Outline of the Two Lectures

(A) Past and Future

(B) The Large Hadron Collider (LHC)

(C) LHC Upgrades, VLHC-I and II
(A) Past and Future

past, operating, or under construction:

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR</td>
<td>1970</td>
</tr>
<tr>
<td>SPS</td>
<td>1981</td>
</tr>
<tr>
<td>Tevatron</td>
<td>1987</td>
</tr>
<tr>
<td>RHIC</td>
<td>2000</td>
</tr>
<tr>
<td>LHC</td>
<td>2006</td>
</tr>
</tbody>
</table>

contemplated: LHC-II, VLHC HF or LF, and Eloisatron
ISR - the first hadron collider!

Limitations and Successes

- space-charge tune shift & spread, trapped e$^-$
- proton-electron instabilities, pressure bumps
- detector background
- coherent beam-beam effects
- detector missed the J/$\psi$ and b quark
- $I = 38-50$ A, coasting beam, 31 GeV
- $L \approx 2.2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ peak luminosity
- with bunched beams $\xi = 0.0035$ per IP (8 crossings)
- first p$\bar{p}$ collisions
### Parameters for pp or p\(p\) Colliders

<table>
<thead>
<tr>
<th>acc.</th>
<th>SppS</th>
<th>TeV2a</th>
<th>LHC</th>
<th>LHC-II</th>
<th>VLHC-I</th>
<th>VLHC-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{beam}}) [TeV]</td>
<td>0.32</td>
<td>0.98</td>
<td>7</td>
<td>14</td>
<td>20</td>
<td>87.5</td>
</tr>
<tr>
<td>(B) [T]</td>
<td>1.4</td>
<td>4.34</td>
<td>8.4</td>
<td>16.8</td>
<td>2</td>
<td>9.8</td>
</tr>
<tr>
<td>(C) [km]</td>
<td>6.9</td>
<td>6.28</td>
<td>26.7</td>
<td>26.7</td>
<td>233</td>
<td>233</td>
</tr>
<tr>
<td>(n_b)</td>
<td>6</td>
<td>36</td>
<td>2800</td>
<td>5600</td>
<td>40000</td>
<td>40000</td>
</tr>
<tr>
<td>(N_b) ([10^{11}])</td>
<td>1.7 (p)</td>
<td>2.7 (p)</td>
<td>1.05</td>
<td>1.05</td>
<td>0.26</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>0.8 ((\bar{p}))</td>
<td>(\sim) 1.0 ((\bar{p}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(L) ([10^{34}\text{cm}^{-2}\text{s}^{-1}])</td>
<td>0.0006</td>
<td>(\sim) 0.02</td>
<td>1.00</td>
<td>10.</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>(\beta_{x,y}^*) [m]</td>
<td>0.6, 0.15</td>
<td>0.35</td>
<td>0.5</td>
<td>0.22</td>
<td>0.3</td>
<td>0.71</td>
</tr>
<tr>
<td>(\gamma \epsilon_{x,y}) ([\mu \text{m}])</td>
<td>3.75</td>
<td>(\sim) 3</td>
<td>3.75</td>
<td>3.75</td>
<td>1.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

\[\rightarrow 1.0\] \[\rightarrow 0.04\]
Empirical Scaling

Circumference vs. beam energy: \( C \propto E^{1/2} \)
Dipole field vs. beam energy: $B \propto E^{1/2}$
Luminosity vs. beam energy: \( L \propto E^2 \) event rate = luminosity 
\( \times \) cross section
stored particles execute transverse betatron oscillations

\[ \frac{d^2 x}{ds^2} = -k(s) x \]

with quadrupole focusing force \( k \) \([m^{-2}]\):

\[ k = \frac{eB_T}{pa} \]

\((B_T: \text{pole-tip field, } a: \text{radius, } p: \text{momentum})\)

**Betatron Tune**: number of betatron oscillations per turn

**Emittance**: phase space area of beam distribution \( \epsilon = \int x' \, dx / \pi \)

\((x' \equiv dx/ds)\); \( \gamma \epsilon \) is **invariant** under acceleration (‘normalized emittance’)

