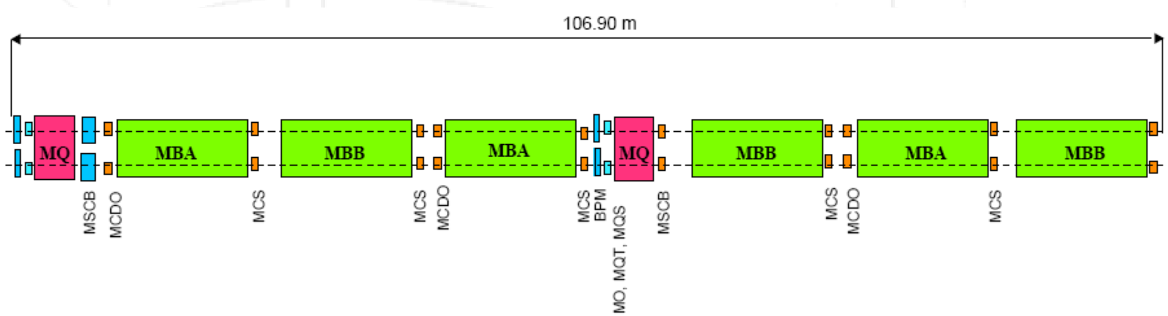
- LHC is responsible for accelerating protons from 450 GeV up to 7000 GeV
- 450 GeV protons injected into LHC from the SPS
- PS injects into the SPS
- LINACS injects into the PS
- The protons are generated by a Proton Source



