Outline (2 + discussion lecture)

- Concepts: Energy Gain, E / B field. Units
- Types of accelerators. Linac, Ring, Collider
- Components: Source, Magnets, resonant Cavities
- Energy and Luminosity
- Synchrotron Radiation
- Electron vs Proton Colliders
- LEP, LHC, ILC

Both: Principles and examples of real bits and pieces with figures and number from CERN machines

Current and future challenges.

Acknowledgement: thanks to many of my CERN colleagues. In particular Oliver Brüning (HST previous years), Richard Scrivens (Sources), Werner Herr,…
The CERN accelerator complex: injectors and transfer

Beam 1

Beam 2

LHC

SPS

450 GeV

26 GeV

2

3

4

5

6

7

8

LHC

LINACS

Booster, 1.4 GeV

CPS

TI2

TI8

protons

Ions

LEIR

26 GeV

450 GeV
LEP Beam pipe

vacuum channel

131 mm x 70 mm
beam channel

cooling channel

LHC dipole magnet cross section

Single cell 1.3 GHz Tesla test cavity

LHC cable NbTi

131 mm x 70 mm beam channel
About Me

Helmut.Burkhardt@cern.ch  http://hbu.home.cern.ch/hbu/Welcome.html

PhD Oct. 1982 in Exp. Physics at Hamburg University, study of e+e- coll. 14 - 35 GeV
Since then at CERN, as Fellow and Siegen Univ. PostDoc. Working on SPS proton fixed
target experiments (protons 450 GeV)
\( \mu \) likesign analysis \( \nu \) - CDHS, NA31 direct CP violation experiment (HEPP-EPS price 2005)
\( \aleph \) Aleph-Experiment @ LEP 1985-1900 with Luminosity / Background monitors.

CERN-Staff (1990) :
1990 - SPS / LEP operation as “Engineer In Charge”
1995 - SPS / LEP machine coordination. LEP e+e-, 90 - 209 GeV
1999 - now :
Senior Accelerator Physicist in Accelerator Physics Group (AB/ABP)
Studies, improvements and upgrade of present (SPS) and design and commissioning of new/
future machines :
**LHC 14 TeV pp, SPS-LHC transfer lines**, ELFE study, ECFA-TESLA study, EuroTeV-ILC
study 0.5 -1 TeV e+e-, CLIC study 3 TeV e+e-
Motivation

The progress of our understanding of fundamental particles and forces is very closely linked to the progress in accelerators.

What do I need to discover a new particle, like the Higgs?

An accelerator which provides enough Energy and collisions (Luminosity)

Beam 1 \[\rightarrow\] new particles \[\rightarrow\] Beam 2

**LEP** (e+e- collider @ CERN, 1990-2000):
- $E = 90 - 209$ GeV, ideal to study $Z$ and $W^+W^-$.  
- $e^+e^- \rightarrow HZ \quad m_Z \cdot 91$ GeV \quad Leaves at best $209 - 91$ GeV $= 118$ GeV.  
- Higgs not found in direct search at LEP. \quad Implies \quad m_H > 114$ GeV

**LHC** will provide collisions at $14$ TeV (7 TeV + 7 TeV protons) from 2008 on and directly produce Higgs and / or other new particles previously out of reach.
Progress in Accelerators: The Energy Frontier

My current version of the Livingston Plot

**Exponential growth** of $E_{\text{cms}}$ in time

Starting in 60’s with $e^+e^-$ at about 1GeV

Factor 4 every 10 y

$pp, \bar{p}p: \frac{E_{\text{cms}}}{6}$

5 x above $e^+e^-$ at same time discovery machines.

Accelerator R&D was originally and still is to a large extent) driven by particle physics. Impressive progress. Besides top energy: increase in intensity (number of particles), reliability, cost effectiveness. Accelerators widely used as synchrotron light sources, for medicine (diagnosis and treatments),…
Concepts and Units