**Beta function**: determines local rms beam size:

\[ \sigma_{x,y}(s) = \sqrt{\beta_{x,y}(s) \epsilon_{x,y}} \]
Betatron tune $Q_{x,y}$ equals the number of transverse oscillations per revolution. Avoid resonances $kQ_x + mQ_y = p$ ($k, m, p$ integers)! [CERN SPS: $|k| + |m| \leq 12 \rightarrow$ poor lifetime]
Betatron tune vs. circumference: \( Q_\beta \propto C^{1/2} \)
\[
(\rightarrow L_{\text{cell}} \propto C^{1/2}, \ \beta \propto C^{1/2}).
\]
(B) The Large Hadron Collider (LHC)

- parameter choice
- magnets, schedule, layout & optics
- head-on beam-beam interaction & luminosity
- long-range collisions
- strong-strong beam-beam & Landau damping
- dynamic aperture, snap-back, power converters, novel diagnostics
- heat load, collimation, vacuum system
- protection & beam dump
- filling pattern, (pre-)injectors, ion collisions
- electron cloud
**LHC Parameter Choice**

- LEP circumference + highest magnetic field
  \[ E[\text{TeV}] \approx 0.84 \ B[\text{T}] \rightarrow \text{beam energy} = 7 \ \text{TeV} \]
  with \( B = 8.4 \ \text{T} \)

- maximum ‘beam-beam tune shift’ \( \xi \propto N/\epsilon + \) available aperture \( \rightarrow \) bunch population

- desired luminosity \( \rightarrow \) number of bunches \( \rightarrow \) beam current, synchrotron radiation power
## LHC S.C. Dipole Magnets

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Dipole Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>1.8 T</td>
</tr>
<tr>
<td>Tevatron</td>
<td>4 T</td>
</tr>
<tr>
<td>HERA</td>
<td>5 T</td>
</tr>
<tr>
<td>SSC</td>
<td>6 T</td>
</tr>
<tr>
<td>LHC</td>
<td>8.4 T</td>
</tr>
</tbody>
</table>
Persistent Currents

SC strand

superconducting cable

SC filament
dipole magnet basics

dipole field generation

cable and insulation

conductor lay-out

coil winding

support structure
The LHC dipole n. 0001

Artist view of the LHC in the LE P Tunnel

March 9, 2001

L. Maiani. WHAT'S NEXT?
October 2004: Octant test 01/04 to 31/08

March 2005: Last dipole delivered 31/03

July 2005: Ring closed and cold 31/12

January 2006: Pilot run 01/04 to 30/04

October 2006: Physics run 7 months L>2x10^{33}

December 2006: Shutdown 3 months

January 2007: First beam 01/02

October 2007: Pb-Pb run 6 weeks

LHC commissioning schedule

March 9, 2001 L. Maiani. WHAT'S NEXT? 45
Collision lattice for beam 1 at IP5 ($x = D \Delta p/p + x_\beta$).
LHC design orbit for beam 1 near IP5 (CMS) in collision.
Magnet layout (top view) around IP 1 (ATLAS).
Head-On Beam-Beam Collision

Repelling force of opposing beam acts like defocusing lens $\rightarrow Q_{x,y}$ decreases
nonlinear lens $\rightarrow$ tune spread
maximum acceptable tune spread $\rightarrow$ beam-beam limit.
ΔQ_{x,y} is characterized by the beam-beam tune shift parameter:

\[ \Delta Q_{x,y} \approx \xi_{x,y} \equiv \frac{r_p \beta^{*}_{x,y} N_b}{2\pi \gamma \sigma^{*}_{x,y}(\sigma^{*}_x + \sigma^{*}_y)} \]

Compare tune shift caused by a quadrupole of strength ΔK:

\[ \Delta Q \approx \frac{1}{4\pi} \beta \Delta K \]

and take ΔK = Δx′/x (or Δy′/y) as the kick imparted by the opposing beam.
Comparison of Beam-Beam Tune Shifts

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>TeV-IIa</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi/\text{IP}$</td>
<td>0.005</td>
<td>0.01</td>
<td>0.0034</td>
</tr>
<tr>
<td>$\xi_{\text{tot}}$</td>
<td>0.015</td>
<td>0.01</td>
<td>0.009</td>
</tr>
</tbody>
</table>
Luminosity

Reaction rate $R = L\sigma$ ($\sigma$: cross section)

Standard expression for $L$:

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4\pi \sigma_y^* \sigma_x^*} = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4\pi \epsilon_{x,N} \beta_x^* \kappa}$$

$N_b$: bunch population, $n_b$ number of bunches, $f_{\text{rev}}$ revolution frequency, $\gamma$ beam energy divided by rest mass, $\epsilon_{x,N} = \gamma \epsilon_x$ normalized emittance, and $\kappa = \sigma_y / \sigma_x$ aspect ratio.