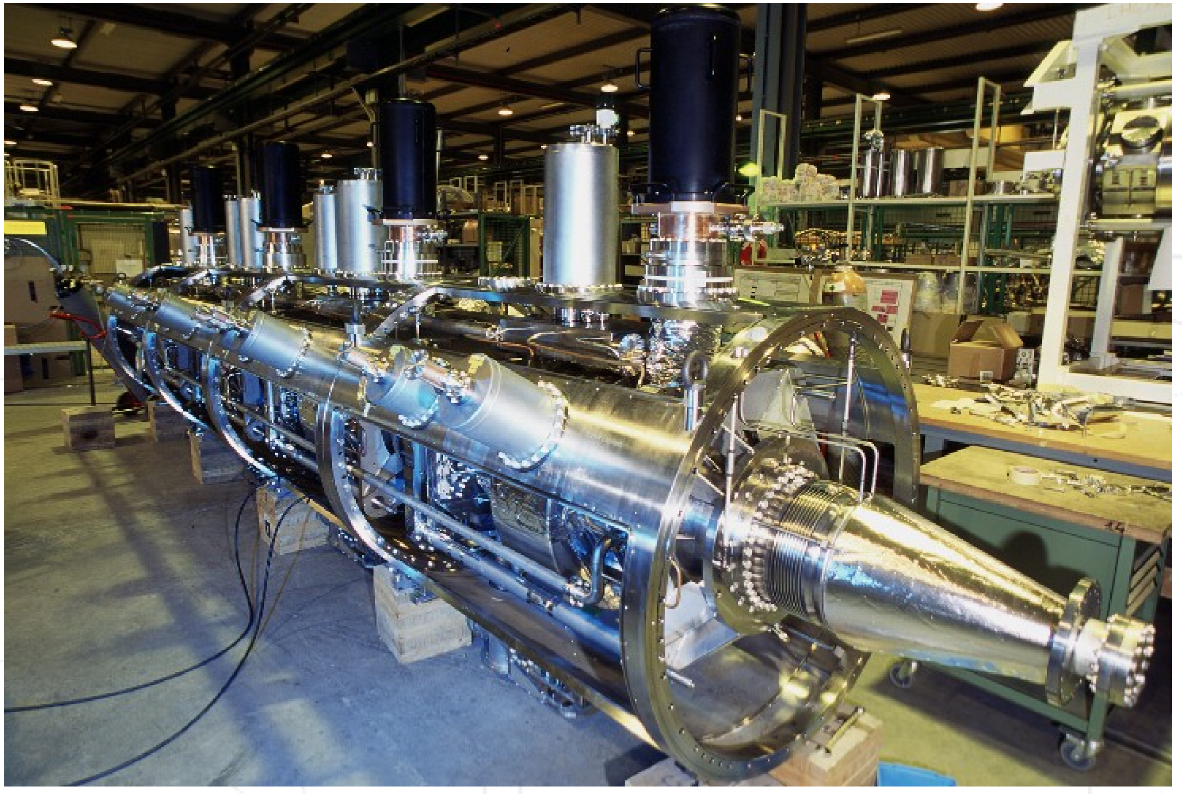
LHC layout

- circumference = 26658.9 m
- 8 interaction points, 4 of which contains detectors where the beams intersect
- 8 straight sections, containing the IPs, around 530 m long
- 8 arcs with a regular lattice structure, containing 23 arc cells
- Each arc cell has a regular structure, 106.9 m long





LHC cavities



- Superconducting RF cavities (standing wave, 400 MHz)
- Each beam: one cryostats with 4+4 cavities each
- Located at LHC point 4

LHC main parameters

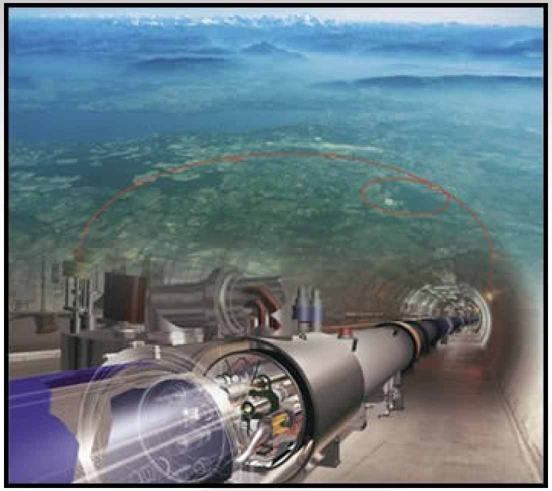
at collision energy

Particle type	p, Pb
Proton energy E_p at collision	7000 GeV
Peak luminosity (ATLAS, CMS)	10×10^{34} $cm^{-2}s^{-1}$
Circumference C	26 658.9 m
Bending radius ρ	2804.0 m
RF frequency f_{RF}	400.8 MHz
# particles per bunch n_p	1.15×10^{11}
# bunches n_b	2808

LEP, LHC and CLIC

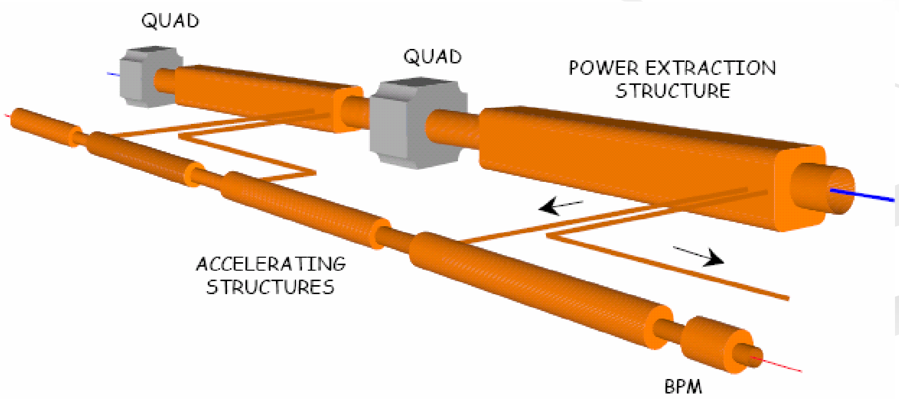
This decade: both LEP and LHC

LEP: 1989 - 2000



LHC: 2008 -

Next generation being studied:



CLIC: The future

Limitations LEP and LHC

- We want E_{cm} as high as possible for new particle accelerators
- circular colliders ⇒ particles bended ⇒ two limitations occurs:

