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Particle Accelerators

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Course Outline

- Part 1: History and Basic Concepts
  - Why? -- e vs. p -- circular vs. linear -- luminosity
- Part 2: Transverse Beam Dynamics
  - Ray tracing -- orbit -- emittance -- correction
- Part 3: Diagnostics and Correction
  - Devices -- Methods
- Part 4: Accelerator Subsystems
  - Sources -- RF -- Magnets -- Diagnostics
- Part 5: LHC and CLIC/ILC
  - Requirements -- Implementation -- What's special?

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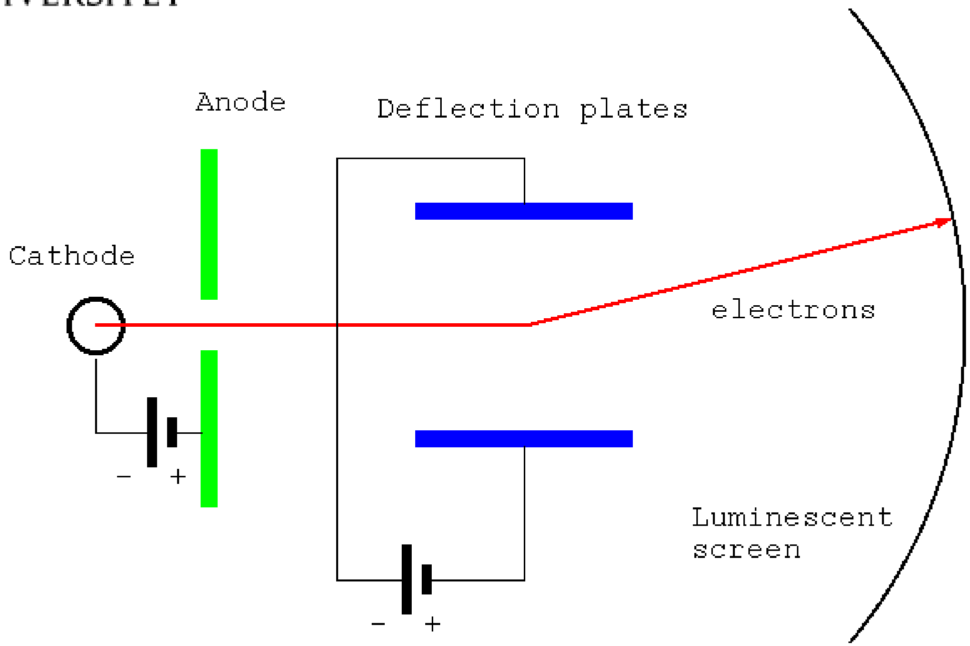
Accelerator Timeline

- 1897: Cathode ray tube → next slide
- 1929: van-deGraaff, Cyclotron
- 1932: Cockroft-Walton
- 1940: Betatron
- 1950: Phase stability
- 1957: CERN-PS
- 1957: Cancer therapy with protons
- 1962: Stanford Linear Accelerator
- 1960s: 1G light sources
- 1971: ISR, first hadron collider
- 1976: SPS
- 1970s: electron and stochastic cooling
- 1978: Tevatron (1992 as collider)
- 1980: SppS
- 1989: LEP and SLC
- 1990s: 3G light sources
- 1992: HERA
- 1993: SSC cancelled
- 1990s: Factories (KEKB,PEPII,DaΦne)
- 2000: RHIC
- 2004: decision that ILC will be s.c.
- 2008: LHC

Cathode Ray Tube



- It's a TV, well nearly
- Karl Braun, 1897
- Evacuated tube
- Thermionic cathode
- Accelerating voltage
- Electric or magnetic deflection system
- Luminescent screen

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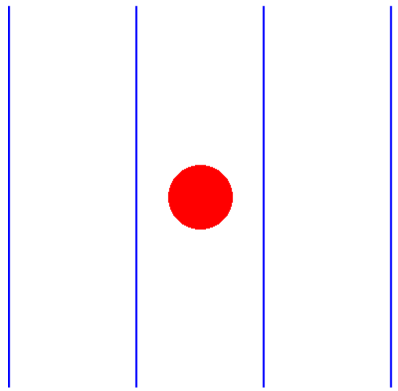
Why high energies?

