ABSTRACT

Over the last few years, the possibility of installing a Large Hadron Collider (LHC) on top of LEP in the LEP tunnel has been considered. This double-channel, superconducting machine would collide protons at an energy of about 8 TeV per beam, provided a magnetic field as high as 10 T can be reached in the main bending magnets. The present design allows for a very high luminosity in excess of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in proton-proton mode, while the possibility of providing heavy ion collisions and electron-proton collisions considerably increases the potential of the CERN accelerator complex. The structure and performance of the machine are described, as well as the present status of the ongoing research and development programme which has been launched to make this project possible.
DESIGN OF THE LHC

J. Garayle

A
General features
Performance limitations
Main choices
Injectors
Operational aspects

B
Magnet errors
Effect of errors on particle dynamics
How to minimize the effect of errors
Dynamic aperture

C
Intensity limitations
Beam-beam effects
e-p option
Ion-Ion option

Experimental areas
Project time scale
Research and development
A high field, twin aperture collider

Aim: make the best use of existing CERN infrastructure (CERN tunnel)

$\text{NbTi at } 1.8 \text{ K} \rightarrow 10 \text{ T}$

- high technology - lower cost

drawbacks:
- mutual influence of channels
- difficulty of alignment
- coupled operation

A very high luminosity collider

Aim: Physics at $\sim 1\text{ TeV}$ at parton level $\Rightarrow \geq 6 \text{ TeV}$ proto

when $E^p$, parton collisions probe matter at smaller distances ($\Rightarrow \frac{1}{E}$)

But: cross sections $\downarrow$ like $\frac{1}{E^2}$

$\Rightarrow$ importance of event rates emphasized by physics working groups

$F_\text{prod}$ abandoned ($x > 10^{30} \text{ cm}^{-2}$)

$\Rightarrow L \sim 4.10 \text{ min}$
CURRENT DENSITY in COMMERCIAL SUPERCONDUCTING WIRES (non-Cu part)
COIL THICKNESS ($W$) in DIPOLE MAGNETS

(with graded current density and Cu/SC=1.7)
COST OF MAGNETS+CRYOSTATS
DIPOLES with 50 mm coil aperture
\textbf{Performance limitations}

\textit{Luminosity}

Def: \[ \mathcal{L} = \frac{\text{event rate}}{\text{cross section} \ \Sigma} \implies \frac{1}{\Sigma} \] \[ \Rightarrow \sum \binom{N_1, N_2}{k \neq} \frac{\Sigma}{S} \]

\begin{align*}
\text{for equal, round, bi-gaussian beams:} & \quad N_1 N_2 = N^2 \\
\text{Def: } \varepsilon^* & \quad = \frac{4 \sigma \gamma}{\beta^*} \\
\Rightarrow \quad \mathcal{L} & \quad = \frac{N^2 k \neq \gamma}{\pi \varepsilon^* \beta^*}
\end{align*}

\textit{Beam-beam:}

\begin{align*}
\text{defining } \Sigma & \quad = \frac{\gamma_E N}{\pi \varepsilon^*} \\
\text{From SPPS experience:} & \quad \Sigma \times \text{nb. of interaction regions} = \text{total tune spread} \leq 0.01
\end{align*}

For 3 int. regions \( \Rightarrow \Sigma_{\text{max}} = 0.003 \)

at beam-beam limit \( \Rightarrow \frac{N}{\varepsilon^*} = 6.76 \ 10^{15} \)
Synchrotron radiation:

\[ P = \frac{2}{3} \frac{e^2 c}{R \rho} \frac{\gamma^4}{4 \pi \varepsilon_0} \]

LEP at 90 GeV: \( P = 15 \text{ MW} \)

\[ \rightarrow \text{RF Volt. limit} \]

\[ \text{chamber cooling} \]

\[ \text{radiation hazards} \]

LHC: \( \text{Ps} \gamma \) goes into cold vacuum chamber (4 T)

\[ P_{\text{300k}} \sim 300 P_{4k} \]

\[ \rightarrow 6 \text{ MW} \sim 20 \text{ kW} \text{ (10 kW/beam)} \]

\[ \text{Ps} \gamma = \frac{4 \pi c e R}{3} B N k f \gamma^3 \]

\[ \rightarrow N k f \gamma = \frac{P_{\text{300k}}}{3 \times 10^{-28} B \gamma^2} \]

\[ \mathcal{L} = \frac{4}{\pi \beta^* (N / E^*)} (N k f \gamma) = \frac{6.5 \times 10^4}{\beta^*} \frac{P_{\text{300k}}}{8 \gamma^2} \text{ at the b.b. limit} \]