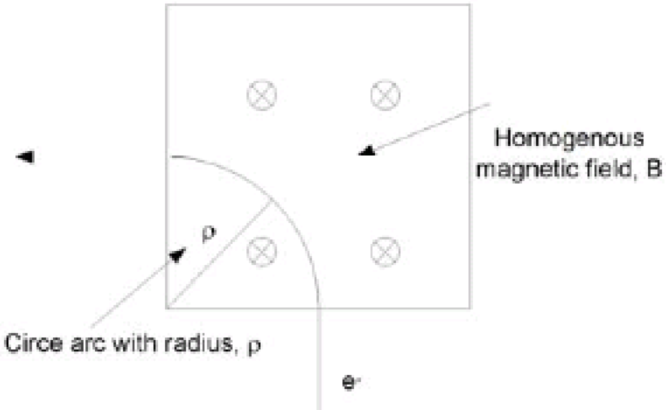
I) synchrotron radiation energy loss

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

$P \propto E^4$ ⇒ **Limited LEP to E_{cm}**=209 GeV (RF energy replenishment)
$P \propto m_0^{-4}$ ⇒ changing to p in **LHC** ⇒ **P no longer the limiting factor**

II) Magnetic rigidity

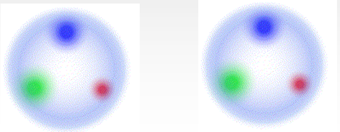
$$B\rho = \frac{p}{e}$$



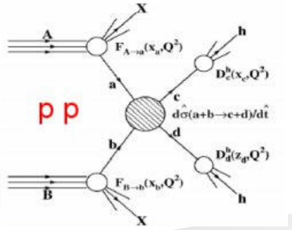
Technological limit of bending magnet field strength
⇒ **Limits LHC to E_{cm}=14 TeV** ($\propto$ B)
⇒ Superconducting magnets needed

Hadron versus lepton collisions

- Colliding particles can be elementary particle (lepton) or composite object (hadron)
  - LEP: e^+e^- (lepton)
  - LHC: pp (hadron)

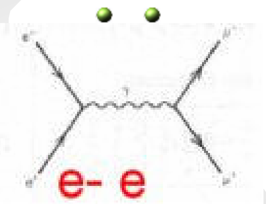


- Hadron collider:
  - Hadrons easier to accelerate to high energies



- Lepton collider (LC):
  - well-defined E_{CM}
  - well-defined polarization (potentially)

  $\rightarrow$ are better at **precision measurements**



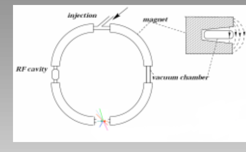
Proton proton collision are more complex

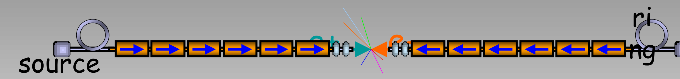
Example of LHC versus lepton colliders: Higgs

- LHC might discover one, or more, Higgs particles, with a certain mass
- However, discovery and mass are not enough
- Are we 100% sure it is really a SM/MSSM Higgs Boson?
  - What is its spin?
  - Exact coupling to fermions and gauge bosons?
  - What are its self-couplings?
- So, are these properties exactly compatible with the SM/MSSM Higgs?