Electric E field:
- Acceleration or rather Energy gain of 1 eV

Electric charge e and electric field E

1 eV $\approx 1.60 \times 10^{-19}$ J

$1 \text{ GeV} = 10^9 \text{ eV}$

$1 \text{ TeV} = 10^{12} \text{ eV}$

$m_e \approx 0.511 \text{ MeV}/c^2 = 9.11 \times 10^{-31}$ kg

$m_p \approx 938 \text{ MeV}/c^2 = 1.67 \times 10^{-27}$ kg

for precise numbers see http://pdg.lbl.gov/2005/reviews/consrpp.pdf

Einstein’s special relativity, Lorentz transformation

$E = \gamma m c^2$

$p = \beta \gamma m c$

$\beta = \frac{v}{c}$

$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$

Comparison for 10 GeV total energy

Electron $\beta = 0.999\,999\,9987$ $\gamma = 19569.5$

Proton $\beta = 0.995\,588\,4973$ $\gamma = 10.6579$
Particle sources

Thermionic electron source principle
( Cathode ray tube )

Example:
e-gun in CTF3

100 - 150 kV
Proton and ion sources

Various methods exist to produce p (H\(^+\)), H\(^-\) (p with 2 e\(^-\)) and heavy ions (heavier atoms, most electrons removed)

Typically involves:
low pressure heated gas (ionized gas / plasma, inject H\(_2\) to get protons),
or surface sputtering, electric and magnetic fields (keep the electrons)
Linear Acceleration with Electrostatic Field

limited by HV-breakdown ~ 1 MV / m

Cockcroft Walton voltage multiplier

Van de Graaff generator static electricity from belts

Oak Ridge Tandem Van de Graaff generator reached 25.5 MV using pressurised SF$_6$

800 kV proton pre-injector used at CERN until 1993
Time Varying Fields

Radiofrequency or short RF acceleration allows for multiple passages.

Higher RF frequencies also allow for higher acceleration gradients—no time for breakdown - flashover.

- LEP: 8 MV/m at 352 MHz
- Tesla / ILC: 30 MV/m at 1.3 GHz
- CLIC: 150 MV/m at 30 GHz
Lorentz Force

- Electric field $\mathbf{E}$ provides the acceleration / energy gain
- The magnetic field $\mathbf{B}$ keeps the particles on their path

Simple case - circular motion:
$\mathbf{E} = 0 \quad \mathbf{v} \perp \mathbf{B}$

Example LHC:
- Momentum $p = 7000 \text{ GeV/c}$
- LHC bending radius $\rho = 2804 \text{ m}$
- Bending field $B = 8.33 \text{ Tesla}$
- Provided by superconducting magnets cooled with He to 1.9 K

\[
B = \frac{p}{q \rho}
\]

For $q = e$ numerically

\[
B[T] = p[GeV/c] \frac{3.336 \text{ m}}{\rho}
\]
Circular Accelerator

- **Cyclotron**: constant rf-frequency and magnetic field radius $\rho$ increases with energy. Used for smaller machines.

- **Synchrotron**: $\rho = \text{const.}$, $B$ increased with energy. rf-frequency adjusted slightly ($\beta = 0.999.. 1.0$)

The CERN ring accelerators PS, SPS, LEP - LHC are of this type.

\[ p \, [\text{GeV/c}] = B \, [\text{T}] \, \rho / 3.336 \, \text{m} \]

LHC:
\[ B = 8.33 \, \text{T} \]
\[ \rho = 2804 \, \text{m} \]
\[ p = 7 \, \text{TeV} / \text{c} \]
Phase stability I

Revolution frequency \( f_{\text{rev}} = h f_{\text{rf}} \)

Circumference \( L = \frac{v}{f_{\text{rev}}} = \beta c / f_{\text{rev}} \)

LEP \( h=31320 \) \( f_{\text{rf}} = 352.209 \text{ MHz} \) \( L = 26658.9 \text{ m} \)

\( f_{\text{rev}} = 11.2455 \text{ kHz} \) 1 turn in 88.9244 µs
Magnets and Power Consumption

\[ P = R I^2 \]

**LEP**

\[ B = 0.1 \text{ T} \]

\[ I = 4500 \text{ A} \quad R = 1 \text{ m}\Omega \quad P = 20 \text{ kW / magnet} \]

c. 500 magnets \[ \rightarrow P = 10 \text{ MW} \]

**LHC** \[ B \propto I \]

\[ B = 8.38 \text{ T} \]

\[ I = 280 \text{ kA} \quad R = 1 \text{ m}\Omega \quad P = 78 \text{ MW / magnet} \]

c. 500 magnets \[ \rightarrow P = 39 \text{ GW} \]

