Lead ions in LHC main ring

Hans Braun - collimation
Moira Gresham (Reed College) – ECPP, software
Bernard Jeanneret – nuclear effects, aperture
John Jowett
Edgar Mahner - vacuum
Igor Pshenichnov (INR, Moscow) – nuclear cross sections
Karlheinz Schindl – overall I-LHC project leader
Elena Shaposhnikova – longitudinal dynamics
+ many others in LHC project
Optics, instrumentation, etc.
Pre-2003: Daniel Brandt, ...
Collisions with ions

Consider $^{208}\text{Pb}^{82+}$ collisions for now

CM energy 1.15 PeV with nominal dipole field.
2.76 TeV/amu

p-Pb, p-A etc. later

ALICE detector specialises in heavy ion physics

CMS and ATLAS are also interested in ions

At nominal luminosity/bunch, initial lifetime is short with 3 active experiments.

Run with 1 or 2 experiments or adapt luminosity during fill.
Parameters for Lead Ions in LHC

Revision/verification of all parameters
Started at Chamonix Workshop 2003
Summarised in forthcoming LHC Design Report Vol I, Chapter 21

Recent changes:
Optics update, crossing scheme for ALICE
Introduction of “Early Ion Scheme”
Performance limit from ECPP, magnet quench
Complete revision of lifetimes, IBS, etc.
First studies of collimation of lead ions
No 200 MHz RF system for capture at injection now
# Nominal scheme parameters

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Injection</th>
<th>Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead ion energy</td>
<td>36900</td>
<td>574000</td>
</tr>
<tr>
<td>Lead ion energy/nucleon</td>
<td>177.4</td>
<td>2759.</td>
</tr>
<tr>
<td>Relativistic “gamma” factor</td>
<td>190.5</td>
<td>2963.5</td>
</tr>
<tr>
<td>Number of ions per bunch</td>
<td>7. × 10^7</td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td>592</td>
<td></td>
</tr>
<tr>
<td>Transverse normalized emittance</td>
<td>1.4a</td>
<td>1.5</td>
</tr>
<tr>
<td>Peak RF voltage (400 MHz system)</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>63.7</td>
<td>23.0</td>
</tr>
<tr>
<td>RF bucket half-height</td>
<td>1.04 × 10(^{-3})</td>
<td>3.56 × 10(^{-4})</td>
</tr>
<tr>
<td>Longitudinal emittance (4(\sigma))</td>
<td>0.7</td>
<td>2.5(^b)</td>
</tr>
<tr>
<td>RF bucket filling factor</td>
<td>0.472</td>
<td>0.316</td>
</tr>
<tr>
<td>RMS bunch length(^c)</td>
<td>9.97</td>
<td>7.94</td>
</tr>
<tr>
<td>Circulating beam current</td>
<td>6.12</td>
<td></td>
</tr>
<tr>
<td>Stored energy per beam</td>
<td>0.245</td>
<td>3.81</td>
</tr>
<tr>
<td>Twiss function (\beta_x = \beta_y = \beta^*) at IP2</td>
<td>10.0</td>
<td>0.5</td>
</tr>
<tr>
<td>RMS beam size at IP2</td>
<td>280.6</td>
<td>15.9</td>
</tr>
<tr>
<td>Geometric luminosity reduction factor (F^d)</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Peak luminosity at IP2</td>
<td>-</td>
<td>1. × 10^{22}(^r)</td>
</tr>
</tbody>
</table>
# Nominal scheme, lifetime parameters