Confidence requires a need for precision

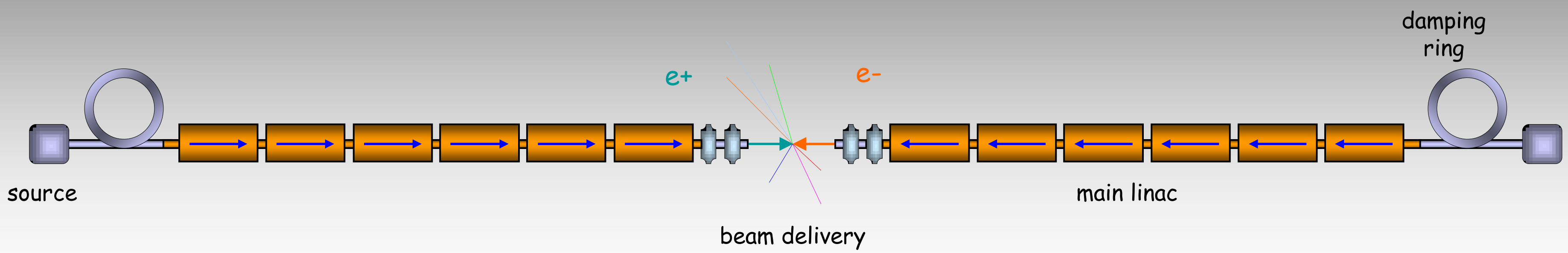
The three main parameters





	Rings	Linear colliders
Particle type(s)	ions, p/$\overline{\text{p}}$, $e^{+/-}$	ions, p/$\overline{\text{p}}$, $e^{+/-}$
Collision energy	accelerating cavities reused	accelerating cavities used once
Luminosity	▪ bunches collided many times ▪ several detectors simultaneously	▪ each bunch collide only once ▪ only one detector in use at a given time

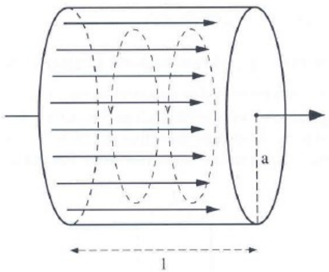
What is a linear collider?

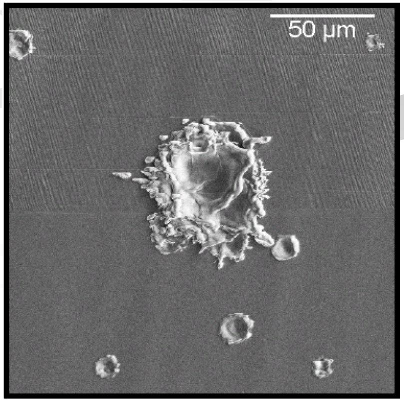


- Main part: two long linear accelerators (linacs), with as high accelerating gradient as possible
- The two beams are "shot" into the collision point, with a moderate repetion rate $f_r \sim 10$ Hz
- Damping rings needed to get the initial emittance, ε, as low as possible
- Beam Delivery System and final focus are needed to prepare the the beam for collisions (remember: very small beta function, $\beta(s)$, needed at the collision point)

1^{st} challenge: E_{COM}

- Accelerating cavities used once
- The length of the linac is then given by
  1. E_{CM}
  2. Accelerating gradient [V/m]
- E.g. for E_e=0.5 TeV and an average gradient of g=100 MV/m we get: l=E[eV] / g[V/m] = 5 km
  - Needs two linacs (e^+ and e^-) and a long final focus section ~ 5 km ⇒ total length for this example 15 km
- ⇒ 1^{st} main challenge of future linacs: **maximize gradient** to keep collider short enough !
- Gradient limited by field break down





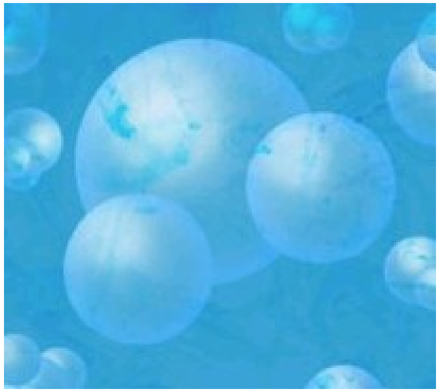
2nd challenge: $\mathcal{L}$

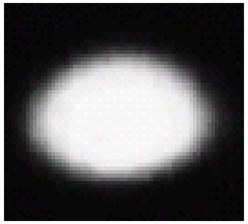
$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

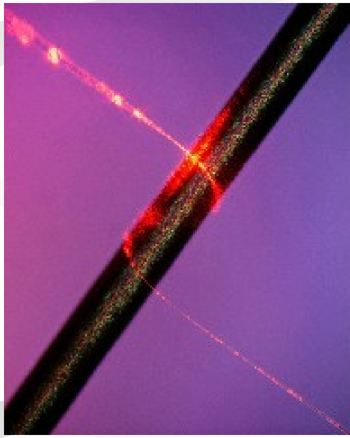
σ_x=40 nm, σ_y=0.9nm (!)