head-on beam-beam tune shift:

$$\xi_{x,y} = \frac{\beta_{x,y}^* r_p N_b}{2\pi \gamma \sigma_{x,y}^* (\sigma_x^* + \sigma_y^*)} = \frac{r_p N_b}{2\pi \gamma \epsilon_x (1 + \kappa)}$$
Assuming $\beta^*_y / \beta^*_x = \epsilon_y / \epsilon_x = \kappa \rightarrow \xi_x = \xi_y \equiv \xi$:

$$L = (f_{\text{rev}} n_b N_b) \frac{1 + \kappa}{\beta^*_y} \gamma \frac{\xi}{2r_p}$$

Four factors:

- emittance ratio $\kappa$
- IP beta function $\beta^*_y = \beta^*_x \kappa$
- maximum beam-beam tune shift $\xi$
- total beam current $f_{\text{rev}} n_b N_b$

Flat beams: $\kappa \ll 1$ and $L_{\text{flat}} \approx L_{\text{round}}/2$, unless $\beta^*_y$ can be reduced. (This seems difficult for $pp$ colliders.)
Each bunch experiences up to 15 long-range collisions on either side of each head-on collision. Bunches with an unequal number of encounters will likely have a poor lifetime (PACMAN bunches).
new regime of beam-beam interaction: long-range encounters on either side of the interaction points are the dominant perturbation, rather than the head-on collisions. The long-range collisions give rise to a well defined diffusive aperture

\[ x_{da} = x_{sep} - \Delta \quad \text{with} \quad \frac{\Delta}{\sigma} \propto \sqrt{\frac{N_b}{A\epsilon_N} Z} \]

where \( x_{sep} \) denotes the beam-beam separation. The diffusive aperture in units of \( \sigma \) is independent of the beta function and the beam energy. For nominal LHC parameters: \( x_{sep} \approx 9.5\sigma \) and \( x_{da} \approx 6\sigma \).
Left: tune footprints due to head-on and long-range beam-beam effects in LHC IPs 1 and 5. Right: total tune footprint in LHC for regular bunch and for PACMAN bunch. [Courtesy H. Grote]. $\Delta Q$ from long-range collisions is approx. cancelled by alternating crossing at IP 1 and 5.
LHC tune footprints with head-on & long-range collisions and triplet errors (work with Y. Papaphilippou)

Red dots: $x, y_{in}$ up to $5\sigma_{x,y}$; blue dots: $x, y_{in}$ up to $10 \sigma_{x,y}$. 
Change of action variance per turn as a function of starting amplitude, for the **LHC**. Compared are different combinations of head-on collisions, long-range collisions, triplet-field errors, tune modulation, and Moebius twist (Y. Papaphilippou & F.Z.)
Dependence of diffusion due to long-range collisions on the beam current. Left: change of action variance per turn vs. bunch population; right: approximate diffusive aperture vs. bunch population; vertical axis distance to other beam at parasitic collision point; a square root dependence is also indicated for comparison (Y. Papaphilippou & F.Z.)
Minimum $\beta^*$

1st limit — hourglass effect: $\beta^*_{x,y} \geq \sigma_z$

$(\beta_{x,y}(s) = \beta^*_{x,y} + s^2/\beta^*)$

2nd limit — long-range collisions:

dynamic aperture caused by parasitic collisions

$x_{da} \approx n_{\text{sep}}\sigma_x - \Delta \rightarrow n_{\text{sep}} \geq 10; \text{ for LHC: } \Delta \approx 3.5\sigma_x$

luminosity loss due to crossing angle:

$$\theta_c \equiv n_{\text{sep}}\sqrt{\frac{\epsilon_{x,y}}{\beta^*_{x,y}}} < 2\sigma_x/\sigma_z$$

combining these two equations

$$\beta^*_{x,y} \geq n_{\text{sep}}\sigma_z/2 \approx 5\sigma_z$$

for the LHC $\beta^*_{x,y} > 0.38 \text{ m (design value 0.5 m)}$
Minimization of tune footprint using pulsed electric wire mimicking long-range encounters of opposite charge
[J.-P. Koutchouk, PAC2001]
The diffusion per turn as a function of the start amplitude. An electric wire increases the diffusive aperture by about 2σ, even with strength error.
Complementary approach  Tevatron electron lens for beam-beam tune-shift compensation  [Courtesy V Shiltsev, 2001].
Tevatron proton tune shift as a function of electron current [Courtesy V. Sliltsev, 2001].
Strong-Strong Beam-Beam Effects at LHC