Use superconducting technology !
Synchrotron Radiation

Generally: any accelerated charge emits radiation
Significant for highly relativistic particles $\gamma > 1000$ on curved path

Critical energy, energy loss / turn and Power

$$E_c = \frac{3}{2} \frac{\hbar c \gamma^3}{\rho} = 2.96 \times 10^{-7} \text{eV m} \frac{\gamma^3}{\rho}$$
$$U_0 = \frac{e^2 \gamma^4}{3\varepsilon_0 \rho} \approx 6.0317 \cdot 10^{-9} \text{eV m} \frac{\gamma^4}{\rho}$$
$$P_b = \frac{U_0 I_b}{e}$$

**LEP:** $E_{b\text{max}} = 104.5 \text{ GeV}$ $\gamma = 204501$ $\rho = 3026 \text{ m}$ $E_c = 836 \text{ keV}$
$U_0 = 3.49 \text{ GeV}$ total beam current $I_b = 5 \text{ mA}$ $P_b = 18 \text{ MW}$
Limited by Energy Loss in Synchrotron Radiation / superconducting RF system
Magnetic field “only” 0.115 T

Much higher beam energy: needs linear collider (ILC / CLIC) or
**LHC** with $p$ instead of $e$ $\gamma^4 : (m_p/m_e)^4 = 1.13 \times 10^{13}$
$E_b = 7 \text{ TeV}$, $\gamma = 7460$, $U_0 = 6.7 \text{ keV/turn}$, $E_c = 44 \text{ eV}$ $I_b = 1.07 \text{ A}$ $P_b = 7.2 \text{ kW}$
# LEP / LHC syn.rad. comparison

<table>
<thead>
<tr>
<th></th>
<th>E (GeV)</th>
<th>$\rho$ (m)</th>
<th>$\gamma$</th>
<th>$E_c$ (keV)</th>
<th>$U_0$ (MeV)</th>
<th>$N_{10^{12}}$</th>
<th>I (mA)</th>
<th>$P_b$ (MW)</th>
<th>B (T)</th>
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<tbody>
<tr>
<td>LEP1</td>
<td>45.6</td>
<td>3026</td>
<td>89237</td>
<td>69.5</td>
<td>126</td>
<td>2.22</td>
<td>4</td>
<td>0.5</td>
<td>0.05</td>
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<tr>
<td>LEP2</td>
<td>104.5</td>
<td>3026</td>
<td>204501</td>
<td>836</td>
<td>3490</td>
<td>2.8</td>
<td>5</td>
<td>18</td>
<td>0.115</td>
</tr>
<tr>
<td>LHC</td>
<td>7000</td>
<td>2804</td>
<td>7460.5</td>
<td>0.044</td>
<td>0.0067</td>
<td>646</td>
<td>1163</td>
<td>0.0072</td>
<td>8.33</td>
</tr>
</tbody>
</table>


The long dipole synchrotron radiation spectrum is very broad. Half of the power is radiated above the critical energy. With increasing $E_b$, $\gamma$ the spectrum gets extended to higher energies / frequencies.
Synchrotron light monitor

Here a picture from LEP.

Typical transverse rms beam size
0.15 mm vertical
1.5 mm horiz.

Mirror, telescope and camera: beams continuously visible. Will also be used for protons in the LHC.
Fixed Target vs Collider

Fixed target, high energy collisions:
Energy “lost” as kinetic energy

$$E_{\text{cm}} \approx \sqrt{2E_b m_T c^2}$$

High Energy $e^+e^-$ and very high energy pp:
needs colliders

$$E_{\text{cm}} = 2E_b$$
**Luminosity**

**Event rate** for process with cross section $\sigma$

$$\dot{n} = L \sigma$$

**Luminosity** from bunch crossings at frequency $f = f_{\text{rev}} n_b$

$$L = \frac{N_1 N_2 f}{A}$$

For Gaussian bunches with rms sizes $\sigma_x, \sigma_y$

$$A = 4 \pi \sigma_x \sigma_y$$

High $L$ : collide many particles, squeezed in small bunches
LHC $1.15 \times 10^{11}$ protons, $n_b = 2808$ (crossings at 25 ns intervals),
Beams squeezed using strong large aperture quadrupoles around the interaction points
from $\sim 0.2$ mm to $\sigma_x = \sigma_y = 17 \mu$m