9Å ! Vertical bunch-width of a water molecule!

(LEP: width of a human hair)







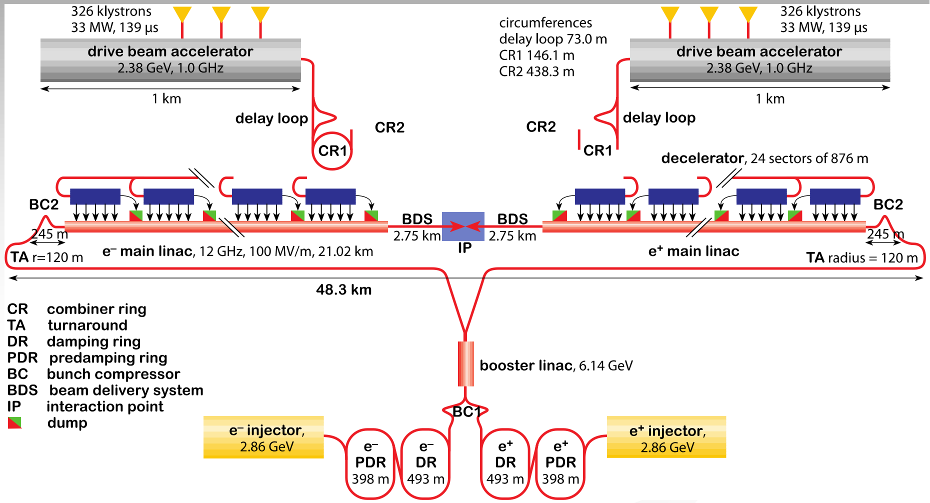
- Future linear colliders: truly **nanobeams**

The CLIC collaboration

- CLIC:

Compact Linear Collider

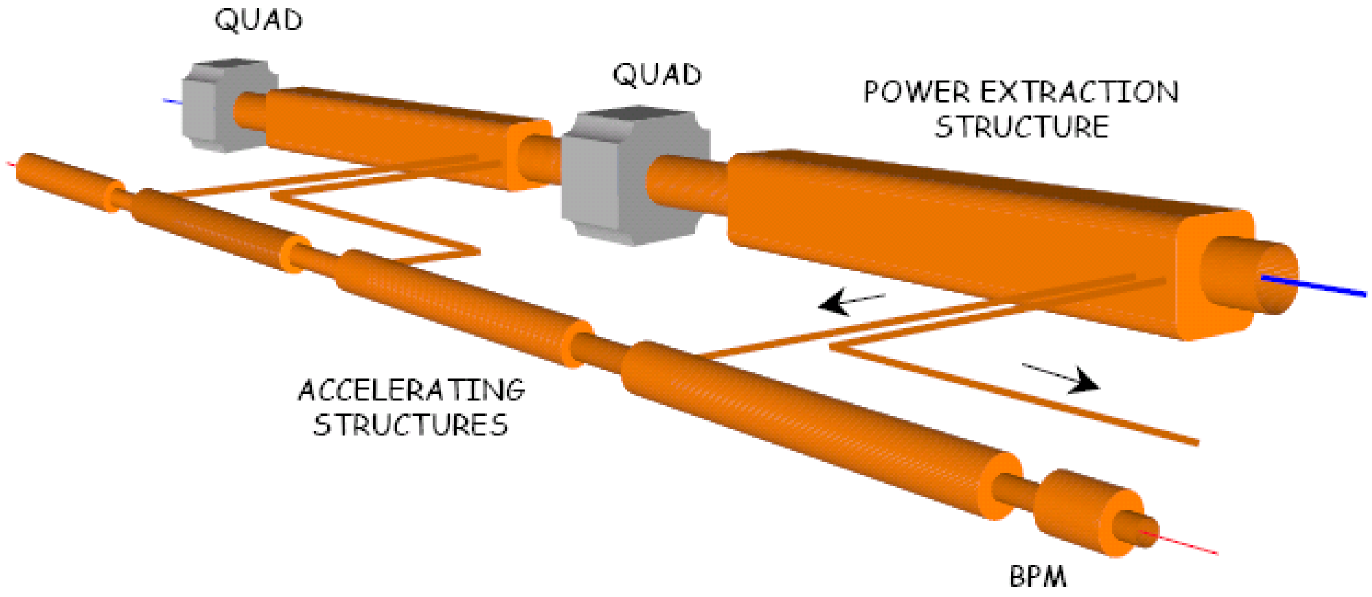
- Normal conducting cavities
- Gradient 100 MV/m
  - Limited by breakdown