For \( \beta^* = 0.25 \) m
\[ B = 10 \text{ T} \]

\[ \mathcal{L} = 2.6 \times 10^4 \frac{P_{\text{300k}}}{\gamma^2} \text{ m}^{-2} \text{ s}^{-1} \]

\[ \mathcal{L}_{20 \text{ kw}} = 3.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]
Psy.: Synchrotron Radiation
Power per beam (kw)

\[ \beta^* = 0.25 \text{ m} \]
\[ B = 10 \text{ T} \]
\[ \xi = 0.003 \]

\[ L = 2.6 \times 10^{38} \frac{\text{Psy}}{Y^2} \]
IV Stored Energy

\[ U = \gamma E_0 N R_k \quad \Rightarrow \quad \gamma N R_k = \frac{U}{1.5 \times 10^{-10}} \]

\[ L = \frac{1}{\pi \beta^*} (N \xi \sigma^* \sigma^*) \]

\[ f = \frac{c}{2 \pi R} = \frac{c}{2 \pi \rho \times 1.4} = \frac{3/9 \times 10^6 B}{2 \pi \times 1.4} \frac{B}{\gamma} \]

\[ L = 1.4 \times 10^{32} \frac{B}{\beta^*} \frac{U}{\gamma} \]

for \( \beta^* = 0.85 \, m \)

\[ B = 10 \, T \]

\[ L = 5.7 \times 10^{32} \frac{U}{\gamma} \quad m^{-2} s^{-1} \]

\[ L_{1000 \, MJ} = 6.7 \times 10^{34} \quad m^{-2} s^{-1} \]

\[ \times 1000 \, MJ \sim 200 \, kg \, TNT \]
\[ L \left( \text{cm}^2 \text{s}^{-1} \right) \]

-10-

\[ U_{\text{MJ}} \]

2000

1000

600

400

LHC

\[ \frac{1}{E} \]

6

8

10

15

20

30

\[ U = \text{beam stored Energy (MJ)} \]

\[ B = 10 \, T \]

\[ \beta^* = 0.25 \, m \]

\[ \xi = 0.003 \]
Main Choices For the LHC

I Parameters:

\[ \langle n \rangle = \frac{L \sum}{k_f} \]

\( L = 100 \text{ mbar}ns \left( 10^{-25} \text{ cm}^2 \right) \)

\( k_f = 4 \times 10^{-34} \text{ cm}^{-2} \text{ s}^{-1} \)

\( (k_f)^{-1} = 15 \text{ ns} \)

\[ \Rightarrow \langle n \rangle = 60 \]

II Structure:

- general
- arc cell
- insertions
### TABLE 1. LHC parameters. [12]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>26658.833 m</td>
</tr>
<tr>
<td>Revolution time</td>
<td>88.924 µs</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>11.246 kHz</td>
</tr>
<tr>
<td>Nominal bending field</td>
<td>10.0 T</td>
</tr>
<tr>
<td>Nominal beam energies</td>
<td>8 TeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>0.45 TeV</td>
</tr>
<tr>
<td>No. of interaction regions</td>
<td>3</td>
</tr>
<tr>
<td>• High Luminosity</td>
<td>1</td>
</tr>
<tr>
<td>• Medium Luminosity</td>
<td>2</td>
</tr>
<tr>
<td>Free space for experiments</td>
<td></td>
</tr>
<tr>
<td>• High Luminosity</td>
<td>12 m</td>
</tr>
<tr>
<td>• Medium Luminosity</td>
<td>40 m</td>
</tr>
<tr>
<td>Full bunch length (4σ)</td>
<td>0.31 m</td>
</tr>
<tr>
<td>RF frequency</td>
<td>400.8 MHz</td>
</tr>
<tr>
<td>Acceleration time</td>
<td>1200 s</td>
</tr>
<tr>
<td>Inter-bunch spacing</td>
<td>15 ns</td>
</tr>
<tr>
<td>No. of p bunches/beam</td>
<td>4810</td>
</tr>
<tr>
<td>No. of p / bunch</td>
<td>1.0 x 10^{11}</td>
</tr>
<tr>
<td>No. of p / beam</td>
<td>4.81 x 10^{14}</td>
</tr>
<tr>
<td>Intensity / beam</td>
<td>865 mA</td>
</tr>
<tr>
<td>Energy / beam</td>
<td>597 MJ</td>
</tr>
<tr>
<td>Total synch. rad.</td>
<td>18.3 kW</td>
</tr>
<tr>
<td>Transverse emittance 4π γ σ^2 / β</td>
<td>15 πμm</td>
</tr>
<tr>
<td>Beam radius (2σ) at β* = 0.25 m</td>
<td>21 μm</td>
</tr>
<tr>
<td>Design luminosity at β* = 0.25 m</td>
<td>3.8 x 10^{34} cm^2 s^{-1}</td>
</tr>
</tbody>
</table>
Principle layout of the LHC
**Low Beta Insertion Principle**

- $\beta_{max} = 5\, \text{km}$
- $\beta = 0.25\, \text{m}$

**Inner Triplet**

**Outer Triplet**

**Dispersion Suppressor**

**Normal Lattice**
High Luminosity insertion

\[ \beta = 0.25 \text{m} \rightarrow 2.2 \text{m} \]

\[ \hat{\beta} = 5 \text{ km.} \]

\[ B' < 250 \text{ T/m} \]

HIGH INTENSITY BEAM

\[ \epsilon^* = 15\pi \text{ mm mr} \]

\[ \sigma^* = 10.5 \mu \text{ m} \]

\[ \hat{\sigma} = 1.48 \text{ mm} \]

\[ \alpha = 96 \mu \text{ rad} \]