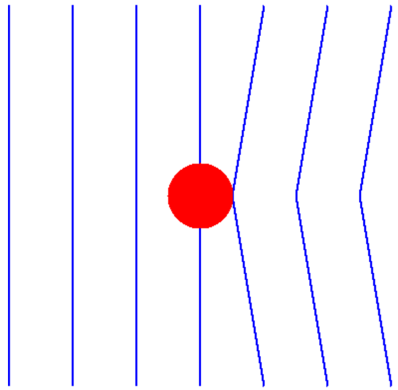


- To measure something small requires something smaller.
  - long wavelength waves in water do not produce a diffraction pattern off a buoy.
  - short wavelength waves produce such a pattern
  - Interference
- de'Broglie and the wave-particle dualism

  $\lambda = h/p$, p = momentum of particle

- Large particle momentum needed to discern small structures

  $\rightarrow$ Accelerators



➔ Make the beam particles behave as “short wavelength light” to probe the substructure of atoms or nuclei.

➔ Create sufficient **energy density** to create new particles.

➔ Emit **synchrotron radiation** for experiments in solid state physics or biology or material science

Electrons vs. Protons

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- Electrons are
  - point-like → precision, clean
  - light → limited in energy
  - emit synchrotron radiation

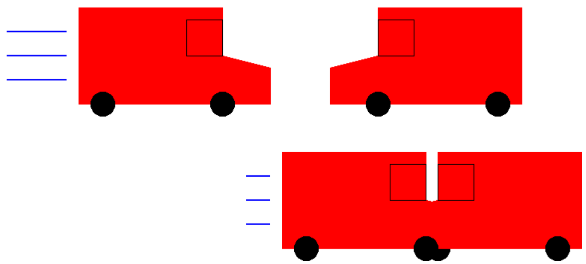
$$\Delta E[\mathrm{keV}] = 88.5\frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]}$$

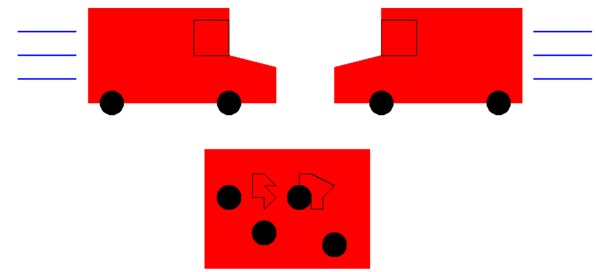
- Protons are
  - 2000 times more heavy than electrons → high energies, but large magnets are required
  - conglomerates of quarks and gluons → a lot happens in a collision and is more difficult to interpret and hadronization is not fully understood.

Circular vs. Linear

- Linear accelerator
  - every acceleration structure is only used once, but few magnets needed
  - negligible synchrotron radiation for electrons
  - low bunch repetition rate (SLC: 120 Hz)
- Circular accelerators
  - recycle acceleration structures, but many magnets
  - synchrotron radiation losses
  - high bunch repetition rate (LHC: 11 kHz) → luminosity
  - iterated systed → beam stability more difficult