<table>
<thead>
<tr>
<th>Interaction data</th>
<th>Injection</th>
<th>Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cross section</td>
<td>[mb]</td>
<td>-</td>
</tr>
<tr>
<td>Beam current lifetime (due to beam-beam)$^a$</td>
<td>[h]</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intra Beam Scattering</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS beam size in arc</td>
<td>[mm]</td>
<td>1.19</td>
</tr>
<tr>
<td>RMS energy spread $\delta E/E_0$</td>
<td>$[10^{-4}]$</td>
<td>3.9</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>[cm]</td>
<td>9.97</td>
</tr>
<tr>
<td>Longitudinal emittance growth time</td>
<td>[hour]</td>
<td>3</td>
</tr>
<tr>
<td>Horizontal emittance growth time$^b$</td>
<td>[hour]</td>
<td>6.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Synchrotron Radiation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power loss per ion</td>
<td>[W]</td>
<td>$3.5 \times 10^{-14}$</td>
</tr>
<tr>
<td>Power loss per metre in main bends</td>
<td>[Wm$^{-1}$]</td>
<td>$8 \times 10^{-8}$</td>
</tr>
<tr>
<td>Synchrotron radiation power per ring</td>
<td>[W]</td>
<td>$1.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Energy loss per ion per turn</td>
<td>[eV]</td>
<td>19.2</td>
</tr>
<tr>
<td>Critical photon energy</td>
<td>[eV]</td>
<td>$7.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Longitudinal emittance damping time</td>
<td>[hour]</td>
<td>23749</td>
</tr>
<tr>
<td>Transverse emittance damping time</td>
<td>[hour]</td>
<td>47498</td>
</tr>
<tr>
<td>Variation of longitudinal damping partition number$^c$</td>
<td>[hour]</td>
<td>230</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial beam and luminosity lifetimes</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current lifetime (due to residual gas scattering)$^d$</td>
<td>[hour]</td>
<td>?</td>
</tr>
<tr>
<td>Beam current lifetime (beam-beam, residual gas)</td>
<td>[hour]</td>
<td>-</td>
</tr>
<tr>
<td>Luminosity lifetime$^e$</td>
<td>[hour]</td>
<td>-</td>
</tr>
</tbody>
</table>

---

$^a$ Beam current lifetime (due to beam-beam).

$^b$ Horizontal emittance growth time.

$^c$ Variation of longitudinal damping partition number.

$^d$ Beam current lifetime (due to residual gas scattering).

$^e$ Luminosity lifetime.
### Early scheme Parameters

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Injection</th>
<th>Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bunches</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td>Circulating beam current</td>
<td>[mA]</td>
<td>0.641</td>
</tr>
<tr>
<td>Stored energy per beam</td>
<td>[MJ]</td>
<td>0.0248 0.386</td>
</tr>
<tr>
<td>Twiss function $\beta_x = \beta_y = \beta^*$ at IP2</td>
<td>[m]</td>
<td>10.0 1.0</td>
</tr>
<tr>
<td>RMS beam size at IP2 $^e$</td>
<td>[$\mu$m]</td>
<td>280.6 22.5</td>
</tr>
<tr>
<td>Peak luminosity at IP2</td>
<td>[cm$^{-2}$sec$^{-1}$]</td>
<td>- $5.4 \times 10^{25}$</td>
</tr>
</tbody>
</table>

### Interaction data

| Beam current lifetime (due to beam-beam)$^a$ | [h] | - | 21.8 |

### Synchrotron Radiation

| Power loss per metre in main bends | [Wm$^{-1}$] | $8.5 \times 10^{-9}$ | $5.0 \times 10^{-4}$ |
| Synchrotron radiation power per ring | [W] | $1.5 \times 10^{-4}$ | 8.8 |

### Initial beam and luminosity lifetimes

| Beam current lifetime (beam-beam, residual gas) | [hour] | - | $< 21.8$ |
| Luminosity lifetime (as in Table 21.3) | [hour] | - | $< 11.2$ |

Only show parameters that are different from nominal scheme

---

J.M. Jowett, LHC Machine Advisory Committee, 11 Dec 2003
Some things are straightforward

Beam current and stored energy 100 times lower

Many limits to performance of proton beams are not a problem for lead ion beams

- impedance-driven collective effects
- beam-beam
- electron cloud (?)
- activation and maintenance of collimators

Same geometrical transverse beam size and emittance ⇒ some aspects are similar

Optics, dynamic aperture, mechanical acceptance, etc. more or less carry over from protons.
### Electromagnetic Interactions of Heavy ions

#### QED effects in the peripheral collisions of heavy ions

<table>
<thead>
<tr>
<th>Effect</th>
<th>Reaction</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rutherford scattering:</strong></td>
<td>$^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \xrightarrow{\gamma} ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+}$</td>
<td>Copious but harmless</td>
</tr>
<tr>
<td><strong>Free pair production:</strong></td>
<td>$^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \xrightarrow{\gamma} ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} + e^+ + e^-$</td>
<td>Copious but harmless</td>
</tr>
<tr>
<td><strong>Electron capture by pair production (ECPP)</strong></td>
<td>$^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \xrightarrow{\gamma} ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{81+} + e^+$</td>
<td>Electron can be captured to a number of bound states, not only 1s.</td>
</tr>
<tr>
<td><strong>Electromagnetic Dissociation (EMD)</strong></td>
<td>$^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \xrightarrow{\gamma} ^{208}\text{Pb}^{82+} + (^{208}\text{Pb}^{82+})^*$  \downarrow \quad ^{207}\text{Pb}^{82+} + n</td>
<td>Secondary beam out of IP, effectively off-momentum: $\delta_p = -\frac{1}{A-1} = -4.8 \times 10^{-3}$ for Pb</td>
</tr>
</tbody>
</table>
Nuclear cross sections