Triplet

Separating Doublet of Dipoles

180 mm
12 batches of $\sim 4 \times 10^9$ each

4810 bunches ($\Delta t = 15$ ms)
Injectors

I Injection scheme

II Injection sequence

Bunch formation

- CPS accelerates $1.4 \times 10^{13}$ p to 26 GeV on $h = 20$ (9.5 MHz) debunch, recapture on $h = 240$ (66 MHz)
- Transfer to SPS; capture into 66 MHz RF buckets
- Repeat 3 times $\rightarrow \sim 4 \times 10^{13}$ in SPS

Bunch compression

- SPS: compression of bunches to $\sim 4$ ms, capture by 200 MHz RF system (every 5th bucket filled)
- Acceleration to 450 GeV, transfer to LHC, capture in 400 MHz RF buckets (every 6th bucket)
- Repeat 12 times

$\rightarrow \sim 5 \times 10^{14}$ in LHC
E = 8 TeV
L = 4.10 \textsuperscript{34} \text{cm}^{-2}\text{s}^{-1}

Initial beam lifetime: \( T_b = 2.5 \text{ h (1 exp.)} \)

**LHC filling:**

1. 3CPS cycles fill \( \frac{1}{3} \) of SPS circumf. (4.10p) ... 7.2
SPS ramp to 400 GeV .... 5

2. repeat 12 times per ring \( \rightarrow 8 \text{ min. total!} \)

*big advantage of fast injectors*

**Collisions scenario:**

- ramp down \( 15' \)
- checks \( 20' \)
- Pilot shot \( 40' \)
- injection full beam \( 5' \)
- ramp up \( 20' \)
- establish collisions \( 20' \)

Total \( \sim 2 \text{ h} \)

**Cycle duration:** \( 9' \)
**Data taking:** \( 7' \)
\( \langle L \rangle = 2.4 \times 10^{34} \)
Evolution of $L(t)$

\[
\begin{align*}
L_0 &= 4.10 \\
\text{filling time} &= 2 \text{ h} \\
\text{1 exp}.
\end{align*}
\]

$\langle L \rangle = 2.5 \times 10 \text{ cm}^{-2} \text{ s}^{-1}$
Ratio of average to maximum luminosity
(for a filling time of 2 hours)

① 1 exp. at $L_{\text{max}}$
② 1 exp. at $L_{\text{max}}$
   2 exp. at $L_{\text{max}}/2$
Beam vacuum chamber
(radiation shield)
LHC: cryogenic distribution in one half-octant

5K cooling loop (monophase helium)

1.8K cooling loop (Superfluid helium)

80K cooling loop (liquid nitrogen)
MAGNET ERRORS and DYNAMIC APERTURE

Magnet Errors

*CAS on Superconductivity
CERN 89-04

I. Multipoles

Consider a cylinder of radius a: a current density $I(\phi) = I_0 \cos(m\phi)$ creates a pure multipole of order m inside the cylinder.

- **Dipole**
  \[ B_y = -\frac{\mu_0 I_0}{2a} \]
  \[ B_x = 0 \]

- **Quadrupole**
  \[ B_y = -\frac{\mu_0 I_0}{2a^2} \]
  \[ B_x = -\frac{\mu_0 I_0}{2a^2} y \]

- **Sextupole**
  \[ B_y = -\frac{\mu_0 I_0}{2a^3} (x^2 - y^2) \]
  \[ B_x = -\frac{\mu_0 I_0}{2a^3} (xy) \]

$\Rightarrow I(\phi) = I_0 \sin(m\phi)$ \rightarrow Skew terms (rotated by $\frac{\pi}{2m}$)
Usual formula:

\[(B_x + iB_y) = B_0 \sum_{n=1}^{\infty} (b_m + i\alpha_n)(\frac{\pi}{R_r})^{n-1}\]

- \(B_0\) dipole field (y direction)
- \(b_m\) normal multipole coefficient
- \(\alpha_n\) skew
- \(Z = x + iy\)
- \(R_r\) reference radius.

Convention: \(R_r = 1\ \text{cm}\)

\(a_m, b_m\) in units of \(10^{-4}\)
Errors:

1) From design

Dipole

- Simplest approximation: current sh
  generates only normal multipole
  of odd order \( m = 1, 3, 5, 7, \ldots \)

with \( \phi_1 = 60^\circ \rightarrow \text{Sext. (}m = 3\text{)} \neq 0 \)

but decapole too large

- with two layers \( \rightarrow \) decap. \( = 0 \)
- with wedges \( \rightarrow \) minimize higher multipoles

2) Geometrical distortions

a) Mechanical tolerances

\( \delta l = 0.02\text{mm} \)
Figure 1: Geometry of the magnet with excitation of all coils at I=8625 A
2) **Coil deformation**

huge magnetic forces:  
\[ \sim 400 \text{ T/m for LHC} \]

\( \rightarrow \) prestress \( S \)

\( \rightarrow \) LHC design

3) **Two in one**

\( \rightarrow \) quad. effect - eliminated at low field by shaping the iron

4) **Iron Saturation**

\( \rightarrow \) quad., sext, oct., \( \rightarrow \) need correction at high field