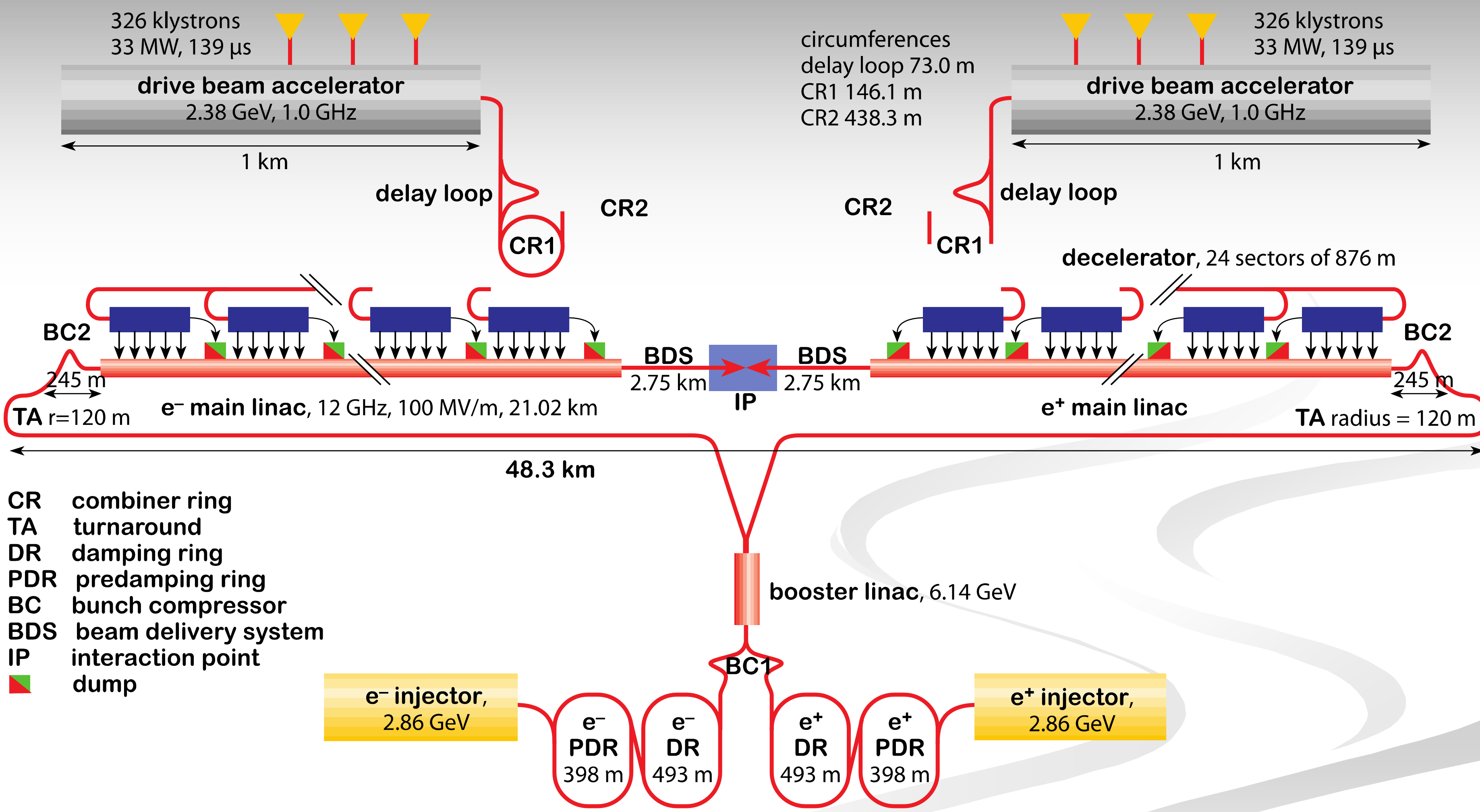
- Two-beam based acceleration
  - Instead of Klystrons use an e^- drive beam to generate power
  - For high-energy: klystrons (> 10000 needed) will be more costly, and must be extremely fail-safe
  - Power is easier to handle in form of beam ⇒ short pulses easier
  - Depending on final CLIC parameters klystrons might not even be feasible (too high POWER wrt. RF)

