Lead Ion Injectors

- What do the Clients (ALICE) Require?
- Injector Chain - Overview and Key Parameters
- Overview of Hardware Upgrades
- Source and Linac3
- LEIR
- PS
- SPS
- “Early Scheme”: A Simplified Scheme for Early Operation
- Project Schedule
- Summary: Project Status, Issues
People involved in the I-LHC Project

I-LHC ("Ions for LHC") Project definition, beam dynamics:

Charles Hill, Detlev Kuchler, Richard Scrivens (source + linac3)
Michel Chanel (LEIR project leader), Christian Carli (LEIR), Gerard Tranquille (Electron Cooling)
Michel Martini, Steven Hancock (PS)
Elena Chapochnikova, Django Manglunki, Helmut Burkhhardt (SPS)
John Jowett, Hans Braun (LHC)
Karlheinz Schindl (I-LHC Project Leader)

Hardware tasks, key people:

Thomas Zickler/AT (Magnets)
Jan Borburgh (Septum Magnets)
Anthony Fowler (Kicker Magnets)
Trevor Linnecar, Carlo Rossi, Flemming Pedersen (RF systems and Beam Control)
Andre Beuret, Jean-Pierre Royer (Power Converters)
Edgar Mahner/AT (Vacuum)
Uli Raich (Beam Diagnostics)
Marine Gourber-Pace (Controls)
Christian Lacroix (Installation), Jean-Michel Lacroix/EST (Designer-Draughtsman)
Karsten Kahle/ST (ST Linkman: water, electricity,...)
Bernard Prouteau/TIS (Asbestos), Fritz Szoncso/TIS (Electrical Safety)

\(^1\)AB Division if not indicated otherwise
LHC: Layout

CMS

Beam dumps

Arrêts des faisceaux

Beam cleaning

Nettoyage des faisceaux

Nettoyage des faisceaux

ATLAS

ALICE

Injection des protons

Injection des protons

p-p (Pb-Pb)

p-p (Pb-Pb?)

LHCMAC 11 December 2003

Lead Ion Injectors - Karlheinz Schindl/AB

3/22
ALICE (CMS, + ATLAS?) Planning

- Running-in detector in 2007 with p-p, followed by p-p physics run
- Year 1: Pb-Pb pilot run “at the end of first p-p run”, normally in April 2008, ~1 week, L a few $10^{25}$ cm$^{-2}$s$^{-1}$ (corresponds to “Early Scheme”)
- Years 2 (2009?) and 4: Pb-Pb @ L ~ $10^{27}$ cm$^{-2}$s$^{-1}$ (Nominal Pb beam) for rare observables
- Year 3: p-Pb @ L ~ $10^{29}$ cm$^{-2}$s$^{-1}$ for nuclear modifications of structure functions
- Year 5 (2012?): Ar-Ar @ L ~ $10^{27}$ - $10^{29}$ cm$^{-2}$s$^{-1}$ for energy density dependence

I-LHC Planning

- Deal exclusively with Pb ions
- “Early Pb Scheme“ - much easier to achieve - for 2008 (and 2009?)
- Nominal Pb Scheme by 2009 (2010?)
- Other ion-ion collisions (typically In, Kr, Ar, O) by ~2012 → improvement programme albeit without major hardware changes
The LHC Injector Chain - Overview

- **LEIR 72 MeV/n Pb**
- **6 GeV/n Pb**
- **177 GeV/n Pb**
- **SPS 450 GeV**
- **PS 25 GeV**
- **BOOSTER 1.4 GeV**
- **LEIR 72 MeV/n**
- **LHC 7 TeV p-p**
  - **2.76 TeV/n Pb-Pb**