Collider vs. Fixed Target





- Consider the energy available to create new particles
- Momentum is conserved and therefore there is energy in the center-of-mass motion.
- The available energy is

$$E_{CM} = \sqrt{m_b^2 c^4 + m_t^2 c^4 + 2 m_t c^2 E_L}$$

- In head on collisions all energy is available

$$E_{CM} = 2\, E_L$$

Luminosity

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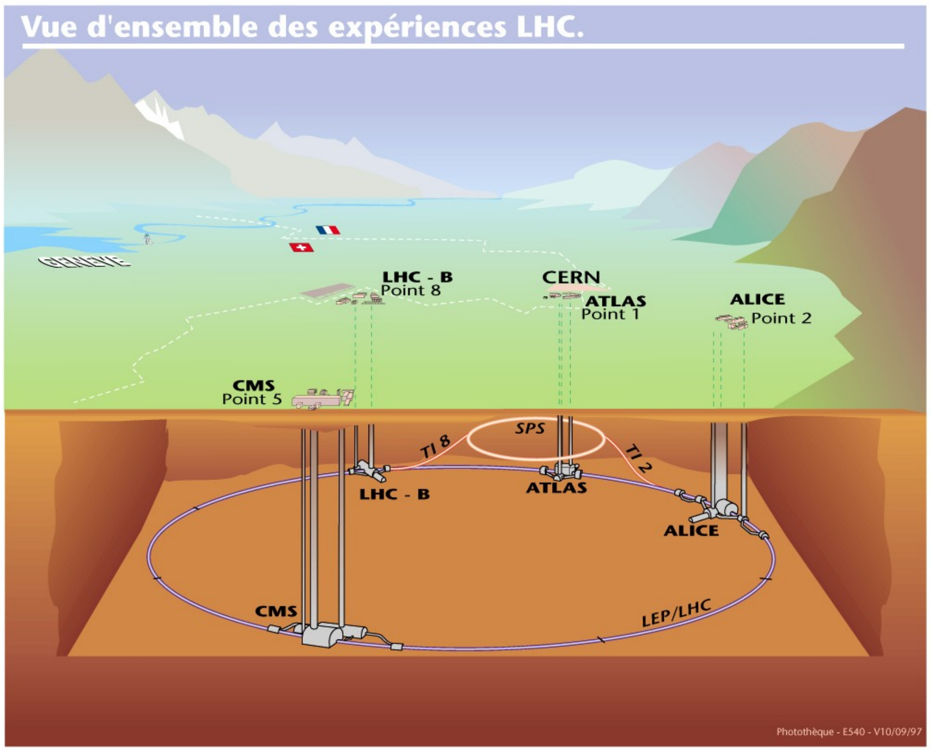
- Count rate in experiment is determined by the
  - cross section σ [barn = 10^{-24} cm^2]
  - machine dependent properties → Luminosity [1/cm^2 s]
- Luminosity for fixed targets
  - L = (number of target particles/cm^2) times (number of beam particles/s)
- Luminosity for colliding beams (equal and gaussian)

$$\begin{aligned} \mathcal{L} &= N_1 N_2 f_c \int d^2x \rho_1(\vec{x}; \sigma_x, \sigma_y) \rho_2(\vec{x}; \bar{\sigma}_x, \bar{\sigma}_y) \\ &= \frac{N_1 N_2 f_c}{2\pi \sqrt{(\sigma_x^2 + \bar{\sigma}_x^2)(\sigma_y^2 + \bar{\sigma}_y^2)}} = \frac{N_1 N_2 f_c}{4\pi \sigma_x \sigma_y} \end{aligned}$$