Rare new processes, like Higgs production can have very small cross section,
like $1 \text{fb} = 10^{-39} \text{cm}^2$. LHC designed for very high Luminosity $L = 10^{34} \text{cm}^{-2}\text{s}^{-1}$
Event rate for such rare processes : $\sim 1$ new particle every 28h. Instead pp 20 / crossing
Vacuum, Beam Gas interaction

Beam blow up, core + halo
Background to experiments
loss, radiation, beam and
Luminosity lifetime

Minimize:
Good vacuum
Collimation

\[ \rho_m = 1 \text{ ntorr} = 1.33 \times 10^{-7} \text{ Pa} \]
\[ \rho_m = \frac{p}{kT} = 3.26 \times 10^{13} \text{ molecules / m}^3 \]

typical cross section \( \sigma = 6 \text{ barn} = 6 \times 10^{-28} \text{ m}^2 \)

collision probability \( P_{\text{coll}} = \sigma \rho_m = 1.96 \times 10^{-14} \text{ / m} \)

for \( v \approx c \) 1 collision every \( \frac{1}{P_{\text{coll}} c} = 1.7 \times 10^5 \text{ s} = 47 \text{ hours} \)
Quadrupole focusing

Lens focusing in x
defocusing in y
or vice versa

alternate gradient focusing

FODO
Betatron Oscillations, $\beta$-Function and Tune

Here somewhat qualitatively. Formally: solve equation of motion: “Hill’s” equation.

Courant and H. S. Snyder, 1957, Annals of Physics 281, 360

Particle trajectories:
Solution with betatron oscillations around a stable orbit.

Tune $Q =$ **number of betatron oscillations**

Magnets as lattice elements, to first order described by a linear transformation: Matrix multiplication with particle vector

$$
\begin{pmatrix}
x(s)
ox'(s)
\end{pmatrix} = M
\begin{pmatrix}
x(s_0)
x'(s_0)
\end{pmatrix}
$$

simple example, IP - IP

$$
M = \begin{pmatrix}
\cos 2\pi Q & \beta \sin 2\pi Q \\
-\frac{1}{\beta} \sin 2\pi Q & \cos 2\pi Q
\end{pmatrix}
$$
Orbit stability and tune

Misalignments and dipole field errors → orbit perturbations would add up on successive turns for integer tune $Q = N$

Higher order field errors, Quad., Sext. Perturbations. Avoid simple fractional tunes $nQ_x + mQ_y + mQ_s = \text{int.}$

Minimise field and alignment errors
Orbit and Tune measurement, Peak current

Beam Pickup Monitor

\[ \langle I_b \rangle = n e f_{rev} \quad I = \frac{\langle I_b \rangle L}{\sqrt{2\pi} \sigma_z} \]

<table>
<thead>
<tr>
<th></th>
<th>\langle I_b \rangle</th>
<th>\sigma_z</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>( 4 \times 10^{11} )</td>
<td>0.72 mA</td>
<td>2 cm</td>
</tr>
<tr>
<td>LHC</td>
<td>( 1.15 \times 10^{11} )</td>
<td>0.21 mA</td>
<td>7.55 cm</td>
</tr>
</tbody>
</table>

LEP/LHC \( f_{rev} = 11245 \text{ kHz}, L = 26658.9 \text{ m} \)

Bunch peak currents are many Amperes!

“Easy” to measure. Unwanted effects:
wake fields, heating, ~ instabilities
Transverse Beam Size and Emittance

The emittance $\varepsilon$ is a constant for the machine (phase space density or kind of temperature)

Ideal machine: $x$, $y$, $z$ motion uncoupled, 3 emittances $\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$

$\text{IP: squeeze } \beta \text{ to a minimal } \beta^* \implies \text{maximum of divergence, aperture}$
Emittance

e+ e- ring : equilibrium emittance from synchrotron radiation quantum excitation and energy loss / rf-acceleration damping

Distance between synchrotron photon emissions

\[ \lambda = \frac{\lambda_B}{B_{\perp}} \quad \text{where} \quad \lambda_B = \frac{2\sqrt{3}}{5} \frac{mc}{\alpha e} = 0.16183 \text{Tm} \]

horizontal emittance :

vertical emittance < 1 nm
naturally flat large x, small y beams

Linac, proton-ring (synchrotron radiation small) :

constant normalised emittance \( \epsilon_N = \beta \gamma \epsilon \) \( \text{3.75} \mu \text{m for LHC} \)

geometrical emittance decreases in acceleration \( \epsilon = \frac{\epsilon_N}{\beta \gamma} \) \( 7.8 \rightarrow 0.5 \text{ from 0.45 to 7 TeV} \)

Emittance given by injectors. For protons and ions typically round, \( \epsilon_x = \epsilon_y \)
Momentum compaction and transition

High energy: $\beta \cdot 1$ revolution time constant

“no more acceleration” in velocity, $v \cdot c$.

