Ion Collimation in LHC
Status and plans

John Jowett

Thanks for slides and information to: Giulia Bellodi, Hans Braun, Roderik Bruce, Alfredo Ferrari, George Smirnov, Vasilis Vlachoudis, + Collimation Working Group
Collimation of Pb ions in LHC

- Performance of Phase I collimation system for ions
  - Physics is different because of ion fragmentation: halo from primary collimators is mostly lost in SC magnets.

- Operation in initial phases
  - BLMs added for collimation losses
  - Avoid magnet quenches

- Test understanding on SPS
  - MDs this year

- Possible solutions
  - Adapting optics of collimation insertions
  - High Z spoilers – to be studied
  - Magnetised collimators
  - Crystal collimation, to be tested in H8 beam line
  - Nonlinear collimation?
  - Hollow electron beam (Shiltsev at LUMI06 workshop)
## Nominal and Early Pb Ion Beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Nominal</th>
<th>Early Beam</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>No. 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</td>
<td>$\mu$m</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>eV s/charge</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Luminosity half-life (1,2,3 expts.)</td>
<td>H</td>
<td>8, 4.5, 3</td>
<td>14, 7.5, 5.5</td>
</tr>
<tr>
<td>Stored energy /beam</td>
<td>MJ</td>
<td>3.81</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Operational Parameter Space for Pb Ions

Thresholds for visibility on BPMs and BCTs.

Ions with *betatron amplitude* $\gg$ *acceptance* cause no problems

*interaction length* $\ll$ *collimator length*

---

Ions with *betatron amplitude* $\approx$ *acceptance* can be subject to a single nuclear reaction, thus ending in SC magnets because of resulting wrong $Z/A$

Unfortunately most halo generating processes tend to have maximum halo density just at this amplitudes
The LHC collimation system

Based on a two-stage collimation concept, with short TCPs and longer TCSs downstream with larger gap aperture to capture halo particles (multi-turn effect, amplitude increase via MS).

\[
\delta x' > \frac{\sqrt{(N_2^2 - N_1^2)} \epsilon_N}{\gamma_{REL} \beta_{TWISS}}
\]

\(\delta x'\) mainly due to multiple Coulomb scattering, with

\(<\delta x'^2> \sim L\)
Ion collimation: why it’s a problem

Nominal ion beam has **100 times less beam power** than proton beam, but particle-collimator physics very different:

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Proton</th>
<th>$^{208}$Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dE}{Edx}$ due to ionisation</td>
<td>-0.12 %/m</td>
<td>-9.57 %/m</td>
</tr>
<tr>
<td></td>
<td>-0.0088 %/m</td>
<td>-0.73%/m</td>
</tr>
<tr>
<td>Mult. Scattering (projected r.m.s. angle)</td>
<td>73.5μrad/m$^{1/2}$</td>
<td>73.5μrad/m$^{1/2}$</td>
</tr>
<tr>
<td></td>
<td>4.72μrad/m$^{1/2}$</td>
<td>4.72μrad/m$^{1/2}$</td>
</tr>
<tr>
<td>Nucl. Interaction length</td>
<td>38.1 cm</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>≈ fragment. length for ions</td>
<td>38.1 cm</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Electromagnetic dissociation length</td>
<td>-</td>
<td>33 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19 cm</td>
</tr>
</tbody>
</table>

High probability to undergo nuclear interactions in the TCP before 2-stage collimation condition is satisfied

\[ L \approx L_{\text{int}} = \frac{A_{\text{coll}}}{N_A \rho (\sigma_{\text{had}} + \sigma_{\text{emd}})} \]

~20 times higher probability of nuclear interactions
Ion-collimator interactions

Hadronic Fragmentation cross sections for $^{208}$Pb on $^{12}$C

Electromagnetic Dissociation cross sections for $^{208}$Pb on $^{12}$C

Large variety of daughter nuclei, Monte Carlo calculated specific x-sections

Mainly loss of 1 neutron (59%) or 2 (11%) $\rightarrow$ $^{207}$Pb, $^{206}$Pb

Change in magnetic rigidity:

$$\Delta P = \frac{Z_2}{A_2} \frac{A_2}{Z_2} - 1$$
Collision:

Losses confined to IR7 dispersion suppressor, cells 9 & 11

Two peaks downstream in the arc for Beam2

Nominal Quench limit

Slide from G. Bellodi
Injection:

Beam 1

Beam 2

Slide from G. Bellodi
BLM coverage for Pb ions

- **Additional BLMs**
  - Some of the extra BLMs are required because of the ion collimation inefficiency
  - Motivation and BLM configuration described in detail in LHC Project Note 399
BLMs coverage:

Adding 1mm to aperture (all elements) causes a shift in the beam loss peaks by up to 2m

BLMs coverage of IR7:
3 patches available in cells 8,9,11 (dipoles) × 8 channels (max) × 2 BLMs
2 channels available on quad patches (regions 8,9,10,11,13)
Need tight coverage of cells 9-11

Numbers:

BLM active length = 40 cm
Dipole length = 14.3 m (x2)

Long. spread of energy deposition=
2.5 m FWHM
peak @ 1.5 m from impact

For coil deposition peak @ 30cm from impact point
Simulation tools

FLUKA: for prediction of heat deposition, ratio between local losses and BLM signals etc.

ICOSIM:

ICOSIM (H. Braun)
- Generates initial beam distribution
- Tracks particles through machine
- Simulates ion-matter interactions in collimators
- Computes impact sites of ions in LHC lattice

Nuclear interaction cross-sections from RELDIS & ABRATION/ABLATION routines
(Igor Pshenichnov)

MAD-X optics files and aperture tables

OUTPUT
- Loss patterns
- Collimation efficiencies

Plans to replace by integrating FLUKA and ICOSIM

Slide from G. Bellodi
New ICOSIM simulations to be done

- Better incorporation of orbits (IR bumps)
  - Under way (G. Bellodi)
- Inclusion of all items (TCLAs)
  - Under way (G. Bellodi)
- Energy ramping
  - Depends on integration with FLUKA
- Effects of high-Z scrapers
  - Depends on integration with FLUKA
Testing of methodology in SPS

- Compare ICOSIM predictions for protons
  - MDs/SIXTRACK simulations done in 2004 (Roderik Bruce, Simone Gilardoni)
  - Interfaced ICOSIM to MARS, results soon

- MDs with Pb beam and LHC collimator in SPS (Sep-Oct 2007)
  - Once Pb beam commissioned in SPS, compare measured losses from BLMs with predicted loss maps of fragments from ICOSIM at 106 GeV/A and at 10.3 GeV/A (injection energy).
  - Proton loss maps at same magnetic rigidities (270 GeV and 26 GeV) for comparison.
  - Need few extra BLMs installed temporarily at critical locations.
  - Need help of collimation team …
Changes of optics in IR3, IR7

- Look at possibility of improving situation by changing the optics of the collimation insertions
  - Increase bx at primary collimators
  - Maximise dispersion created after primary collimators

- I plan to look at this but a priori not very hopeful …

- Ideal, simple solution: rebuild of the cleaning insertions
  - Increased beam separation (4 times) in the collimation doglegs
  - Expensive, long shutdown of LHC
  - Also good for protons though …
Introducing a magnetic field which extends over the diffuse boundary region of the collimator assures that all particles getting close to surface will be deflected to secondary collimator.

\[ B_L > \sqrt{\frac{(N_2^2 - N_1^2)\varepsilon_N}{\gamma_{REL.} \beta_{TWISS}}} \frac{P}{Ze} \approx 0.2 \text{ Tm} \]

Condition to bend particle sufficiently to hit secondary collimator.
Magnitized Jaw for primary collimator, first attempt with 2D magnet code

Slide from H. Braun
3D structure with iron sheets between poles

Interleaved positioning to cover all initial $y$ positions

Sheet thickness allows to adjust “skin depth of magnetic field”
Interleaved positioning to cover all initial y positions
Size and distance of iron rods allows to adjust “skin depth of magnetic field”
Rods instead of sheets probably allow faster field drop towards beam core
Proposed development program

1. Magnet design studies with 3D magnet code to find configuration with best properties. Problems:
   • Get right “magnet field skin depth” in the order of 100 μm
   • Minimize or linearize residual field at beam core
   • Thin sheets of ferromagnetic materials have not necessary same magnetic properties as bulk material

2. Implement magnet model in ICOSIM and predict cleaning efficiency

3. Engineering design of prototype

4. Build prototype

5. Check performance with prototype test in SPS

6. Implement dedicated ion primary collimators in LHC IR7

Can we shortcut the magnet calculations and make quicker simulation?
Crystal collimation