Cross-section for Pb totally dominated by electromagnetic processes
Values for non-Pb ions may need upward revision

Total cross-section for ion removal from beam

\[ \sigma_{tot} = \sigma_H + \sigma_{EMD} + \sigma_{ECPP} \]

<table>
<thead>
<tr>
<th>Element</th>
<th>(\sigma_H)</th>
<th>(\sigma_{EMD})</th>
<th>(\sigma_{ECPP})</th>
<th>(\sigma_{tot})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>0.105</td>
<td>0</td>
<td>4.25 \times 10^{-11}</td>
<td>0.105</td>
</tr>
<tr>
<td>Helium</td>
<td>0.35</td>
<td>0.002</td>
<td>1. \times 10^{-8}</td>
<td>0.352</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.5</td>
<td>0.13</td>
<td>0.00016</td>
<td>1.63016</td>
</tr>
<tr>
<td>Argon</td>
<td>3.1</td>
<td>1.7</td>
<td>0.04</td>
<td>4.84</td>
</tr>
<tr>
<td>Krypton</td>
<td>4.5</td>
<td>15.5</td>
<td>3.</td>
<td>23.</td>
</tr>
<tr>
<td>Indium</td>
<td>5.5</td>
<td>44.5</td>
<td>18.5</td>
<td>68.5</td>
</tr>
<tr>
<td>Lead</td>
<td>8</td>
<td>225.</td>
<td>280.756</td>
<td>513.756</td>
</tr>
</tbody>
</table>

\[ \delta(\Delta Q, \Delta A) \approx \frac{1 + \Delta A/A}{1 + \Delta Q/Q} - 1 \]
Main and ECPP secondary beams

$5\sigma$ beam envelopes, emerging to right of IP2

Beam sizes different, strong chromatic effects

Equivalent $\delta_p = \frac{1}{Z - 1} = 0.012$ for Pb

Shifted momentum outside momentum acceptance $\delta_p^\text{max}$

$|\delta_p| > \delta_p^\text{max} \approx 6 \times 10^{-3}$

Collimation of secondary beam not easy, to be studied.

J.M. Jowett, LHC Machine Advisory Committee, 11 Dec 2003
Secondary beam spot

Quench limit (conservative) is $8 \times 10^4 \text{ Pb/m/s}$

Dilution over $l_d \approx 1 \text{ m}$,

In quadrature with shower length $1 \text{ m} \approx 1.4 \text{ m}$

Beam screen in a dispersion suppressor dipole

Energy deposition by ion flux from ECPP exceeds quench limit of superconducting magnets by factor 2 at nominal luminosity. (some safety factors in hand ?)
Consequences of EMD effect

Magnetic rigidity of ion decreased
Not studied in much detail so far

\[(Z_1, A_1) + (Z_2, A_2) \rightarrow (Z_1, A_1) + (Z_2, A_2)^*\]
\[\downarrow\]
\[(Z_2, A_2 - 1) + n\]

Equivalent \(\delta_p = -\frac{1}{A-1} = -4.8 \times 10^{-3}\) for Pb

Compare shifted momentum spread to momentum acceptance \(\delta_p^{\text{max}}\)

\[|\delta_p| + \sigma_\delta = 4.8 \times 10^{-3} + 0.8 \times 10^{-3} < \delta_p^{\text{max}} \approx 6 \times 10^{-3}\]

\(\Rightarrow\) should be taken up by momentum collimation system
Collimation

$^{208}$Pb$^{82+}$ ion-graphite interactions compared with p-graphite interactions.