**PROTONS**

**IONS**
# LHC Pb Injector Chain: Key Parameters for LHC Pb Luminosity $10^{27} \text{cm}^{-2} \text{s}^{-1}$

<table>
<thead>
<tr>
<th>ECR Source</th>
<th>Linac 3</th>
<th>LEIR</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output energy</td>
<td>2.5 KeV/n</td>
<td>4.2 MeV/n</td>
<td>72.2 MeV/n</td>
<td>5.9 GeV/n</td>
<td>177 GeV/n</td>
</tr>
<tr>
<td>$^{208}\text{Pb}$ charge state</td>
<td>27+</td>
<td>27+</td>
<td>54+</td>
<td>54+</td>
<td>82+</td>
</tr>
<tr>
<td>Output $B\rho$ [Tm]</td>
<td>2.28</td>
<td>1.14</td>
<td>4.80</td>
<td>86.7</td>
<td>57.1</td>
</tr>
<tr>
<td>bunches/ring</td>
<td>2 (1/8 of PS)</td>
<td>4x2</td>
<td>52,48,32</td>
<td>592</td>
<td></td>
</tr>
<tr>
<td>ions/pulse</td>
<td>9 $10^9$</td>
<td>1.15 $10^9$</td>
<td>9 $10^8$</td>
<td>4.8 $10^8$</td>
<td>$\leq 4.7 \times 10^9$</td>
</tr>
<tr>
<td>ions/LHC bunch</td>
<td>9 $10^9$</td>
<td>1.15 $10^9$</td>
<td>2.25 $10^8$</td>
<td>1.2 $10^8$</td>
<td>9 $10^7$</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>95/5 ns or 100 ns</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varepsilon^*$(nor. rms) [$\mu$m]$^2$</td>
<td>~0.10</td>
<td>0.25</td>
<td>0.7</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Repetition time [s]</td>
<td>0.2-0.4</td>
<td>0.2-0.4</td>
<td>3.6</td>
<td>3.6</td>
<td>~50</td>
</tr>
<tr>
<td>$\varepsilon_{\text{long}}$ per LHC bunch$^3$</td>
<td>0.025 eVs/n</td>
<td>0.05</td>
<td>0.4</td>
<td>1 eVs/n</td>
<td></td>
</tr>
<tr>
<td>total bunch length [ns]</td>
<td>200</td>
<td>3.9</td>
<td>1.65</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

$^1$50 $e\mu$A$_e$ x 200 $\mu$s Linac3 output after stripping

$^2$ Same physical emittance as protons, with the same tight emittance budget

$^3$For $^{208}\text{Pb}^{82+}$, 1 eVs/n $\sim$ 2.5 eVs/charge
Pb Ions for LHC: Hardware Upgrades

- Repetition rate 1 → 5 Hz
- New power converters
- RF upgrade to 5 Hz
- Pb$^{27+} \rightarrow$ Pb$^{54+}$
- Energy ramping cavity $Dp/p \sim 0.4\%$
- Bi-directional injection/transf. Line
- Multiturn inject. into 6-D phase space
- Powerful electron cooling
- UH vacuum by beam scrubbing
- RF cavities with frequency “swing” ~8

- Inject. of 52 pairs of bunchlets or 52 bunches at 5.9 GeV/n
- Recombination of 52 pairs of bunchlets to 52 bunches at 177 GeV/n by 100 MHz system(?)

- New injection equipment
- RF gymnastics to obtain 4 pairs of bunchlets or 4 bunches, spacing 100 ns

- Al Stripper Pb$^{54+} \rightarrow$ Pb$^{82+}$; low-beta insertion

200 eμA Pb$^{25+}$:
RF generator 14.5 → 18 GHz
or: improved 14.5 GHz CEA
Grenoble

LHC

SPS

PS

LEAR

RFQ

LINAC3

ECR
The Heavy Ion (Lead) Linac 3

Present ECR (Electron Cyclotron Resonance) Source (from GANIL) was used for the fixed-target Pb and In runs. It delivers ~120 e\(_\mu\)A x 200 \(\mu\)s of Pb\(^{27+}\). To get to or near the desired 200 e\(_\mu\)A, two alternatives are considered:

- Upgrade of the present source from 14.5 to 18 GHz microwave power (>150 e\(_\mu\)A);
- Purchase a markedly improved 14.5 GHz source from CEA Grenoble (>200 e\(_\mu\)A).

Acceleration of several charge states (e.g. 27+, 28+, 29+) in Linac3 is being studied, potential Pb\(^{54+}\) intensity increase >1.5.
- Lattice with twofold symmetry circumference 25 $\pi$ m (1/8 PS)
- Multiturn injection into hor. + ver. phase planes + longitudinal by ramping the energy (0.4 %) during the linac pulse (200 $\mu$s)
- Dipole field from 0.27 to 1.15 T
- $Q_x, Q_y = (1.82/2.72)$ nominal $\gamma_t = 2.84$
- RF harmonics 2 or 1
- LEIR Upgrading: $\sim \frac{3}{4}$ of I-LHC project resources
LEIR Acceleration Cycle

Expected Cycle for Lead Ions

- **Electron cooling**
- **Acceleration**
- **Extraction**

**Main dipole Current [A]**

- Injection

**Main dipole field [T]**

- 4.2 MeV/u
- 72 MeV/u
Electron Cooler (photo GSI)

**LEIR Electron Cooler**

- Voltage: up to 40 kV (cooling of ions up to 64 MeV/u possible)
- electron current (at energy)
  - 0.05 – 0.6 A (2.3 – 6 keV)
  - up to 3 A (6 – 40 keV)
- “hollow” electron beam reduces recombination Pb^{54+} with electrons
- solenoidal field in gun 6 kG
- field in toroid 1.5 kG
- field in 2.5 m cooling length 0.75 kG
- Being manufactured at INP Novosibirsk
LEIR RF Cavities

Two cavities (1 + 1 live spare)
Low voltage (4 kV each)
Frequency swing requirement for Pb
0.36 - 2.84 MHz (h = 1 and 2)
Low-Q Finemet® magnetic ribbon
large band 0.36 - 5 MHz without a tuner
(favouring future lighter ions programme)
RF gap closed during accumulation and cooling

Collaboration with KEK
Pb$^{54+}$ ions capture electrons from residual gas - requires UHV for good lifetimes.