Two colliding bunches → two coherent modes: \( \sigma \) mode (in phase oscillation), and \( \pi \) mode (out-of phase). Frequency of \( \sigma \) mode = unperturbed betatron tune; frequency of the \( \pi \) mode is shifted downwards.
Different oscillation frequencies of individual particles tend to stabilize the coherent beam motion against excitation frequencies within the frequency spread. This is called **Landau damping**.

Driven particle motion: \( \ddot{x} + \omega^2 x = A e^{-i\Omega t} \); beam centroid response: 
\[
< x > = \frac{A}{2\omega} e^{-i\Omega t} \int d\omega \frac{\rho(\omega)}{\omega^2 - \Omega^2 - i\epsilon} \quad (\epsilon \to 0^+).
\]
Prediction: coherent $\pi$ mode in LHC will not be Landau damped! $|(N_1 - N_2)/N_2| < 40\% \rightarrow Q_\sigma - Q_\pi > \xi$ (coherent tune shift $>$ incoherent tune spread) (Alexahin, Yokoya).

De-Stabilizing effect of long-range collisions?

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>TeV-II</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>intensity ratio $N_1/N_2$</td>
<td>2</td>
<td>9 → 2</td>
<td>1</td>
</tr>
</tbody>
</table>

Simulation studies (M. Zorzano) support predictions, and also indicate that long-range collisions will not stabilize the $\pi$ mode.
Simulation of coherent modes (M. Zorzano): frequency spectrum of the bunch centroid motion; horizontal axis \( w = (\nu - Q)/\xi \). The \( \pi \)- and \( \sigma \)- oscillation modes are clearly visible.
Possible cure: separate the tunes in the two rings! (Hofmann). Simulations suggest that Landau damping may be restored, if the tune split is larger than the beam-beam tune shift.

However, at alternative asymmetric working points coherent resonances may be encountered (Alexahin, Herr, Zorzano)

Both theory and simulations rely on various approximations and assumptions. Experimental studies of the $\pi$ mode stability in LEP (done) and at RHIC (planned).
Various Single-Beam Collective Effects...

- **Coherent Synchrotron Tune Shift**: loss of Landau damping requires controlled emittance blow up

- **Longitudinal Microwave Instability**: safely stable.

- **Transverse Mode Coupling**: threshold $N_b^{\text{thr}} \approx 5.9 \times 10^{11}$ at injection.

- **Resistive Wall Instability**: nominal LHC: $\tau \approx 30$ ms (300 turns); double bunches and ultimate bunch population: $\tau \approx 10$ ms (100 turns).

- **Tune Shift Variation for Partially Filled Ring** due to ac magnetic field leakage and finite resistive wall (small effect - J. Gareyte).

- **Incoherent Tune Shift due to Collective Fields**: Nominal LHC: $\Delta Q_y \approx 0.02$; higher intensity: $\Delta Q_y \approx 0.07$; Potential problems: (1) a reduction of dynamic aperture (2) resonance crossing of the coherent multi-bunch modes.
Dynamic Aperture at Injection

Nonlinear field errors can destabilize particle motion after 1000s of turns. Error sources:

- persistent currents (eddy currents in the superconductor)
- coil geometry
- current redistribution during ramping

Maximum stable area in phase space: dynamic aperture

Approach:

- computer simulations or particle motion over $10^6$ turns
- experimental comparisons at SPS and HERA
- require $12\sigma$ aperture to be sure actual aperture $> 6\sigma$
**Persistent Currents - \( I_{\text{min}} \)**

Measurement in MBP2O1 - Aperture 1

![Graph showing persistent currents](image)

- Hysteresis crossing: no overshoot possible!
Decay and SB

LHC operation cycle

Measurements performed using a prototype of LHC digital controller (SL-PO)
Principle of chromaticity measurement via head-tail phase shift.
Chromaticity measurement via head-tail phase shift in the SPS.

\[ \xi_{x,y} = -\eta \Delta \phi(n) / [Q_{x,y} \omega_0 \Delta \tau (\cos(2\pi n Q_s) - 1)] \].