Two-beam accelerator scheme

- Power extracted from one beam (the drive beam) to provide power main beam
- Special Power Extraction Transfer Structure (PETS) technology
- Particles generate wake fields ↔ leaves behind energy

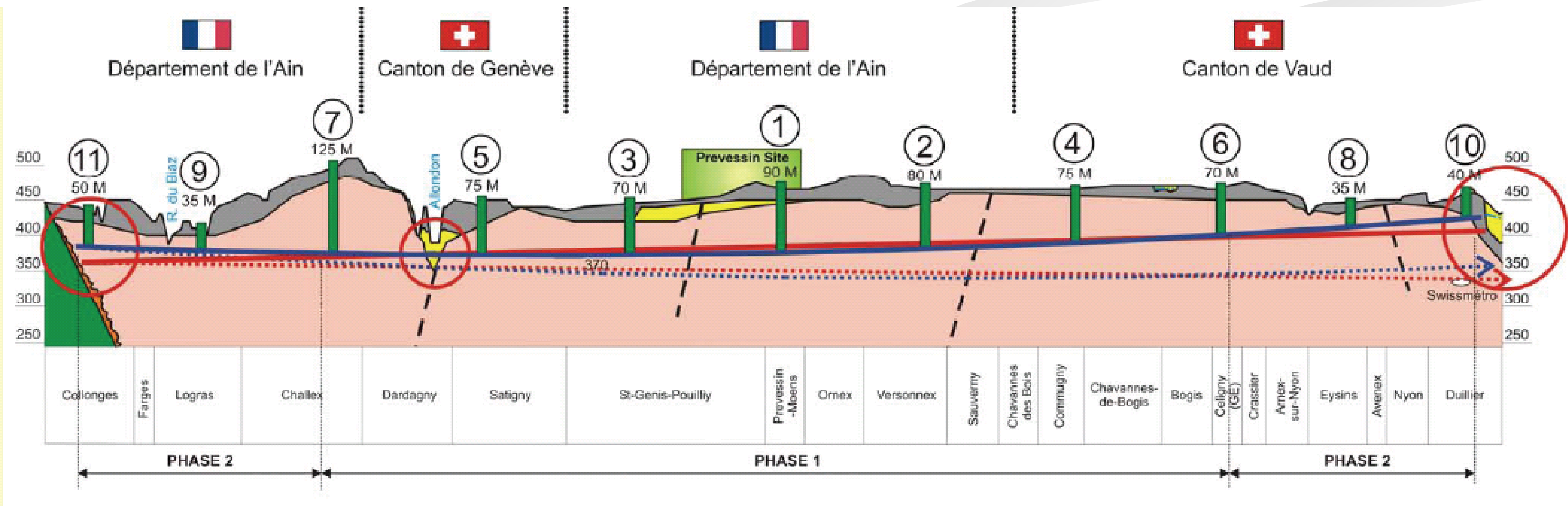


The CLIC Layout



Potential site at CERN

- Global project → interests in Europe, USA, Asia
- In fact two different designs being studied CLIC and the ILC
- Which design, and where, depends on many factors, including the results of LHC physics
- CERN: advantage of quite nice stable ground