5) **Persistent currents**

Supercond. = perfect diamagnetic

\( -J_c \)

\( +J_c \)

\( -J_c \)

\( +J_c \)

- Current and field free region

\( a) \) Low field

\( b) \) Maximum field which can be shielded

\( c) \) After field reversal

*Persistent currents depend on previous history*
Multipolar errors generated

Further complication: Persistent currents decay slowly

Change of main dipole field at injection

\[ B(4000\text{s}) = 23.26.8 \text{ Gauss} \]

NMR measurement in HERA magnets

\[ B(0) = 23.25.2 \text{ Gauss} \]
Big advantage of CERN fast injectors (5 min)

To minimize this effect → small filament diameter $a$

but: for distances between filaments $d \sim 1 \mu m$, there is a tunneling effect of Cooper pairs

→ difficult to go below $a \sim 5 \mu m$
  (nominal LHC cable)

* Efforts to go to $a = 2.5 \mu m$
Fig. 7a

Measurements of 52 Disps

$I = 5000 \ A$

$a_n / E^{-4}$

$b_m / E^{-3}$

Multipole $n$

Grad. skew oct.
6) Estimated errors for the LHC

<table>
<thead>
<tr>
<th>multipole</th>
<th>Systematic</th>
<th>Random (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_2$</td>
<td>$\pm 0.6$</td>
<td>1.7</td>
</tr>
<tr>
<td>$b_2$</td>
<td>$\pm 1.6$</td>
<td>1.2</td>
</tr>
<tr>
<td>$a_3$</td>
<td>$\pm 0.4$</td>
<td>0.5</td>
</tr>
<tr>
<td>$b_3$</td>
<td>$-3.7%$</td>
<td>1.7</td>
</tr>
<tr>
<td>$a_4$</td>
<td>$\pm 0.03$</td>
<td>0.2</td>
</tr>
<tr>
<td>$b_4$</td>
<td>$\pm 0.05$</td>
<td>0.15</td>
</tr>
<tr>
<td>$a_5$</td>
<td>$\pm 0.03$</td>
<td>0.07</td>
</tr>
<tr>
<td>$b_5$</td>
<td>$0.45%$</td>
<td>0.22</td>
</tr>
<tr>
<td>$a_7$</td>
<td>$\pm 0.01$</td>
<td>0.04</td>
</tr>
<tr>
<td>$b_7$</td>
<td>$0.13%$</td>
<td>0.02</td>
</tr>
<tr>
<td>$a_9$</td>
<td>$\pm 0.001$</td>
<td>0.002</td>
</tr>
<tr>
<td>$b_9$</td>
<td>$0.024$</td>
<td>0.005</td>
</tr>
</tbody>
</table>

III. Effect of errors on the particle dynamics

1) **Systematic:**

- tune shifts $\rightarrow \Delta \phi (a_x, a_y, \delta)$

   - $a = \text{betatron amplitude}$
   - $\delta = \frac{\Delta P}{P}$

2) **Random:**

   - excite resonances $\rightarrow$ Smear $S = \sqrt{\frac{\sum (E - \langle E \rangle)^2}{N\langle E \rangle}}$

   - $E = \frac{\text{Invariant}}{x}$
     - Linear $\rightarrow$ Non-linear $\epsilon$ fluctuates
4) Particle motion

Computer tracking:

1. Particle lost
   ($\sim 10^3$ turns)

2. Chaotic motion detected
   ($\Rightarrow$ diffusion)

3. Regular motion
   - evaluate $\Delta Q$
   - evaluate Smear

Slides: difference between regular
and chaotic motion
Problem: need stability for ~10 min at injection
\[ \rightarrow \sim 10^7 \text{ turns} \]
- can track only for ~10^4 turns
  - if motion regular (non chaotic)
  \[ \rightarrow \text{hope of stability for a few } 10^4 \text{ turns} \]
- need to define a Linear Aperture inside which motion is stable for \( 10^7 \text{ turns} \)

Criteria:
\[ \Delta \Phi < 0.005 \]
\[ \text{Smear} < 10\% \]

Apertures

![Diagram of apertures with linear and chaotic regions](image)
SPS experiment: perturb an otherwise linear machine with strong sextupoles
- measure dynamic aperture, diffusion rate
- compare with tracking

- onset of chaos (from tracking) coincides with losses (expt.) in a few seconds (10^5 turns)

![Graph showing tune shift and stability](image)

Fig. 2: Tune shift and stability

- Slow diffusion can be measured down to small amplitudes

![Graph showing diffusion rates](image)

Fig. 3: Measurement of diffusion rates

- is the LHC criterion sufficient to ensure stability?