On the contrary. **Higher momentum particles on**

longer path, **slower in revolution:** above transition.

$\Delta p / p = 10^{-3}$ should remain within the

machine, say $\Delta \rho < 1$ mm. For large machines

LEP/LHC we have $\rho = 3$ km. This implies

strong momentum focusing

LHC: $\alpha_c = 3.4 \times 10^{-4}$

Also implies:

Large machines are very sensitive.

Very small circumference changes

produce noticeable momentum changes.

Tidal effects $\Delta L/L \sim 10^{-8}$ visible in LEP.

High (integer) tunes $Q \sim 100$

Still adjust fractional part to $10^{-3}$

Need for precise magnet control $\sim 10^{-5}$
Bunch length and Damping

negligible synchrotron radiation:
rf- only needed to keep particles bunched and accelerate, which
Ramping usually very slow - of order seconds or minutes
> $10^5$ turns, gain per turn small < MeV
Bunches can fill a large fraction of an rf-bucket
LHC $f_r= 400$ MHz $\lambda_{rf} = 75$ cm $\sigma_z = 11$ cm (450 GeV)

in case of strong synchrotron radiation (e-rings):
Major loss $U_0$ each turn, LEP2 : 3.5 GeV,
“all energy lost” in $E_b / U_0 = 104.5$ GeV / 3.49 GeV = 30 turns or 3 ms - damping time
Major continuous “acceleration” from RF to compensate for loss.
Bunch length small faction of $\lambda_{rf}$.
LEP $f_r = 352$ MHz, $\lambda_{rf} = 85$ cm, $\sigma_z = 1$ cm
rf-bucket, energy acceptance, e-ring

RF: more than $U_0$ needed for good energy aperture

Relative energy spread
$\sigma_e \sim 1.5 \times 10^{-3}$ for e-rings, LEP
Tails refilled by quantum fluctuations
Needs good rf-acceptance > 6.5 $\sigma_e$

Large acceptance and damping:
Allows for injection with accumulation.

good quantum lifetime: provide enough rf-voltage such that
loss by quantum fluctuations very improbable $\Delta E/E > 6.5 \sigma_e$
LHC Filling capture with animation

Filling: > 9 min (2 x 12 inj. x 21.6 sec.)

Off-energy particles remain in the machine
Slowly fill the abort gap
- cleaning foreseen (using the transverse damper), latest removed during start of ramp in the momentum cleaning section

LHC momentum collimation at $3 \times 10^{-3}$

RF-frequency 400 MHz
RF-bucket length $\lambda = 0.75$ m or 2.5 ns
RF-acceptance (bucket- 1/2 height) ~ $10^{-3}$
$\sigma_e = 3 \times 10^{-4}$ LHC 450 GeV

Shown here: simulation of injection with $3 \times 10^{-4}$ energy offset

Here 5000 particles, 100 turns. 3 sec CPU on iMac G5 2.1 GHz. using ps -> pdf -> quicktime movie conversion
Filling pattern - bunches, buckets, …

\[ f_{RF} = 400 \text{ MHz} \]
\[ \lambda_{RF} = 0.75 \text{ m or } 2.5 \text{ ns} \]
35,640 RF buckets
Bunches spaced by
25 ns or 10 buckets
Inject batches of
2, 3 or 4 \times 72 bunches
39 \times 72 = 2808 bunches in LHC
Leave a 119 bunch abort gap free \( \sim 3 \mu s \)
A full turn is 88.9 \mu s

Crossing angle needed for > 156 bunches
to avoid encounters closer than \( \sim 6 \sigma \)
Angle needed depends on \( \beta^* \)
Nominal angle \( \pm 150 \mu \text{rad} \)
SPS cycle for LHC injection