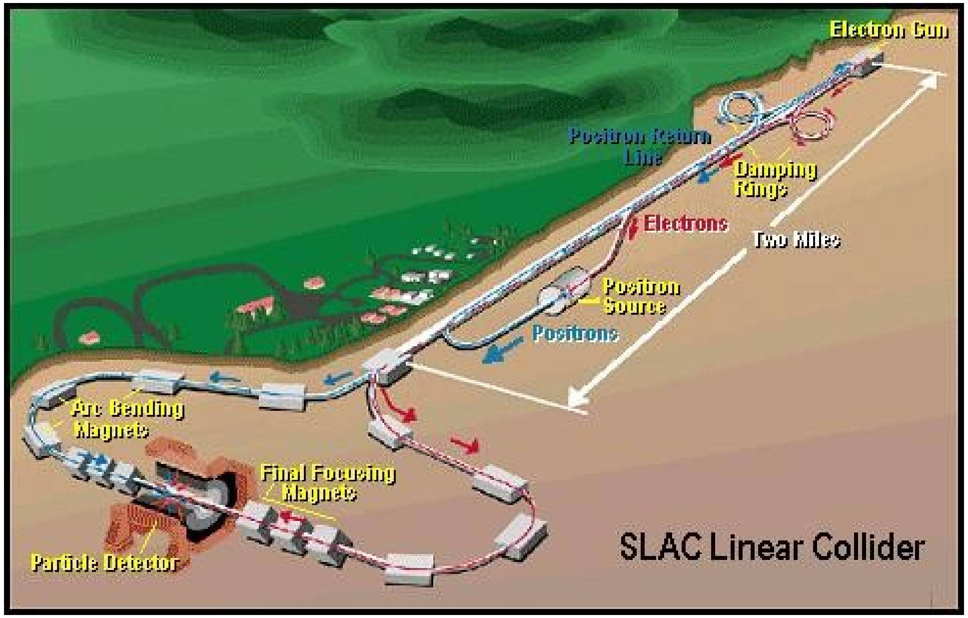
LEP and LHC at CERN, Geneva



- Both ~~in~~ under Switzerland and France
- crosses border 22000/s
- LHC starts operation this Wednesday

- **SPS** (Nobel prize for W discovery in 82) is used as injector
- **LEP:** e+e- collider with 27 km circumference and 100 GeV maximum energy per beam
- LEP was built in the 80s to invetigate the electro-weak theory, Z and W bosons
- Only 3 families
- Enormous s.r. losses up to 3 GeV per turn
- Superconducting accelerating cavities
- **LHC:** p-p-collider up to 7.7 TeV
- 1200 Superconducting Magnets with 8 T field cooled by 1.8 K Helium
- Four major experiments: CMS, LHCb, ALICE, ATLAS

Stanford Linear Collider



- 3 km long e+e- linac with 3GHz RF
- Microwave and Vacuum technology allowed RF to reach up to 20 GeV in the 60s
- Upgraded to 50 GeV in 80s
- Revolutionary concept: Linear collider
- low rep rate of 120 Hz, but micron size spots at interaction point
- Much new diagnostics and control: beam-beam, feedback
- in operation until 200?
- Now injector for the B-factory based on PEP
- Linac for SLAC's X-ray free-electron laser LCLS and its precursor SPPS

Scandinavian Accelerators

- Astrid in Århus, Denmark
  - Electrons and Ions, C_{60}, ELISE
- MAXLAB in Lund
  - Synchrotron light sources Max I through IV?
- Cryring in Stockholm (to FAIR eventually)
  - Atomic physics, dissociative recombination
- CELSIUS in Uppsala until 6/2005
  - Electron Cooler Ring for Nuclear Physics
- GW-cyclotron and then SPTC for cancer treatment in Uppsala
- Jyväskylä, Finland: 130 MeV cyclotron
  - Ions for Nuclear Physics and Biology

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Synchrotron Light Sources

- Generate Photons
  - Short wavelength → resolve small structures
  - High intensity → short time and weak processes
  - Short pulses → fast processes, down to fs
- 1st generation: Parasitic at HEP accelerators
- 2nd generation: add special magnets (wiigler and undulators
- 3rd generation: Dedicated accelerators
- 4th generation: Free-Electron Laser, often SASE

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SPEAR at SLAC

- Late 60s: 3.5 GeV e+e- collider → J/ψ → ½ Nobel prize for Burt Richter '74
- 270 m circumference
- Turned in 80s to synchrotron radiation research from bending magnets (1st generation light source)
- Added Undulators and Wigglers in the 90s (2nd generation light source
- Major rebuild in early 2000s turned it into a 3rd generation light source with a low emittance optics
- *4G: X-ray Free-Electron laser → LCLS*