![Graph showing tune shift and smear](image)

Fig. 5: Tune shift and smear at the dynamic aperture.
How to minimize the effect of magnet errors

1) Correctors for systematic effects
   - Bore tube windings (Hera)
   - Local correction
   - But technical difficulties — reliability
   - Lumped correctors (LHC)
     - Only near quadrupoles $\rightarrow$ insufficient
     - Need of an additional element in the middle of each half cell (Neuffer scheme)

   $\rightarrow$ LHC half cell layout
   $\rightarrow$ Good results with Sext, Oct, Dec. lenses
   but $b_7$ and $b_9$ pose problems

2) Sorting for Random errors
   - Measure error in each magnet (ex: $b_3$)
   - Build up a sufficient stack of magnets
   - Install magnets in a prescribed way to minimize cumulative excitation of resonances

   * More complicated with the "2 in 1" design
Layout of the standard half-cell

\[ \beta (\text{m}) \]

\[ \beta_H \]

\[ \beta_V \]

49.980

LHC HALF-CELL
Systematic errors

Effect of correctors (with $b_3 = 0.03$

$bg = 0.01$)
Tune shifts with Systematic errors + correctors

- with $b_T = 0.13$, $b_g = 0.14$
- with $b_T = 0.23$, $b_g = 0.024$
Fig. 1  Dynamic aperture with $b_3$ random only for 20 different random seeds

\begin{align*}
&\begin{array}{cccccccccc}
18 & 12 & 19 & 9 & 5 \\
2 & 20 & 6 & 15 & 17 & 8 & 10 & 7 & 1 & 11 & 4 & 14 & 13 & 16 & 3
\end{array} \\
&0.7 \quad 0.8 \quad 0.9 \quad 1.0 \quad 1.1 \quad 1.2 \quad 1.3 \quad 1.4 \quad 1.5 \quad 1.6 \quad 1.7 \quad 1.8 \quad 1.9 \quad 2.0 \quad 2.1 \quad 2.2 \quad 2.3 \quad 2.4 \quad 2.5 \quad 2.6 \quad 2.7 \quad 2.8
\end{align*}

40 mm

13 mm

Fig. 10  Dynamic apertures with sequence H of Scheme 2 $b_3$ sorted
Fig. 17 Dynamic Apertures with all the multipole errors in random sequence for 20 different seeds

Fig. 18 Dynamic Apertures with sextupole ordered in Scheme 2, sequence H + all higher multipole imperfections randomly with 20 seeds in dipoles
3) Choice of magnet coil diameter

Errors measured at the same reference radius \( r \) (i.e. 1cm) scale with the coil radius \( R \) as:

\[
\frac{b_{m,1}}{b_{m,2}} = \left( \frac{R_2}{R_1} \right)^n \quad \text{for persistent currents}
\]

\[
\frac{b_{m,1}}{b_{m,2}} = \left( \frac{R_2}{R_1} \right)^{n-\frac{1}{2}} \quad \text{for mechanical tolerances on coil dimensions and position}
\]

*a large bore suppresses high order errors.*

Example: reduction factors obtained by going from \( \phi = 50 \text{ mm} \) (present LHC) to \( \phi = 60 \text{ mm} \) (\( R = \) middle of first layer)

<table>
<thead>
<tr>
<th>( n )</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{b_{m,50}}{b_{m,60}} )</td>
<td>1.4</td>
<td>1.9</td>
<td>2.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>

but: price increases \( \sim \phi \)
4) Choice of cell length

Tune shifts from:

**Octupoles:** \( \Delta Q_x = \frac{3}{2} b_4 \left[ \delta^{2} - \frac{1}{2} (2 \varepsilon_x \beta_x^2) \right] \)

**Sextupoles:** \( \Delta Q_x = b_3 \delta \beta_x D + \text{octupole-like term} \)

\[ \text{chromaticity } \xi \]

* For \( b_n \)'s given, reduce betatron functions \( \beta, D \) → stronger focusing → short cells

**FODO cells:**

\[ \beta_{\text{max}} = \frac{2L}{\sin \mu} \left[ 1 + \sin \left( \frac{\pi}{2} \right) \right] \quad L = \text{half cell length} \]

\[ D = \frac{\alpha \frac{L}{\sin \mu/2}}{\sin \mu/2} \left[ 1 + \frac{1}{2} \sin \mu/2 \right] \quad \alpha = \text{bend angle} \]

but: small \( D \) means strong sextupoles to correct \( \xi \) → compromise

**LHC:** \( \mu = 90^\circ \)

\[ 2L = 100 \text{ m} \]

5) Choice of injection energy: higher \( E_{\text{inj}} \) means -

- reduced beam size: \( \sigma \sim \sqrt{\frac{E}{\mu}} \)
- much reduced persistent currents
- Higher cost for injectors
Aperture available

① 400 turns Aperture all randoms in dip. + quad.
② Linear Aperture - random \{ randoms in dipoles
③ Linear Aperture - b3 sorted \}

Aperture needed.

* For $\varepsilon = 15 \times 10^{-6}$ and 100 m cell length: $\sigma = 1.2 \text{ mm } \Delta\beta_{\text{max}}$.

$$A = 3 \sigma + 4 \ldots + 12 \ldots + 1.5 \text{ mm } \text{sagitta} + \text{ C.O. inj. oscill. safety margin}$$

$\Rightarrow A = 7. \text{ mm } \text{safety margin}$

* 5 not included!