SPS proton cycle for LHC injection, total 21.8 s
LHC cycle

**Diagram Description:**
- **Injection plateau:** 0
- **alpha:** 5.92105E-06
- **Current rate end snapback:** 0.6
- **Current at injection:** 760
- **Current variation during snapback:** 20
- **Parabolic segment duration:** 405.333
- **Current at end exp:** 4110.000
- **b at end exp:** 3.000
- **Current to field scaling factor:** 1370.000
- **Max current rate:** 10.000
- **Current rate end parabolic:** 3.648
- **Exp time constant inverse:** 2.433E-03

**Timeline:**
- **Ramp down:** ≈ 18 Mins
- **Pre-Injection Plateau:** 15 Mins
- **Injection:** ≈ 15 Mins
- **Ramp:** ≈ 28 Mins
- **Squeeze:** < 5 Mins
- **Prepare Physics:** ≈ 10 Mins
- **Physics:** 10 - 20 Hrs
Major LHC challenges

Centre-of-mass energy of 7 TeV in given (ex LEP) tunnel
- Magnetic field of 8.33 T with superconducting magnets
- Helium cooling at 1.9 K
- Large amount of energy stored in magnets
- “Two accelerators” in one tunnel with opposite magnetic dipole field and ambitious beam parameters pushed for very high of luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$
- Many bunches with large amount of energy stored in beams

Complexity and Reliability
- Unprecedented complexity with 10000 magnets powered in 1700 electrical circuits, complex active and passive protection systems,….

- Emittance conservation $\varepsilon_n = \beta \gamma \varepsilon$ const., related to phase space density conservation, Liouville in absence of major energy exchange in synchrotron radiation / rf damping clean, perfectly matched injection, ramp, squeeze, minimize any blow up from: rf, kicking beam, frequent orbit changes, vibration, feedback, noise,…
- Dynamic effects - persistent current decay and snapback
- Non-linear fields (resonances, diffusion, dynamic aperture, non-linear beam dynamics (.. chaos) )
LHC dipole magnet

Dipole current distribution

\[ I(\Phi) = I_0 \cos(\phi) \]

field from current distribution

LHC dipole
LHC dipole magnet

2-in-1 dipole magnet design
8.4 T, 15 m long, 30 Ton
Operational margin of a superconducting LHC dipole

Applied magnetic field [T]

- Bc critical field
- 8.3 T
- 0.54 T

Superconducting state

- 1.9 K
- quench with fast loss of ~ 5 \cdot 10^9 protons

Normal state

- 9 K
- QUENCH

Temperature [K]

- 9 K
- Tc critical temperature

- 1.9 K
- quench with fast loss of ~ 5 \cdot 10^6 protons

- 7 TeV quench with fast loss of ~ 5 \cdot 10^6 protons
LHC beam parameters at 7 TeV

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum at collision</td>
<td>7 TeV/c</td>
<td>0.1 TeV/c</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$\sim 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Dipole field at 7 TeV</td>
<td>8.33 Tesla</td>
<td>0.11 T</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>4</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$1.15 \cdot 10^{11}$</td>
<td>$4.2 \cdot 10^{11}$ e$^+$, e$^-$</td>
</tr>
<tr>
<td>Typical beam size (ring)</td>
<td>200-300 µm</td>
<td>1800/140 µm (H/V)</td>
</tr>
<tr>
<td>Beam size at IP</td>
<td>16 µm</td>
<td>200/3 µm (H/V)</td>
</tr>
</tbody>
</table>

- Energy stored in the magnet system: 10 GJoule
- Energy stored in one (of 8) dipole circuit: 1.1 GJ
- Energy stored in one beam: 362 MJ
- Energy to heat and melt one kg of copper: 0.7 MJ

The LEP2 total stored beam energy was about 0.03 MJ
The total stored energy of the LHC beams

Nominal LHC design: \(3 \times 10^{14}\) protons accelerated to 7 TeV circulating at 11 kHz in a SC ring

LHC: > 100 x higher stored energy and small beam size: ~ 3 orders of magnitude in energy density and damage potential. Active protection (beam loss monitors, interlocks) and collimation for machine and experiments essential. Only the specially designed beam dump can safely absorb this energy.
Schematic layout of beam dump system in IR6