- **Bend crystal collimator for channeling (or volume reflection)**
  - See recent workshop, talk by Giulia Bellodi
  - May benefit from suppression of fragmentation and electromagnetic dissociation of ions
  - Long history already, not yet made practical
Crystal angular scan (H8 RD22)

2. channelling, 4. volume reflection, 5. volume capture

Channelling:
def. angle~160 μrad
prob. ~50%

V reflection:
Def. angle~10 μrad
prob~97%
Pb-Beam Transport in Continuum Potential

Trajectory is defined by the transverse energy of Pb ion:

distance $b$ of the ion from row of atoms

Distance of closest approach to the row of atoms:

$r = 2.5 u_1 = a$

$a = 0.8853 a_0 \left(Z_1^{2/3} + Z_2^{2/3}\right)^{-1/2}$

$r < b < d/2$

$r = 1 \times 10^4 f$

$d/2 = 2.7 \times 10^5 f$

$Largest time to stay in the channel$

$Slide from G. Smirnov$

$u_1$ is the amplitude of crystal atoms thermal oscillations

$a$ is the screening length

$a_0 = 0.529 \times 10^5 f$ — Bohr radius
Electromagnetic Interactions of Channeled Ions

No channeling

Photon flux from Pb or Si at LHC after integrating over impact parameter \( b \)

\[ n(\omega) = \frac{2Z^2\alpha}{\pi} \ln\left(\frac{\gamma}{\omega R_A}\right) \]

Potential \( U_\perp \) at some arbitrary temperature of the Si crystal

Distance from the atomic row (Angstrom)

Slide from G. Smirnov
Photon spectrum and photonuclear reactions

**discrete potential**

\[ b_{\text{min}} = 2.9 \text{ f} \]

\[ 1 \text{ MeV} < E_{\gamma} < 10^5 \text{ MeV} \]

**continuum potential**

\[ b_{\text{min}} = 9400 \text{ f} \]

\[ E_{\gamma} < 1 \text{ MeV} \]

\[ \gamma + {}^{208}\text{Pb} \]

<table>
<thead>
<tr>
<th>Threshold Energies (MeV)</th>
<th>( \gamma, n )</th>
<th>( \gamma, p )</th>
<th>( \gamma, t )</th>
<th>( \gamma, \text{He-3} )</th>
<th>( \gamma, \alpha )</th>
<th>( \gamma, 2n )</th>
<th>( \gamma, np )</th>
<th>( \gamma, 2p )</th>
<th>( \gamma, 3n )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.37</td>
<td>8.01</td>
<td>12.88</td>
<td>14.39</td>
<td>-0.52</td>
<td>14.11</td>
<td>14.85</td>
<td>15.38</td>
<td>22.19</td>
</tr>
</tbody>
</table>

No reaction on Pb with photon energy < 1 MeV

*Slide from G. Smirnov*
Simulation of EMD of deuterons in a tungsten crystal under different channeling conditions

Fig. 8 from the talk presented at “Channeling-06” (Frascati, 3-7 July 2006) by Yu. Pivovarov and V. Dolgikh

Slide from G. Smirnov
Further questions on crystals

- **Volume reflection effect**
  - More efficient, smaller deflection
  - Does not benefit from suppression of nuclear electromagnetic interactions
  - Seems to need detailed simulation to evaluate interest compared with channelling
  - Maintain contacts with Tomsk and Dubna groups

- How much can we expect to find out from experiments in H8 beam line later this year?
Conclusions

- **Collimation may be a problem for Pb ion beams in LHC**
  - Operational strategies to alleviate

- **Several possible solutions, none clearly effective**
  - Plan to gain information from experiments and simulations in the coming months
  - Evaluate our best bet
  - Time scales for prototyping and installation at time of Phase II collimator upgrade are tight and manpower is limited (and somewhat fragmented and scattered)

- **Need help of Collimation team and others**

- **In future we need to evaluate collimation of lighter ions**
  - Remember that Pb-Pb runs have goal of 1 nb\(^{-1}\) integrated luminosity
Backup slides
Luminosity evolution: Nominal scheme

An “ideal” fill, starting from design parameters giving nominal luminosity.

Increasing number of experiments reduces beam and luminosity lifetime.

May not want design peak luminosity! Increase $\beta^*$