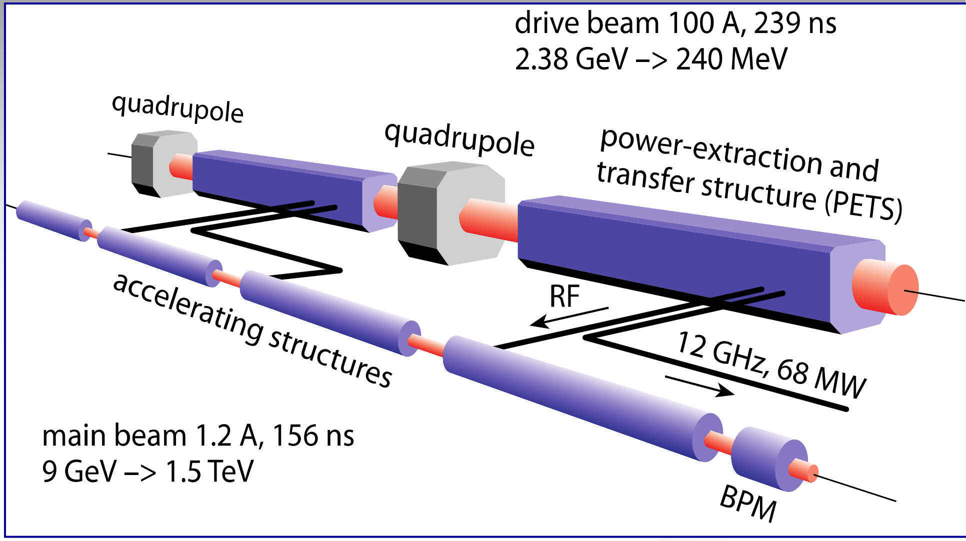


CLIC Main Parameters (3/2007)

- **Particle type: e^- and e^+**

- **E_{cm} = up to 3 TeV studied**
- Gradient: 100 MV/m
- Length: 47.6 km (at 3 Tev)

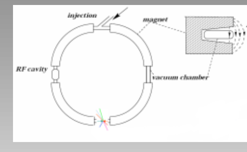
- **Luminosity: 2×10^{34} $cm^{-2}s^{-1}$**
- Particles per bunch: 3×10^9
- Pulse train repetition rate: 50 Hz
- Beam size at IP: σ_x = 40 nm , σ_y = 0.9 nm

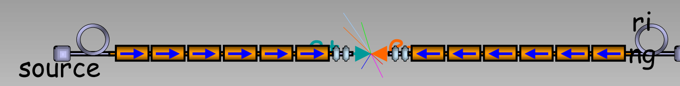


CLIC

Novel two-beam acceleration: the future of linear accelerators?

Grand summary: LHC and CLIC





	LHC	CLIC
Collider type	Ring	Linear, 100 MV/m
Length	27 km circumference	48 km linear length
Particle type(s)	p/p, ions	$e^{+/-}$
Collision energy	**14 TeV** per proton (max. of a few TeV per parton)	**3 TeV**
Luminosity	▪ ~ 10^{11} protons per bunch ▪ f_r = 40 MHz ▪ $\sigma_{ip} \approx 17\ \mu m$ **L ~ 10^{34} $cm^{-2}s^{-1}$**	▪ ~ 10^{9} $e^{+/-}$ per bunch ▪ f_r ~ 50 Hz (train) ▪ $\sigma_{y,ip}$ ~ 1 nm **L ~ 10^{34} $cm^{-2}s^{-1}$**