The LHC injection chain
Outline

- Accelerators
  - Cycles & supercycles
  - CERN’s accelerator complex, quick virtual tour

- Production of the LHC proton beam
  - Linac: intensity
  - PSB: emittance
  - PS: bunch structure
  - SPS: bunch placement in the LHC

- A word on the ion injection chain
  - Linac 3
  - LEIR
Cycles & Supercycles

- **Cycle:**
  - Injection plateau or *flat bottom*
  - acceleration ramp
  - ejection plateau or *flat top*
  - field decrease ramp
PS Supercycle

CPS Supercycle  supercycle length: 43.2 seconds (36 BP)  May 04 18:23:55

CPS User:   TOF  175.95 E10  PROTON  For:  TT2_D3
Beam for Isolde:  0 E10  BPNM = 19/36  MTG-level = 15
Comments:  04 May 2004  11:40:01

Energy, Intensity, Destination...

No Message
SPS supercycle

Double injection

Acceleration ramp

Fixed target cycle

Extraction

LHC pilot cycle

The LHC injector chain
Cycles & Supercycles

- SPS
- CPS
- PSB
Cycles & Supercycles

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The LHC injector chain
Proton beam production for LHC

- Linac2 (50MeV)
- PSB (1.4GeV) 4+2 bunches
- PS (25GeV) 72 bunches
- SPS (450 GeV) 4 x 72 bunches
- LHC (7 TeV) 2 x 2808 bunches
Duoplasmotron proton source
90keV ; 500mA

Radio Frequency Quadrupole (RFQ)
~1m ; 750keV
Radio Frequency Quadrupole (RFQ)
\(~1\text{m} ; 750\text{keV}\)
Linac 2
30m; 50MeV; 180mA
Linac 2
30m ; 50MeV ; 180mA
The LHC injector chain

Transfer line from Linac 2 to Proton Synchrotron Booster (PSB)

PSB distributor
Proton Synchrotron Booster
4 rings ; 157m each
1.4GeV ; $10^{13}$ p$^+/\text{ring}$
Individual extraction lines from each ring of the PSB

Recombinations $1+2 \& 3+4$

Extraction line from PSB to Proton Synchrotron (PS) & Isolde

Recombinations $(1-2) + (3-4)$
Proton Synchrotron (1959)
628 m
25 GeV ; $3 \times 10^{13} \ p^+$
[5.9 GeV/u Pb$^{54+}$]
TT2 transfer line from PS to SPS, AD, nTOF, and D3 dump
Super Proton Synchrotron (SPS)
6.9 km
450 GeV; $5 \times 10^{13}$ p$^+$
[177 GeV/u Pb$^{82+}$]
The LHC injector chain

TI8 counter-clockwise transfer line from SPS to LHC
Large Hadron Collider (LHC)
2 interleaved rings; 26.7 km
7 TeV; 3x10^{14} p^+/ring
[2.8 TeV/u Pb^{82+}]
Double batch injection from PSB to PS

PSB h=1 (573 nS)

1st batch
R1
R2
R3
R4

327 nS

2nd batch
R1
R2
R3
R4

327 nS

1.2 Sec. later

PS h=7

PS cycle: 3.6 S

LHC mode 2 batch filling PSB h1, PS h7

After 3 splitting --> PS ejection = 72 bunches and 84 buckets

[M.Lindroos]
Triple bunch splitting in PS

“Waterfall” representation: V=time, H=position, colour=density
Two more bunch splittings in PS
72-bunch train ready to be sent to SPS
4 bunch trains from PS to SPS
The gaps between trains are necessary to make room for rise/fall times of injection/ejection/abort kicker magnets.
- Linac3
- LEIR
- PS
- SPS
- LHC
Lead ion injector chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb$^{29+}$
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - Strip to Pb$^{54+}$
- LEIR (2005)
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb$^{82+}$
- SPS (2007)
  - Define filling scheme
ECR ion source, RFQ, Linac 3