Multiturn injection loss (∼30%): each Pb ion desorbs $>10^4$ molecules $\rightarrow$ pressure rise.

But beam scrubbing helps, the increase $\Delta p$ with respect to static pressure almost vanishes after beam cleaning.

Beam scrubbing will be used in LEIR.

Overall beam lifetime ∼15 s aimed at.
Pb Accumulation Test in LEAR 1997

Average accumulated intensity: 6E8 ions
Peak intensity: 7.1E8 ions

Linac III rep rate: 2.5 Hz
Ion beam energy: 4.2 MeV/u
Electron energy: 2.35 keV
Electron current: 105 mA

Beam lifetime: 6.5s

Improvements for LEIR
- twice the linac intensity
- faster electron cooling
- better beam lifetime (vacuum, etc) of ~15 s

LEIR required
RF Gymnastics in the PS for Pb ions

- Injection h=16
- h=16 to h=14
- h=14 to h=12
- Splitting h=24
  h=24 to h=21
- h=21 to h=169
- Splitting h=423 (200MHz)

¼ of PS circumference

M. Chanel, S. Hancock, M. Martini
Between PS and SPS an Al stripper foil (0.8 mm) changes Pb$^{54+}$ to Pb$^{82+}$ but beam undergoes Coulomb scattering in the foil. The emittance blow-up at the present stripper location will be about 75% but this can be reduced to about 10% if the foil is at a lower beta (both planes).

A new optics generates a “low-beta insertion” at the foil in a new location, thus reducing beta from ~23 to ~4.5 m.
Features

- Injection plateau at 57.1 Tm, with up to 13 PS batches (4 pairs of bunchlets each) injected, lasting 43.2 s. Very little transverse blow-up/losses allowed.

- 200 MHz system not compatible with ion frequency swing → “fixed-frequency/variable harmonics” acceleration.

- Recombination of “bunchlets” by 100 MHz system before extraction to LHC (optional).

Why bunchlets?

- Pb ions feature incoherent space charge detuning and may suffer from Intra-Beam Scattering (IBS) on the 43.2 s injection plateau. Halving the number of ions per bunch renders these effects acceptable.

- Space charge detuning $\Delta Q$ (~ same in either plane):
  - 0.082 calculated for the nominal Pb ion beam
  - P-Pbar experience: $\Delta Q < 0.07$.
  - Recent measurements (with p): $\Delta Q$ up to 0.2 acceptable

- IBS growth rates: being analysed (results depend on codes used)
  → Do we need bunchlets and to (re-)install 100 MHz system?
Pb Ion Pattern in PS-SPS-LHC

Nominal Ion Bunch Pattern in the LHC

LHC (1-RING) = 88.924 µs

Bunch Train Pattern

81313 121313 121313 121313

Filling Scheme (100ns Bunch Spacing)

891 = (8 x [4b + 1.25e] + 7.75e) + (2 x (13 x [4b + 1.25e] + 7.75e))
+ 3 x [(12 x [4b + 1.25e] + 7.75e) + (2 x (13 x [4b + 1.25e] + 7.75e))]
+ 21e

Beam Gaps

τ₁ = 1.25 missing bunches (SPS Injection Kicker Rise Time = 225ns).
τ₂ = 9 missing bunches (LHC Injection Kicker Rise time = 1.0µs).
τ₃ = 30 missing bunches (LHC Beam Dump Kicker Rise Time = 3.1µs).

P. Collier 05/02/2003
## Pb Ions for LHC: Early Operation Scheme

- Lower $L = 5 \times 10^{25} \, \text{cm}^{-2} \text{s}^{-1}$ (factor 20) by fewer bunches (factor 10) and $\beta^* = 1 \, \text{m}$ (factor 2)
- Keep nominal bunch population ($7 \times 10^7$ ions/bunch) to study limitations without risks
- $L$ useful for physics (early discoveries)
- Much easier for injectors (LEIR, PS), shorter LHC filling time (4'/ring, instead of 10')
- Improved luminosity lifetime because of larger $\beta^*$

![Diagram](image)