<table>
<thead>
<tr>
<th>Physics process</th>
<th>p injection</th>
<th>p collision</th>
<th>$^{208}$Pb$^+$ injection</th>
<th>$^{208}$Pb$^+$ collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization energy loss $\frac{dE}{dx}$</td>
<td>0.12 %/m</td>
<td>0.0088 %/m</td>
<td>9.57 %/m</td>
<td>0.73 %/m</td>
</tr>
<tr>
<td>Multiple scattering projected RMS angle</td>
<td>73.5 $\mu$rad/m$^{1/2}$</td>
<td>4.72 $\mu$rad/m$^{1/2}$</td>
<td>73.5 $\mu$rad/m$^{1/2}$</td>
<td>4.72 $\mu$rad/m$^{1/2}$</td>
</tr>
<tr>
<td>Electron capture length</td>
<td>-</td>
<td>-</td>
<td>20 cm</td>
<td>312 cm</td>
</tr>
<tr>
<td>Electron stripping length</td>
<td>-</td>
<td>-</td>
<td>0.028 cm</td>
<td>0.018 cm</td>
</tr>
<tr>
<td>ECPP interaction length</td>
<td>-</td>
<td>-</td>
<td>24.5 cm</td>
<td>0.63 cm</td>
</tr>
<tr>
<td>Nuclear interaction length (incl. fragmentation)</td>
<td>38.1 cm</td>
<td>38.1 cm</td>
<td>2.5 cm</td>
<td>2.2 cm</td>
</tr>
<tr>
<td>Electromagnetic dissociation length</td>
<td>-</td>
<td>-</td>
<td>33.0</td>
<td>19.0 cm</td>
</tr>
</tbody>
</table>

From Hans Braun
Robustness of collimator against mishaps

The higher ionisation loss makes the energy deposition at the impact side almost equal to proton case, despite 100 times less beam power.

Similar damage potential.

From Hans Braun
Cleaning efficiency

Collimators tend to put fragments on trajectories with large momentum errors and small betatron amplitude – but the secondary collimators are designed to cut betatron amplitudes. Studies under way.

The probability to convert a $^{208}$Pb nucleus into a neighboring nucleus. Impact on graphite at LHC collision energy.

From Hans Braun
Nominal ILHC beam at collision

Fractional heat load in dispersion suppressor, $\tau = 12\text{min}$

Maximum for continuous loss, corresponds to local collimation inefficiency of $1.61 \times 10^{-3} \text{ m}^{-1}$

Distance from TCP.D6L7.B1 (m)
Optics

Ion optics at injection/ramp
assumed to be essentially same as protons

Treat only lead ion optics in collision

Update for move of Q3 magnets (part of V6.5)
Focus on IR2 (ALICE, specialised ion experiment)

Maintain $\beta^*=0.5$ m (unlike protons which have $\beta^*=0.55$ m for reasons of aperture)

Ion collisions for ATLAS/CMS may use proton optics

Or also squeeze further

Main issue is separation
Optics re-matched by T. Risselada
### Longitudinal parameters

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Injection</th>
<th>Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead ion energy</td>
<td>[GeV]</td>
<td>36900</td>
</tr>
<tr>
<td>Lead ion energy/nucleon</td>
<td>[GeV]</td>
<td>177.4</td>
</tr>
<tr>
<td>Relativistic “gamma” factor</td>
<td></td>
<td>190.5</td>
</tr>
<tr>
<td>Number of ions per bunch</td>
<td></td>
<td>$7 \times 10^6$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>592</td>
</tr>
<tr>
<td>Transverse normalized emittance</td>
<td>[$\mu$m]</td>
<td>1.48</td>
</tr>
<tr>
<td>Peak RF voltage (400 MHz system)</td>
<td>[MV]</td>
<td>8</td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>[Hz]</td>
<td>63.7</td>
</tr>
<tr>
<td>RF bucket half-height</td>
<td></td>
<td>$1.04 \times 10^{-3}$</td>
</tr>
<tr>
<td>Longitudinal emittance (4$\sigma$)</td>
<td>[eV s/charge]</td>
<td>0.7</td>
</tr>
<tr>
<td>RF bucket filling factor</td>
<td></td>
<td>0.472</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>[cm]</td>
<td>9.97</td>
</tr>
<tr>
<td>Circulating beam current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stored energy per beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twiss function $\beta_x = \beta_y = \beta^*$ at IP2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS beam size at IP2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometric luminosity reduction factor F$^d$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak luminosity at IP2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Longitudinal emittance at injection from SPS has been reduced since we no longer have 200 MHz RF system for capture.
Intra-beam scattering

Figure 21.6: Emittance growth times from intra-beam scattering as a function of longitudinal emittance for $^{208}\text{Pb}^{82+}$ at injection (left plot) and collision (right plot) energies. The transverse emittances and beam intensities are taken to have their nominal values and the total circumferential voltage from the 400 MHz RF system are $V_{RF} = 8$ MV and $V_{RF} = 16$ MV respectively. Solid and dashed lines correspond to the growth times for horizontal and longitudinal emittances.
## Synchrotron Radiation