$\Rightarrow$ More work needed
LHC DESIGN

C

I. Intensity limitations:

1) Intra-Beam Scattering (I.B.S.):

- Collisions of particles within a bunch
  \[ \rightarrow \text{equalisation of temperatures (in co-moving frame!)} \]

- At high \( \gamma \), the longitudinal temperature is the smallest

\[ E_\sigma \uparrow \]

\[ E_x \uparrow \text{ (coupling due to dispersion) } \]

\[ E_y \downarrow \text{ (if } E_y = 0 \text{, small effect anyway) } \]

\[ \frac{1}{C} \propto \frac{1}{E_x E_y E_\sigma} \]

- \( E_x, E_y \) enter in luminosity formula, \( E_\sigma \) does not

- Control IBS by \( E_\sigma \) \( \rightarrow \) this determines the accelerating voltage in the LHC

Injection: \( E_\sigma = 1 \text{ eV} \) \( \{ \Omega > 20 \text{ h} \)  

Coast: \( E_\sigma = 2.5 \text{ eV} \)
\[ V_{RF} = 12 \text{ MV} \quad \text{(energy lost by synchrotron radiation = 11 kV)} \]

*at 8 TeV, synchrotron rad. damping time = 16 h

2) **Space charge**

\[ \Delta Q = - \frac{N_{pe}}{\gamma^2 B \Sigma} \approx -10^{-3} \quad \text{at 450 GeV} \]

3) **Instabilities**

Interaction of beam with surroundings

a) **Coupling Impedances**

long. retardung voltage \( V = Z_L I \)

Transv. deflecting force \( F = Z_T X \)

\[ Z = R + i \gamma m \]

- Growth rates
- Tune shifts
- Energy loss

Broad-band: wake fields decay between bunches → single bunch effects, tune shifts

Narrow-band: couple bunches together → growth rates proportional to total intensity
**LHC impedance budget:**

- **Resistive wall**
  \[ Z_L(\omega) = \frac{(1+i) R_0}{b \delta} \]
  \[ Z_T(\omega) = \frac{2 \omega}{\omega b^2} Z_L(\omega) \]
  \[ \delta = \sqrt{\frac{2 \rho}{\mu_0 \omega}} \text{ skin depth}; \quad b = \text{chamber radius} \approx 2 \text{ cm} \]
  Stainless steel: \( \rho = 5 \times 10^{-7} \text{ nA m} \)
  Copper 300K: \( \rho = 4 \times 10^{-8} \)
  Copper 4K: \( \rho = 10^{-11} \text{ m in magnetic field} \)

- **Coupled bunch modes**
  \[ f = q \omega_0 = 3.3 \text{ kHz} \]
  Lowest frequency of coupled bunch modes
  \[ f = 1 \text{ kHz} \]
  \[ f = 2 \text{ kHz} \]
  \[ f = 3 \text{ kHz} \]

- **Growth rate**
  \[ \gamma \approx 1000 \text{ turns} \]
  \[ \gamma \approx 10^4 \text{ turns} \]

- **Note**
  - Copper at 300K: \( \gamma \approx 8 \text{ turns} \)
  - Stainless steel: \( \gamma \approx 4.5 \text{ turns} \)
- 3 -

- **Bellows** to absorb variation of length at cool-down → ~1.2% of circumference = 300 m

\[ V \rightarrow 100 \rightarrow \text{tps} \]

\[ \phi \sim 1.4 \]

- **Summary**

LHC coupling

impedance \( Z_L/n \) (in Ω)

<table>
<thead>
<tr>
<th>Component</th>
<th>Impedance (in Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF cavities</td>
<td>0.3</td>
</tr>
<tr>
<td>Bellows (unshielded)</td>
<td>0.6</td>
</tr>
<tr>
<td>Monitors</td>
<td>0.15</td>
</tr>
<tr>
<td>Kickers</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.15</strong></td>
</tr>
</tbody>
</table>

Resistive wall at

\[ \omega/2\pi = 3.3 \text{ kHz} : \]

- \( 0.7(1 + j) \Omega \) at 450 GeV/c
- \( 2.7(1 + j) \Omega \) at 8 TeV/c

- **Single bunch effects**:

  - Microwave instab.: Threshold \( ~7 \times 10^6 \) j/m
  - Mode coupling instab.: \( > 2 \times 10^6 \) j/m
  - Tune shifts → Loss of Landau damping if \( \Delta \phi_c > \text{Tune spread} \)

Long.: dipole + quadrupole unstable → feedback 0–33 M

higher modes stable
Transv. : $m=0$ unstable unless $Q_{spread} = 12 \cdot 10^{-3}$ unaccept. $\rightarrow$ a few 10

Feedback 0 - 33 MHz

$m=1, \ldots$ stable ? not assured

$\rightarrow$ shield bellows to decrease

---

( Multibunch effects

- resistive wall (only transverse)
- spurious modes in RF cavities
- kicker tanks, etc...
II Beam-beam effects

Head-on (well known from SPS) + 
\{ crossing angle
\} Long range

\[ \delta z' = f(z + \Delta \phi) \]

The transverse kick depends on the position in the bunch. It is modulated by synchrotron motion.