- Re-designed after Fixed Target programme (1990’s)
- Injection into PS Booster insufficient performance for I-LHC
  - Source upgrade (still ongoing)
  - Increase of Linac3 repetition rate to 5Hz
  - Injection into a new storage ring: LEIR
The 3 roles of LEIR

- Accumulate enough ions for LHC bunches
- Keep their H, V and // emittances small
- Bring Linac3 ion beam to PS injection energy

- 3 plane stacking
- Cooling
- Acceleration
• Square shaped "circular machine"
• Circumference = 78.54m = PS/8 = SPS/88
• Operated below transition $\gamma_t \approx 2.87$
• 4x90° bending magnets
• 2 SS’s with Q doublets, 2 SS’s with Q triplets,
• Common injection/ejection line
• Electron cooling
Injection and ejection lines

Part of the line is used for injection at 4.2 MeV/u and extraction at 72 MeV/u:
- laminated, pulsed magnets
- Complicated behaviour for the power converters
LEIR’s 3-plane stacking

- Multiturn injection with additional stacking in vertical phase space
- Needs:
  - inclined electrostatic injection septum (complicated geometry of the injection line)
  - a horizontal bump
  - momentum ramping cavity in injection line
- Efficiency on paper $\approx 70\%$ for $\approx 70$ turns injected up to $50\%$ achieved
Electron Cooling

- Principle: an electron beam with *same velocity* as the ion beam is merged with it over a fraction of the circumference (~3%)
- In the moving frame, collisions between electrons and ions correspond to the mixture of a hot ion gas with a cool electron gas
- The heat exchange leads to cooling, i.e. emittance reduction, in all 3 planes (H,V, //) of the ion beam
• Transformation of antiproton ejection line and elements (to LEAR) for ion injection from LEIR: SMH26, KFH28, BSW26
• Design of complicated RF gymnastics
• Low intensity challenge for beam diagnostics
• 1mm Al stripper foil converts Pb$^{54+}$ to Pb$^{82+}$
• Low beta insertion around stripper
  - To minimize emittance blowup
## Parameters for Nominal Luminosity

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<thead>
<tr>
<th></th>
<th>ECR Source</th>
<th>Linac 3</th>
<th>LEIR</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
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<tr>
<td>Output energy</td>
<td>2.5 KeV/u</td>
<td>4.2 MeV/u</td>
<td>72.2 MeV/u</td>
<td>5.9 GeV/u</td>
<td>177 GeV/u</td>
<td>2.76 TeV/u</td>
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<tr>
<td>$^{208}$Pb charge state</td>
<td>29+</td>
<td>29+</td>
<td>54+</td>
<td>54+</td>
<td>82+</td>
<td>82+</td>
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<tr>
<td>Output $B_{\rho}$ [Tm]</td>
<td>2.12</td>
<td>4.80</td>
<td>86.7</td>
<td>57.3</td>
<td>1500</td>
<td>23350</td>
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<td>bunches/ring</td>
<td>$\rightarrow$1.14</td>
<td>2 (1/8 of PS)</td>
<td>4</td>
<td>52</td>
<td>592</td>
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<td>ions/pulse</td>
<td>$9 \times 10^9$</td>
<td>$1.15 \times 10^9$</td>
<td>$9 \times 10^8$</td>
<td>$4.8 \times 10^8$</td>
<td>$4.7 \times 10^9$</td>
<td>$4.1 \times 10^{10}$</td>
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<td>ions/LHC bunch</td>
<td>$1.1 \times 10^{10}$</td>
<td>$1.45 \times 10^9$</td>
<td>$2.25 \times 10^8$</td>
<td>$1.2 \times 10^8$</td>
<td>$9 \times 10^7$</td>
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<td>$\varepsilon^*$ (norm. rms) [\mu m]</td>
<td>0.07</td>
<td>0.25</td>
<td>0.7</td>
<td>1.0</td>
<td>1.2</td>
<td>1.5</td>
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<td>$\varepsilon$ (phys., rms) [\mu m]</td>
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<td>1.75</td>
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<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>$\sim$50</td>
<td>$\sim$10’fill/ring</td>
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Nominal scheme