### Scaling with respect to protons in same ring, same magnetic field

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Proton</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{U_{\text{ion}}}{U_p} )</td>
<td>( A^4 ) ( Z^6 ) ( \approx 162 )</td>
<td>( A^3 ) ( Z^3 ) ( \approx 0.061 )</td>
</tr>
<tr>
<td>( \frac{N_{\text{ion}}}{N_p} )</td>
<td>( A ) ( Z^3 ) ( \approx 2651 )</td>
<td>( Z^5 ) ( A^4 ) ( \approx 0.5 )</td>
</tr>
</tbody>
</table>

- Radiation damping for Pb is twice as fast as for protons
- Many very soft photons
- Critical energy in visible spectrum

Radiation damping enhancement for all stable isotopes

- Lead is (almost) best, deuteron is worst.
Damping partition number variation

Variation of longitudinal damping partition number with momentum deviation of closed orbit:

\[
J_e(\delta_s) = \frac{d\log U(\delta_s)}{d\delta_s} \approx 2 + \frac{I_4}{I_2} + 2 \frac{I_8}{I_2} \delta_s, \quad \delta_s = -\frac{1}{\eta} \frac{\Delta f_{RF}}{f_{RF}}
\]

\[
I_2 \approx \frac{2\pi}{\rho}, \quad I_4 \approx 10^{-3} I_2, \quad I_8 = \int (K_1(s)D_x(s))^2 \, ds
\]

Damping rate for horizontal betatron motion

\[
\alpha_x(\delta_s) = J_x(\delta_s)\alpha_x(0) = (3 - J_e(\delta_s))\alpha_x(0)
\]

Allows us to switch some radiation damping from longitudinal into horizontal motion

Heavily used at LEP, PETRA, TRISTAN, ...

Overcome IBS, shrinking horizontal emittance to maximise integrated luminosity

Price of a few mm negative closed orbit in arc QFs – needs further study
Luminosity and beam lifetime

Initial beam (intensity) lifetime due to beam-beam interactions (non-exponential decay)

\[ \tau_L = \frac{k_b N_b}{n_{exp} L \sigma_{tot}} = \frac{22.4 \text{ hour}}{n_{exp}} \]

for nominal \( L = 10^{27} \text{ cm}^{-2}\text{s}^{-1} \) with Pb - Pb

where \( n_{exp} \) is the number of experiments illuminated

But luminosity may be limited by experiment or quench limit (see later)

\[ L = \frac{k_b N_b^2 f_0}{4\pi \sigma^*} = \frac{k_b N_b^2 f_0}{4\pi \beta^* \varepsilon_n} \gamma \]

\[ \Rightarrow \text{ can have same luminosity by varying} \beta^* \propto N_b^2 \]

Idea of \( \beta^* \)-tuning during collision to maximise integrated luminosity – especially if \( N_b \) can be increased.
### Nominal scheme, lifetime parameters (again)

<table>
<thead>
<tr>
<th>Interaction data</th>
<th>Injection</th>
<th>Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cross section</td>
<td>[mb]</td>
<td>-</td>
</tr>
<tr>
<td>Beam current lifetime (due to beam-beam)$^{a}$</td>
<td>[h]</td>
<td>-</td>
</tr>
</tbody>
</table>

**Intra Beam Scattering**

<table>
<thead>
<tr>
<th></th>
<th>[mm]</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS beam size in arc</td>
<td>1.19</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>RMS energy spread $\delta E/E_0$</td>
<td>$10^{-4}$</td>
<td>3.9</td>
<td>1.10</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>9.97</td>
<td>7.94</td>
<td></td>
</tr>
<tr>
<td>Longitudinal emittance growth time</td>
<td>[hour]</td>
<td>3</td>
<td>7.7</td>
</tr>
<tr>
<td>Horizontal emittance growth time$^{b}$</td>
<td>[hour]</td>
<td>6.5</td>
<td>13</td>
</tr>
</tbody>
</table>