Top: raw head and tail oscillations, bottom left: \( \Delta \phi \) (red), bottom right: chromaticity. (Courtesy R. Jones, 2000.)
## Power Converter Tolerances for LHC

<table>
<thead>
<tr>
<th>Circuit Type</th>
<th>Nominal Current (A)</th>
<th>Current Polarity</th>
<th>One Year Accuracy (ppm of Nominal)</th>
<th>One day Reproducibility (ppm of Nominal)</th>
<th>1/2 hour Stability (ppm of Nominal)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Bends, Main Quads</td>
<td>13000</td>
<td>Unipolar</td>
<td>±50 ±20 with calibration</td>
<td>±5</td>
<td>±3</td>
<td>1</td>
</tr>
<tr>
<td>Inner triplet</td>
<td>8000/6000</td>
<td>Unipolar</td>
<td>±100 ±20 with calibration?</td>
<td>±20</td>
<td>±10</td>
<td>15</td>
</tr>
<tr>
<td>Dispersion suppressor</td>
<td>6000</td>
<td>Unipolar</td>
<td>±70</td>
<td>±10</td>
<td>±5</td>
<td>15</td>
</tr>
<tr>
<td>Insertion quadrupoles</td>
<td>6000</td>
<td>Unipolar</td>
<td>±70</td>
<td>±10</td>
<td>±5</td>
<td>15</td>
</tr>
<tr>
<td>Separators (D1,D2,D3,D4)</td>
<td>6000</td>
<td>Unipolar</td>
<td>±70</td>
<td>±10</td>
<td>±5</td>
<td>15</td>
</tr>
<tr>
<td>Trim quadrupoles</td>
<td>600</td>
<td>Bipolar</td>
<td>±200</td>
<td>±50</td>
<td>±10</td>
<td>30</td>
</tr>
<tr>
<td>SSS correctors</td>
<td>600</td>
<td>Bipolar</td>
<td>±200</td>
<td>±50</td>
<td>±10</td>
<td>30</td>
</tr>
<tr>
<td>Spool pieces</td>
<td>600</td>
<td>Bipolar</td>
<td>±200</td>
<td>±50</td>
<td>±10</td>
<td>30</td>
</tr>
<tr>
<td>Orbit correctors</td>
<td>120/60</td>
<td>Bipolar</td>
<td>±1000</td>
<td>±100</td>
<td>±50</td>
<td>30</td>
</tr>
</tbody>
</table>

### Precision and Control

- Precision
- Control
Results of Resolution Test with the Prototype Digital Controller

$I_0 = 1019.9$ Amps

Current offset in Milliamps

Time in Seconds

Reference

Measured

Current offset in ppm of 20 kA
Measurement of Resonant Terms

Phase Space Distortions

a.) Simulation

b.) Simulation

c.) Simulation

d.) Simulation

CHAMONIX-XI – January 16 2001 – Frank Schmidt
Measurement of Resonant Terms

Example Spectrum for the SPS

Simulation CHAMONIX-XI – January 16 2001 – Frank Schmidt
Measurement of Resonant Terms

Detuning SPS 120GeV

Experimental Data

Prediction

\[ \varepsilon_x [\mu m] = A_x A_x/\beta_x \]
Measurement of Resonant Terms

\[ 3,0, 1,0 \text{ resonances 120GeV} \]

According to the rule these are the \((-2,0), (2,0)\) spectral lines.

![Graphs showing the comparison between theory and experiment for line amplitudes (normalised) vs. \( \varepsilon_x^{1/2} \) for lines (-2,0) and (2,0). The slope ratios are 1.976 and 1.978, respectively.]

CHAMONIX-XI – January 16 2001 – Frank Schmidt 12
Measurement of Resonant Terms
Localisation of Multipoles SPS 120GeV

Longitudinal Position [m]

1000 2000 3000 4000 5000 6000

0.02

Experimental Data

Line (-2,0) (normalised)

1 2 3 4 5 6 7 8

CHAMONIX-XI – January 16 2001 – Frank Schmidt
Heat Load inside the Cold Magnets

4 Sources

- **lost beam particles** (scattered at collision point or at residual gas nuclei; or on unstable trajectory diffusing outwards) → **collimation** → cooling with superfluid helium at 1.9 K

- **synchrotron radiation**: at \( N_b \approx 1.6 \times 10^{11} \) about 0.27 W/m → beam screen

- **image currents**; at \( N_b \approx 1.6 \times 10^{11} \) about 0.46 W/m → beam screen with copper coating