<table>
<thead>
<tr>
<th>Location</th>
<th>Nb of Bunches</th>
<th>Pb Ions / (future) LHC Bunch</th>
<th>Harmonic Number / Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEIR</td>
<td>1</td>
<td>$2.5 \times 10^8$</td>
<td>1</td>
</tr>
<tr>
<td>PS at injection and acceleration</td>
<td>1</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>PS at extraction</td>
<td>1</td>
<td>$1.2 \times 10^8$</td>
<td>16 + 169</td>
</tr>
<tr>
<td>TT2 after stripper</td>
<td>1</td>
<td>No bunch splitting</td>
<td></td>
</tr>
<tr>
<td>SPS at injection (7.2 s flat-bot), after 3 (4) transfers from PS</td>
<td>3 (4)</td>
<td>$9 \times 10^7$</td>
<td>200 MHz</td>
</tr>
<tr>
<td>SPS at extraction, after 3 (4) transfers from PS</td>
<td>3 (4)</td>
<td>$7 \times 10^7$</td>
<td>400 MHz</td>
</tr>
<tr>
<td>LHC at injection, after 16 transfers from SPS</td>
<td>about 60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\beta^* = 1 \, \text{m} \rightarrow L = 5 \times 10^{25} \, \text{cm}^{-2} \, \text{s}^{-1}$

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R. Garoby, M. Chanel, K. Schindl, S. Hancock, C. Carli, D. Manglunki, J. Jowett, M. Martini, …

LHCMAC 11 December 2003

Lead Ion Injectors - Karlheinz Schindl/AB
# Pb Collisions in LHC: Nominal + Early

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Nominal</th>
<th>Early Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per nucleon</td>
<td>TeV/n</td>
<td>2.76</td>
<td>2.76</td>
</tr>
<tr>
<td>Initial Luminosity $L_0$</td>
<td>cm$^{-2}$ s$^{-1}$</td>
<td>$1 \times 10^{27}$</td>
<td>$5 \times 10^{25}$</td>
</tr>
<tr>
<td># bunches/bunch harmonic</td>
<td></td>
<td>592/891</td>
<td>62/66</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>99.8</td>
<td>1350</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>m</td>
<td>0.5 (same as p)</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Number of Pb ions/bunch</strong></td>
<td></td>
<td>$7 \times 10^7$</td>
<td>$7 \times 10^7$</td>
</tr>
<tr>
<td>Transv. norm. rms emittance$^1$</td>
<td>$\mu$m</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>r.m.s. beam radius at IP</td>
<td>$\mu$m</td>
<td>16 (same as p)</td>
<td>16</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>eVs/charge</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>bunch length (r.m.s.)</td>
<td>cm</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Lumi initial decay time (2 exp.)</td>
<td>h</td>
<td>5.5</td>
<td>11</td>
</tr>
</tbody>
</table>

$^1 \epsilon^{*}_{\text{rms}} = (\beta\gamma)_{\text{rel}} \sigma^2/\beta_{\text{Twiss}}$
# Tentative I-LHC Schedule (Early Beam)

<table>
<thead>
<tr>
<th></th>
<th>LEIR injection line</th>
<th>LEIR ring</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start hardw. commissioning</td>
<td>January 2005</td>
<td>April 2005(^1)</td>
<td>February 2006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start beam commissioning</td>
<td>May 2005</td>
<td>August 2005(^1)</td>
<td>May 2006</td>
<td>(late 2006?) spring 2007</td>
<td>from April 2008</td>
</tr>
<tr>
<td>Problems</td>
<td>New source available? Hardware installed? Little time for hardware commissioning</td>
<td>LEIR conversion completed? Maybe running-in through winter 2005/6?</td>
<td>Start-up after an 18-months shutdown with new beams</td>
<td>SPS experts are busy commissioning LHC ring in 2007</td>
<td>ALICE wants beam “at the end of 1st proton period” (Nov. 2007?)</td>
</tr>
</tbody>
</table>

\(^1\) SPS and PS stopped in 2005 → “ideal” year for LEIR commissioning (more help available)
Summary Pb Injectors: Status - Issues

Issues - Technical

- Go for the Early Ion Scheme which is covering needs for 2008 (+2009?)
- ECR Source improvement? Which way to go? Grenoble? Too late? Keep present source?
- LEIR dynamic vacuum (some 10^{-12} Torr) feasible? Will scrubbing with Pb do the job?
- SPS: Are bunchlets required (halving space charge detuning and IBS growth rates)?
  100 MHz cavities to be (re-)installed? Possibly at a later stage, if required

Issues - Managerial

- The Earned Value Management (EVM) system is being extended to the I-LHC Project
- Manpower support often conflicting with other “priority” jobs (LHC, but also non-LHC…)
- I-LHC Project Review by external experts in March 2003:
  “There is no alternative (to the proposed scheme) which can be made available in time”
- The Schedule, in particular for LEIR, is very tight (….realistic?). Concentrating on the much easier “early” ion beam will help to get a lead beam into LHC by spring 2008

Resources: marginal
Open issues: numerous
Schedule: very tight