**Synchrotron Radiation**

<table>
<thead>
<tr>
<th></th>
<th>[W]</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power loss per ion</td>
<td>$3.5 \times 10^{-14}$</td>
<td>2.0 x $10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Power loss per metre in main bends</td>
<td>$8 \times 10^{-8}$</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Synchrotron radiation power per ring</td>
<td>[W]</td>
<td>1.4 x $10^{-3}$</td>
<td>83.9</td>
</tr>
<tr>
<td>Energy loss per ion per turn</td>
<td>[eV]</td>
<td>19.2</td>
<td>1.12 x $10^6$</td>
</tr>
<tr>
<td>Critical photon energy</td>
<td>[eV]</td>
<td>$7.3 \times 10^{-4}$</td>
<td>2.77</td>
</tr>
<tr>
<td>Longitudinal emittance damping time</td>
<td>[hour]</td>
<td>23749</td>
<td>6.3</td>
</tr>
<tr>
<td>Transverse emittance damping time</td>
<td>[hour]</td>
<td>47498</td>
<td>12.6</td>
</tr>
<tr>
<td>Variation of longitudinal damping partition number$^{c}$</td>
<td>[hour]</td>
<td>230</td>
<td>230</td>
</tr>
</tbody>
</table>

**Initial beam and luminosity lifetimes**

<table>
<thead>
<tr>
<th></th>
<th>[hour]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current lifetime (due to residual gas scattering)$^{d}$</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Beam current lifetime (beam-beam, residual gas)</td>
<td>[hour]</td>
<td>-</td>
</tr>
<tr>
<td>Luminosity lifetime$^{e}$</td>
<td>[hour]</td>
<td>-</td>
</tr>
</tbody>
</table>

---

$^{a}$ J.M. Jowett, LHC Machine Advisory Committee, 11 Dec 2003

---

$^{b}$ Initial beam and luminosity lifetimes

---

$^{c}$ Initial beam and luminosity lifetimes

---

$^{d}$ Initial beam and luminosity lifetimes

---

$^{e}$ Initial beam and luminosity lifetimes
Separation in IR2: three illustrative cases

Two ways of getting a crossing angle of 80 $\mu$rad; one way to get zero crossing angle.

Beam 1 / Beam 2

Total separation is superposition of ALICE spectrometer bump and “external” vertical separation.

Animation!
Parasitic beam-beam encounters

Show only vertical separation in units of vertical RMS beam size of Beam 1.

Red lines are possible (ion) encounters ($S_b/2$)

Zero crossing angle is just about achievable with minimum $3\sigma$ separation (strictly need 20 $\mu$rad).
Aperture (APL program)

All meet the canonical aperture requirements with $\beta^*=0.5\text{m}$
Vacuum: ion-induced molecular desorption

During heavy-ion operation, alarmingly large pressure rises observed in diverse machines at CERN, GSI, BNL.

Dynamic pressure rise by molecular desorption from lost beam ions.

Not well understood, data is sparse, little information on parameter-dependences.

Workshop this week at BNL.

First results from recent SPS experiment.

\[ \eta = \frac{\Delta p S}{\dot{N} k_B T} \]

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Energy [MeV/u]</th>
<th>Particle</th>
<th>Desorption yield [molecules/ion]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS</td>
<td>1</td>
<td>Au(^{31+})</td>
<td>(\sim 10^5)</td>
</tr>
<tr>
<td>LINAC3</td>
<td>4.2</td>
<td>Pb(^{53+})</td>
<td>(10^3 \ldots 2 \times 10^4)</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>Pb(^{27+})</td>
<td>(10^3 \ldots 2 \times 10^4)</td>
</tr>
<tr>
<td>SIS18</td>
<td>8.6</td>
<td>U(^{28+})</td>
<td>(4 \times 10^3 \ldots 1 \times 10^4)</td>
</tr>
<tr>
<td>RHIC</td>
<td>8900</td>
<td>Au(^{79+})</td>
<td>(\sim 1.5 \times 10^7)</td>
</tr>
</tbody>
</table>

From Edgar Mahner / AT
Dynamic outgassing tests of graphite collimators with In$^{49+}$ at 158 GeV/u
Beam Instrumentation

Lead beams invisible on arc BPMs at about factor 3 below full intensity.

“Early” scheme – 10 times fewer bunches but full intensity/bunch (limited by injectors)

Visibility on beam current monitors also limited
Operational parameter space with lead ions

Visibility threshold on FBCT
Nominal

Visibility threshold on arc BPM
Nominal single bunch current

ECPP Quench limit

$L / \text{cm}^2 \text{s}^{-1}$

$I_b / \mu \text{A}$
Conclusions

Operation of LHC with lead ions limited by new effects, qualitatively different from protons
Restricted to a narrow operational range of parameters below the nominal luminosity
“Early scheme” will allow relatively safe commissioning, access good initial physics
Reduced risk of magnet quenches from ECPP
Uncertainties to be resolved with further studies
ECPP heating, EMD losses, vacuum, collimation, RF noise, ...

Manpower limited (surprise) so we must choose.