\( \delta z' = f(z + \Delta \phi) \)
2) **Long range**: additional tune shift + spread

   to decrease tune spread → increase \( \phi \)
   \[ \text{but: this enhances synchrotron resonances} \]

   → a working compromise must be found

   use long term tracking

   relevant parameter: \[ \frac{\overline{\Delta x}}{2 \sigma_3 \phi} \]

   \[ \sigma_3 = 4.6 \times 10^{-3} \]
\[ \xi = 0.003 \]

**Beam-beam tune spreads**

- crossing angle \( \xi = 96 \mu \text{rad} \)
- Long range

(0\(\sigma\),0\(\sigma\))

(4\(\sigma\),4\(\sigma\))

(6\(\sigma\),0\(\sigma\))

(0\(\sigma\),6\(\sigma\))
1) Making beams collide

Fig. 3.3 Layout of elements around the ep interaction point; free space = ± 3.5 m (± 10 m)
2) **EP parameters**

- If RF LHC at 400 MHz (as now foreseen),
  - RF LEP at 352 MHz
  - Logwheeling imposes restriction on bunch number \( k \)
    - Larger \( k = 54c \)

  - Optimize parameters:
    - Beam-beam \( \Delta \Phi_p = 0.04 \) (LEP value scaled to 3 interactions)
    - \( \Delta \Phi_p = 0.0033 \)

Intensity:
- Protons \( \rightarrow 3.10^9 / \text{bunch} \)
  - \( E^* = 20 \text{ MeV} \)
  - OK in injector
- Electrons \( \rightarrow \) if RF OK for SmA at 100 GeV
  - Scale beam current like \( E^- \)

\( \rightarrow \text{Luminosity/Energy} \)

3) **Operational procedure**

- Negligible particle losses from collisions (contrary to pp)
  - Long lifetime for e
  - Protons: beam-beam effect from electrons? (noisy; see Hera!)

Filling:
- 20 min to inject 1 proton beam (bunch by bunch)
- Fill LEP while ramping LHC (20 min)
  - Total \( \sim 2 \text{ h} \) as for pp
### Protons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_p$</td>
<td>$3.0 \times 10^{11}$</td>
</tr>
<tr>
<td>$4\pi \gamma \sigma^2 / \beta^* (\mu m)$</td>
<td>$20\pi$</td>
</tr>
<tr>
<td>$\beta_\gamma^* (m)$</td>
<td>2.8</td>
</tr>
<tr>
<td>$\beta_{e\gamma}^* (m)$</td>
<td>45.3</td>
</tr>
<tr>
<td>$k_b$</td>
<td>540</td>
</tr>
<tr>
<td>$\mu_{\text{cell}}$</td>
<td>$\pi/2$</td>
</tr>
<tr>
<td>$E_p (\text{TeV})$</td>
<td>8.0</td>
</tr>
<tr>
<td>$\xi_p$</td>
<td>0.0033</td>
</tr>
</tbody>
</table>

### Electrons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_e$</td>
<td>$8.2 \times 10^{10}$</td>
</tr>
<tr>
<td>$\pi \sigma_\gamma^2 / \beta_e^* (\text{nm})$</td>
<td>26.5$\pi$</td>
</tr>
<tr>
<td>$\pi \sigma_\gamma^2 / \beta_{e\gamma}^* (\text{nm})$</td>
<td>3.4$\pi$</td>
</tr>
<tr>
<td>$\beta_e^* (m)$</td>
<td>0.20</td>
</tr>
<tr>
<td>$\beta_{e\gamma}^* (m)$</td>
<td>0.64</td>
</tr>
<tr>
<td>$k_b$</td>
<td>540</td>
</tr>
<tr>
<td>$\mu_{\text{cell}}$</td>
<td>$\pi/3$</td>
</tr>
<tr>
<td>$E_e (\text{GeV})$</td>
<td>50</td>
</tr>
<tr>
<td>$\xi_e$</td>
<td>0.04</td>
</tr>
</tbody>
</table>

### Luminosity (cm$^{-2}$ s$^{-1}$)

| Value | 2.7 $\times 10^{32}$ |

The shift in quads is $\ell_s = \pm 3.5$ m.
ep collisions

( p beam 8 TeV )
IV. Ion-Ion Collisions in the LHC

Luminosity limited by:
- Phenomena in LHC
  - e.m. dissociation
  - pair production
- Ion source

I. Intra Beam Scattering (I.B.S.)

- Increases longitudinal and horizontal emittances

\[ \frac{1}{\tilde{c}} \sim Z^4 \rightarrow \text{Problem with heavy ion} \]

\[ \mathcal{L} \propto \frac{N}{\varepsilon_T^*} \quad \text{and} \quad \frac{1}{\tilde{c}} \propto \frac{N}{\varepsilon_T^* \varepsilon_L} \]

- \( \mathcal{L} \): transverse emittance
- \( \varepsilon_L \): longitudinal emittance
- \( N \): bunch population
- \( k \): Number of bunches

Solution:
- Increase \( \varepsilon_L \) (more RF voltage)
- Increase \( \varepsilon_T^* \) (and \( N \))
- Increase \( k \)