- **electron cloud**; residual cooling capacity at \( N_b \approx 1.6 \times 10^{11} \) must stay below 0.56 W/m!
Quench Limits:

\[ \Delta T = 7K \text{ at injection, and } \Delta T = 1K \text{ at top energy} \]

Loss mechanisms:

- injection errors (few turns)
- protons outside of the rf bucket: ‘flash’ at start of ramp (\(\sim 1\) s)
- continuous losses in collision

<table>
<thead>
<tr>
<th>process</th>
<th>exp. losses</th>
<th>quench limit</th>
<th>(l_f) factor [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>injection</td>
<td>(\Delta N = 1.25 \times 10^{12})</td>
<td>(\Delta N_q = 10^9)</td>
<td>1250</td>
</tr>
<tr>
<td>ramping</td>
<td>(\Delta N = 9 \times 10^{12})</td>
<td>(\Delta N_q = 2.5 \times 10^{10})</td>
<td>360</td>
</tr>
<tr>
<td>collision</td>
<td>(\dot{N} = 3 \times 10^9 \text{ s}^{-1})</td>
<td>(\dot{N}_q = 6 \times 10^6 \text{ m}^{-1}\text{s}^{-1})</td>
<td>500</td>
</tr>
</tbody>
</table>
Collimation

2-stage system:

3 primary betatron collimators at 6\(\sigma\) & 1 energy collimator;

each followed by a set of three secondary collimators at 7\(\sigma\);

collimation inefficiency depends on ring aperture \(A_{\text{ring}}\);

if \(A_{\text{ring}} = 8\sigma\): \(\eta_{\text{coll}} \approx 10^{-4}\);

collimation must be in working position at injection;

dynamic closed orbit stability < 30 \(\mu\)m \((1/10\sigma)\)
Thermodynamic Considerations

Heat capacities

\[ \Delta T = \frac{1}{C} \frac{\Delta U}{\Delta m} \]

Cu at 1.9 K: \( C_{Cu} \approx 0.03 \text{ J/kg/K} \) → premature quenches

superfluid helium at 1.9 K: \( C_{He} \approx 4000 \text{ J/kg/K} \)

measured helium content in s.c. cable \( \sim 4.5\% \)

the helium absorbs energy and transports it away from the coils

Refrigeration (Carnot) Efficiency

\[ \eta = \frac{T_{\text{cold}}}{T_{\text{warm}}} \quad P_{\text{warm}} = \frac{P_{\text{cold}}}{\eta} = \frac{T_{\text{warm}}}{T_{\text{cold}}} P_{\text{cold}} \]
Schematic of **LHC beam screen** operating at $T \approx 5\text{–}20$ K. (Ian Collins, 2001).
Why Protection?

- Stored magnetic energy = 8*1.3GJ +...
- Beam energy = 0.7 GJ
- Long repair times (if possible at all)
- Long set-up times

Danger
1MJ melts ~1kg copper

Safe
many short interruptions
Why Protection?

- Total stored energy = 11 GJ

at 30 knots
LHC Beam Dump

Layout of the LHC beam abort system. (J.M. Zazula et al.)
Optimized sweep profile and lateral alignment of the graphite block (J.M. Zazula et al.)
Candidate Materials for Dump (J.M. Zazula et al.)

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{\text{melt}}$ [°C]</th>
<th>$T_{\text{max}}$ [°C/bunch]</th>
<th>$T_{\text{front}}$ [°C/beam]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>1280</td>
<td>75</td>
<td>3520</td>
</tr>
<tr>
<td>C</td>
<td>4500</td>
<td>320</td>
<td>3520</td>
</tr>
<tr>
<td>Al</td>
<td>660</td>
<td>360</td>
<td>3390</td>
</tr>
<tr>
<td>Ti</td>
<td>1670</td>
<td>1800</td>
<td>3250</td>
</tr>
<tr>
<td>Fe</td>
<td>1540</td>
<td>2300</td>
<td>3120</td>
</tr>
<tr>
<td>Cu</td>
<td>1080</td>
<td>4000</td>
<td>2980</td>
</tr>
</tbody>
</table>
LHC Filling Pattern

bunch-to-bunch spacing 25 ns, total revolution time: 88.924 μs

\[
(((72 \times b + 8 \times e) \times 3) + 30 \times e) \times 2) \\
+(((72 \times b + 8 \times e) \times 4) + 31 \times e) \times 3) \\
+(((72 \times b + 8 \times e) \times 3) + 30 \times e) \times 3) \\
+ 81 \times e)
\]