Septum magnet deflecting the extracted beam

H-V kicker for painting the beam

Beam Dump Block

Fast kicker magnet.
Rise time ~ 3 $\mu$s matching the abort gap of 119 bunches

about 700 m

about 500 m
Dumping the LHC beam

- Beam absorber (graphite)
- Concrete shielding
- About 8 m
- About 35 cm
Protection and Beam Energy

A small fraction of beam sufficient for damage

Very efficient protection systems throughout the cycle are required

A tiny fraction (~$10^{-4}$ at inj. $10^{-7}$ at 7 TeV) of the beam is sufficient to quench a magnet

Very efficient beam cleaning is required

- Sophisticated beam cleaning with about 50 collimators, each with two jaws + various specialized (injection...), in total about 100 collimators and beam absorbers
- Collimators are close to the beam (full gap as small as 2.2 mm, for 7 TeV with fully squeezed beams), such that particles get lost on collimators first!
Two warm LHC insertions dedicated to cleaning:
IR3  Momentum cleaning
IR7  Betatron cleaning

Collimators for injection, dump and in experimental insertions IR1, IR2, IR5, IR8.

Beam Dump in IR6.

Four large experiments: two multipurpose high L and two dedicated Heavy Ion (ALICE) and B-physics (LHC-B) experiments.

In addition: CMS/Totem $\sigma_{\text{tot}}$, Atlas high $\beta$, LHCf, …
Short outlook into the longer term future

High energy machines need many years to plan and build
about 25 years for the LHC: 1982 (well before LEP start) - 2007

Developments on the longer term future (for Φ > 2015) have
in fact already been going on for several years.

On the high energy frontier mainly:

- $E_{\text{cms}} = 0.2 - 0.5$ TeV (with possible 1 TeV extension) $e^+e^-$ collider ILC
- Multi (3-5) TeV $e^+e^-$ collider: CLIC
- LHC upgrade
ILC  International Linear Collider
www.linearcollider.org/cms/

GDE  Global Design Effort
interactions.org/linearcollider/gde/

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ILC 0.5 TeV, 30 km ; possible extension to 1 TeV  40-50 km.

Acceleration using superconducting (Tesla) RF, Nb, 1.3 GHz
This year : Baseline Configuration Document
Aim for decision in 2010. 1 US/FNAL, 1 Asian/KEK, 2 Europ. CERN, DESY site studies
Multi-TeV collider study: CLIC

- High acceleration gradient (150 MV/m)
  - “Compact” collider - overall length < 40 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)

Two-Beam Acceleration Scheme

- Capable to reach high frequency
- Cost-effective & efficient (~ 10% overall)
- Simple tunnel, no active elements

Central injector complex

- “Modular” design, can be built in stages

Very interesting and ambitious R&D - new accel. concept, innovative instruments..
Current aim: demonstrate feasibility (CTF3) + detailed conceptual design by 2010
LHC upgrade

LHC is designed for very high luminosity and energy. A further upgrade is very difficult but probably feasible. Many years of R&D efforts needed. First studies already started. Mainly along two lines:

**Higher luminosity (2 - 9 x 10^{34})**: SLHC
- \(\beta^*/2\), \(1.7 \times 10^{11}\) p / bunch, more bunches (5161 @ 12.5 ns) …
- new IR, larger crossing angle, also very challenging for the experiments; could be done in steps, timescale \(~ 10y\) from LHC start

**Doubling the Energy**: DLHC
- **new 15 T dipoles** (NbTi(Ta) or Nb\(_3\)Sn cable instead of currently NbTi)
- there are ideas to even triple the energy (Peter McIntyre et al.)
- with 25 T dipoles, inner windings Bi-2212, outer Nb\(_3\)Sn
Answers to Questions

Synchrotron Light Image of the Beam:
In reply to the question how a spot-like image is obtained:
U-shaped mirror + small slit to select radiation centre of bending magnet
optimised at diffraction limit
for details see: http://accelconf.web.cern.ch/AccelConf/d99/papers/CT08.pdf

What is a beam:
the particles moving in a controlled way in the evacuated “beam” pipe

What is a bunch:
group of beam-particles “captured” within one rf-wavelength

Why underground:
environmental / economic
  cosmic rays no problem - relatively small rate and easily identified / rejected by detectors

Movies, pictures:
http://user.web.cern.ch/user/Communication/MediaPublicCorner/MediaPublicCorner.html