Example:
- Pb-Pb
- \( \varepsilon_L = 2 \text{ eVs} \)
- \( \varepsilon_T^* = 5 \pi \mu \text{m} \)
- \( N = 1.6 \times 10^8 \)
- \( k = 643 \)

\[ \mathcal{L} = 10 \text{ cm}^2 \text{ s}^{-1}, \quad \tilde{c} = 4 \text{ hours} \]
II Electromagn. dissociation:
Loss of a nucleon following e.m. nuclear excitation at crossing
(Weizacker-Williams)

\[ \sigma_{WW} = 177 \text{ barns} \]

For: \( L = 10 \text{ cm}^{-2} \text{ sec}^{-1} \) \{ luminosity \( T_{1/2} = 2.2 \) h \}

III Pair production + capture:

\[ Pb^{82+} + Pb^{82+} \rightarrow Pb^{82+} + e^+ + [e^- + Pb^{82+}] \]

\[ \sigma_{PP} = 3.10 \text{ barns} \]

\[ \sigma_{ec} = 80 \text{ barns} \]

- 3.10 pairs/sec!
- Loss of ions \( \sim 1/2 \) as much as for e.m. dissociation

CC1: For Pb-Pb, these effects are not limiting up to \( L \sim 10^{27} \text{ cm}^{-2} \text{ sec}^{-1} \) (next table)

- For lighter ions (S, O), they are unimportant
### TABLE 6. Typical LHC performance as a Ion-Ion Collider.

<table>
<thead>
<tr>
<th><strong>Type of ions</strong></th>
<th><strong>Pb</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity</strong></td>
<td>$1 \times 10^{27} \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td><strong>Number of I.R.</strong></td>
<td>3</td>
</tr>
<tr>
<td><strong>$\beta^*$ at interaction point</strong></td>
<td>0.5 m</td>
</tr>
<tr>
<td><strong>Free space at I.R.</strong></td>
<td>40 m</td>
</tr>
<tr>
<td><strong>Number of bunches</strong></td>
<td>800</td>
</tr>
<tr>
<td><strong>Inter-bunch distance</strong></td>
<td>105 ns</td>
</tr>
<tr>
<td><strong>No of Ions/bunch</strong></td>
<td>$5 \times 10^7$</td>
</tr>
<tr>
<td><strong>No. of Ions/beam</strong></td>
<td>$4.0 \times 10^{10}$</td>
</tr>
<tr>
<td><strong>Transverse emittance, $4\pi\gamma^2/\beta$</strong></td>
<td>5.0 $\mu\text{m}$</td>
</tr>
<tr>
<td><strong>Transverse emittance growth times</strong></td>
<td></td>
</tr>
<tr>
<td>• at injection</td>
<td>12 hours</td>
</tr>
<tr>
<td>• at max. energy</td>
<td>12 hours</td>
</tr>
<tr>
<td><strong>Luminosity half-life</strong></td>
<td>5 hours</td>
</tr>
<tr>
<td><strong>Maximum c.m energy ($\sqrt{s}$) for Pb-Pb</strong></td>
<td>1.312 TeV</td>
</tr>
</tbody>
</table>
IV The Ion Source

The Pb source now envisaged for use in the SPS in fixed-target should provide up to $10^8$ ions per CPS pulse.

with this $L = 10^{2.5}$ cm$^{-2}$s$^{-1}$

To reach $10^{27}$ the beam intensity has to be increased by a factor 10.

To reach $10^{28}$ it has to be increased by a factor 30.

This could be achieved by:

- a better ECR source (higher frequency and power, superconducting coils)

- Accumulation and cooling (either electron cooling at the Linac exit (CLEAR?) or stochastic cooling at higher energy (AA, CPS?).

A study is in progress to see which route is the more promising.

*Light ions*: the existing source would provide:

- $^16O: L = 2 \times 10^{2.6}$ cm$^{-2}$s$^{-1}$
- $^{32}S: L = 3 \times 10^{2.5}$ cm$^{-2}$s$^{-1}$
DIPOLe MODELS and PROTOTYPES UNDER CONSTRUCTION

******************************************************************************

1. NbTi at 2 K

1.1 SHORT MODELS (full x-sect., 1 m long)
   i) SINGLE APERTURE 8/8.5 T \textit{Two First Tested}
   ii) TWIN-APERTURE 10 T

1.2 LONG MAGNETS (full x-sect., 10 m long)
   i) TWIN-APERTURE MAGNET with HERA coils cooled at 2 K.
      PURPOSE: TEST 2 K and "two-in-one" concept. EXPECTED FIELD 7.5 T
   ii) TWIN-APERTURE MAGNET with final coils cooled at 2 K. 10 T \rightarrow \textit{build complete cell}

2. Nb$_3$Sn at 4.5 K

2.1 SHORT MODELS (full x-section, 1 m long) with "wind-and-react" technique. 10 T \textit{First Tested}

3. CRYOGENICS at 2 K

3.1 SIMULATION TESTS of FORCED FLOW of SUPERFLUID He

C.E.N.-C.E.A. Grenoble
Fig. 5: Quench history of the mirror dipole and of the main dipole