\(\tau_1 = 12\)  missing bunches  rise kicker extr. PS
\(\tau_2 = 8\)  missing bunches  rise kicker inj. SPS
\(\tau_3 = 30, 31\)  missing bunches  rise kicker inj. LHC
\(\tau_4 = 111\)  missing bunches  rise kicker extr. LHC
Schematic of injection with septum and kicker magnets
equivalence classes for LHC collision schedule
- graphical representation (J. Jowett)
CERN Accelerators
(not to scale)

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LiNar ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Gran Sasso (I)
730 km

Radolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, EIT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01
LHC (Pre-)Injectors

- 4 PS Boosters
- Proton Synchrotron (PS)
- Super Proton Synchrotron (SPS)
Generating multiple bunches via debunching.

In the past multiple bunches were generated by debunching (rf off) and recapturing in higher-harmonic rf system.
Schematic of phase space evolution during slow debunching.
Local $\mu$-wave instability threshold:

$$
\left( \frac{dN}{ds} \right)_{\text{thr}} \propto \delta_{\text{rms}}^2
$$

(Boussard criterion). During debunching the density $dN/ds$ and local energy spread $\delta_{\text{rms}}$ decrease by the same factor.

$\rightarrow$ beam becomes unstable, when threshold condition is reached! ($\rightarrow$ unequal fill patterns, non-reproducibility,...)
Simulation of bunch splitting in the CERN PS at low energy in preparation for injection into the LHC. (Courtesy R. Garoby, 1999.)
Measured triple bunch splitting in the CERN PS at low energy in preparation for injection into the LHC. (R. Garoby, 2001.)
Simulation of further bunch splitting in the CERN PS at high energy (26 GeV/c) in preparation for injection into the LHC. (Courtesy R. Garoby, 1999.)
Tomographic measurement of bunch splitting in the CERN PS booster ring after acceleration with $3 \times 10^{12}$ protons. (Courtesy R. Garoby, 1999.)
# Status of the PS for the LHC Nominal Beam

<table>
<thead>
<tr>
<th></th>
<th>achieved</th>
<th>nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons per bunch</td>
<td>$1.1 \times 10^{11}$</td>
<td>$1.1 \times 10^{10}$</td>
</tr>
<tr>
<td>hor. emittance $\gamma \epsilon_{x}^{1\sigma}$ [$\mu$m]</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>vert. emittance $\gamma \epsilon_{y}^{1\sigma}$ [$\mu$m]</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>long. emittance $\epsilon_{l}^{2\sigma}$ [eVs]</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>total bunch length $l_{b}$ [ns]</td>
<td>$\leq 4$</td>
<td>4</td>
</tr>
<tr>
<td>momentum spread $2\sigma_{p}/p$ [$10^{-3}$]</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>
# SPS Transverse Impedance

<table>
<thead>
<tr>
<th>$Z_v$ in MΩ/m</th>
<th>Date</th>
<th>$Z_h$ in MΩ/m</th>
<th>Date</th>
<th>$Z_h$ in MΩ/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 MΩ/m</td>
<td>13/08/1999</td>
<td>25 ± 6</td>
<td>17/09/1999</td>
<td>33 ± 3</td>
</tr>
<tr>
<td>47.7 MΩ/m</td>
<td>23/08/1999</td>
<td>24 ± 2</td>
<td>10/11/1999</td>
<td>30 ± 2</td>
</tr>
<tr>
<td>13 MΩ/m</td>
<td>10/11/1999</td>
<td>28 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.8 MΩ/m</td>
<td>17/09/1999</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(23 ± 2) MΩ/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: The table entries for $Z_h$ are not provided in the image.*
Measurement of $Q_{x,y}$ vs. $N_b$ for single proton bunch at 26 GeV.