4 injections

LEIR  \( (9 \times 10^8 \text{ Pb ions / 3.6 s}) \)

PS after splitting

SPS at injection (43.7 s flat-bot), after 13 (12, 8) transfers from PS

SPS at extraction, after 13 (12, 8) transfers from PS

LHC at injection, after 12 transfers from SPS

\( \beta^* = 0.5 \text{ m} \rightarrow L = 10^{27} \text{ cm}^{-2} \text{ s}^{-1} \)

Harmonic number / Frequency

\( 2 \)

\( 16-14-12-24 \)

\( 24-21 \)

\( -169-423 \)

\( 200 \text{ MHz} \)

\( 200 \text{ MHz} \)

\( 400 \text{ MHz} \)

(J.P.Riunaud)
Nominal scheme: PS RF gymnastics

- Two bunches from LEIR injected in PS straight section 26
- Accelerated to intermediate plateau
- Batch expansion (H16->H14->H12)
- Splitting (H12 -> H24)
- Batch expansion (H24->H21)
- Acceleration on H21 through transition
- Synchronisation on SPS RF
- Rebucketing on H169 (80MHz)
- Fast extracted in Section 16
- Stripped in TT2 (new low-beta optics)
Problems of the nominal scheme

- EM interactions in LHC may limit luminosity to $4 \times 10^{26}$ cm$^{-2}$s$^{-1}$ (to be checked)
- Complex RF gymnastics in the PS
  - Multiple harmonic change
- Space charge tune shift and intra beam scattering on SPS front porch
  - Long front porch for up to 13 PS batches: $12 \times 3.6 + 0.5 = 43.7$ s
  - Several alternatives being studied
- First ion operation: “EARLY SCHEME” with $L = 5 \times 10^{25}$ cm$^{-2}$s$^{-1}$
The Early Scheme

- Early Luminosity = Nominal Luminosity/20 = 5 \times 10^{25} \text{ cm}^{-2}\text{s}^{-1}
  - 2 x Larger $\beta^*$ (0.5m -> 1m)
  - 10 times less bunches
    - ~60 instead of ~600
    - but of same intensity $7 \times 10^7$ ions/bunch for LHC BPMs
  - Longer luminosity lifetime

- Only one injection in LEIR
  - Shorter LEIR/PS cycle: 2.4 s instead of 3.6 s
The Early Scheme

- No complex RF gymnastics in the PS
  - Only one bunch injected, accelerated on same harmonic

(J.L. Vallet)
The Early Scheme

- **Shorter SPS front porch:**
  - 3-4 PS batches instead of 12-13
  - Shorter LEIR cycle 2.4s instead of 3.6s
  - Front porch length = 3*2.4+0.5 = 7.7s (for Nominal: 12*3.6+0.5 = 43.7s)
  - Less harmful Space charge tune shift, RF noise and Intrabeam scattering

- **Shorter LHC filling time (5’ instead of 11’)**
Early scheme (L=5E25cm⁻²s⁻¹)

LEIR (2.5 10⁸ Pb ions / 2.4 s)
PS at injection and acceleration
PS at extraction
TT2 after stripper
SPS at injection (7.7 s flat-bottom),
after 3 (4) transfers from PS
SPS at extraction,
after 3 (4) transfers from PS
LHC at injection,
after 16 transfers from SPS

Pb ions / (future) LHC bunch

 Nb of bunches
2.5 10⁸

Harmonic number / Frequency
1 200 MHz
16 200 MHz
16 + 169 400 MHz

β* = 1 m -> L = 5 10²⁵ cm⁻² s⁻¹

(J.P.Riunaud)
Thanks for your attention!