Broadband impedance model with $[R_s] = \Omega \, \text{m}^{-2}$:

$$Z_1^\perp = \frac{c}{\omega \left( 1 + iQ \left( \frac{\omega_r}{\omega} - \frac{\omega}{\omega_r} \right) \right)} \approx -i \frac{c R_s}{Q \omega_r},$$

$$\Delta Q \approx \frac{\beta_{x,y}}{4\pi} \left( -\frac{i e I \text{ Im} Z_1^\perp}{E} \right).$$

So, $\Delta Q/\Delta I \propto \Delta Q/\Delta N_b \rightarrow \text{ Im} Z_1^\perp$. Head-tail growth rates $\rightarrow \text{ Re} Z_1^\perp$. 
# LHC as Heavy Ion Collider

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>species</strong></td>
<td>gold</td>
<td>lead</td>
</tr>
<tr>
<td><strong>energy/charge</strong> $E/Z$ [TeV]</td>
<td>0.25</td>
<td>7</td>
</tr>
<tr>
<td><strong>energy/nucleon</strong> $E/A$ [TeV]</td>
<td>0.1</td>
<td>2.76</td>
</tr>
<tr>
<td><strong>total c.m.</strong> $E_{CM}$ [TeV]</td>
<td>39</td>
<td>1148</td>
</tr>
<tr>
<td><strong>dip. field</strong> $B$ [T]</td>
<td>3.46</td>
<td>8.4</td>
</tr>
<tr>
<td><strong>circumf.</strong> $C$ [km]</td>
<td>3.83</td>
<td>26.66</td>
</tr>
<tr>
<td><strong>#bunches</strong> $n_b$</td>
<td>57</td>
<td>608</td>
</tr>
<tr>
<td><strong>ions per bunch</strong> $N_b$ [$10^7$]</td>
<td>100</td>
<td>6.8</td>
</tr>
<tr>
<td><strong>rms beam size</strong> $\sigma_{x,y}$ [$\mu$m]</td>
<td>110</td>
<td>15</td>
</tr>
<tr>
<td><strong>beta function</strong> $\beta_{x,y}$ [m]</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>tune shift/IP</strong> $\xi_{x,y}$</td>
<td>0.0023</td>
<td>0.00015</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>bunch length</strong> $\sigma_z$ [cm]</td>
<td>18</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>spacing</strong> $L_{sep}$ [m]</td>
<td>63.9</td>
<td>124.8</td>
</tr>
<tr>
<td><strong>tr. emit.</strong> $\gamma\epsilon_{x,y}$ [$\mu$m]</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>long. emit.</strong> $\epsilon_L/Z$ [eVs]</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>IBS gr.t.</strong> $\tau_{IBS}$ [hr]</td>
<td>0.4</td>
<td>9.8</td>
</tr>
<tr>
<td><strong>init. lum.</strong> $L$</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>init. lum.</strong> $[10^{27} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>lum. lifet.</strong> $\tau$ [hr]</td>
<td>$\sim10$</td>
<td>9.3</td>
</tr>
</tbody>
</table>
Limitations for Heavy Ion Operation

- Electromagnetic processes: $e^+e^-$ pair production and subsequent $e^-$ capture

  Cross section $\sigma_c \approx 100$ barn for Pb$^{81+}$-Pb$^{81+}$, or $\dot{N}_c \approx 10^5$ ions s$^{-1}$ per side of IP at $L \approx 10^{27}$ cm$^{-2}$s$^{-1}$ $\sigma_c \propto Z^7$; energy deposition $\propto Z$

  Ions which change charge state by 1 ($\Delta \delta = 1.2\%$ for Pb) are lost over about 1 m in the dispersion suppressor

  Loss rate close to quench limit

  Remedy: dynamic $\beta$ squeeze? local collimators?

- For light ions longitudinal intrabeam scattering (IBS) growth time of 10 hours $1/\tau_{IBS} \propto Z^3/A$

  Initial luminosities: $1.0 \times 10^{27}$ cm$^{-2}$s$^{-1}$ Pb$^{82}_{208}$,
  $6.6 \times 10^{28}$ cm$^{-2}$s$^{-1}$ Kr$^{36}_{84}$, $3.1 \times 10^{31}$ cm$^{-2}$s$^{-1}$ O$^{8}_{16}$.
Intermediate Conclusions

- hadron colliders have performed exceedingly well in the past

- LHC will reach the highest energy (14 TeV) and highest luminosity \((10^{35} \text{ cm}^{-2}\text{s}^{-1})\) ever

- LHC design is based on the experience gained at the ISR, SPS, Tevatron, HERA, RHIC,...; conservative assumptions
yet accelerator physicists face exciting challenges, e.g.,
- magnet technology and cryogenics
- long-range collisions
- strong-strong collisions
- radiation damping stronger than IBS (tomorrow)
- electron cloud (tomorrow)
- demanding upgrade options (tomorrow)