Collimation for Heavy Ions

- Specific issues for ion collimation
- ICOSIM program and results
- BLM sensitivity ions vs. protons
- Mishaps
- Remedies ?
- Heavy Ion – Matter Interactions at high $\gamma$
- Conclusions
## LHC Collimation

<table>
<thead>
<tr>
<th>Issues for p-LHC Collimation</th>
<th>Issues for I-LHC as well?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. cleaning efficiency</td>
<td>✓</td>
</tr>
<tr>
<td>2. protection of magnets against quenches</td>
<td>✓</td>
</tr>
<tr>
<td>3. robustness of collimator against mishaps</td>
<td>?</td>
</tr>
<tr>
<td>4. impedance</td>
<td>- (I_{IONS} \sim I_{PROTON}/100)</td>
</tr>
<tr>
<td>5. activation and maintainability</td>
<td>- (P_{IONS} \sim P_{PROTON}/100)</td>
</tr>
</tbody>
</table>
**Why is heavy ion collimation for LHC a specific issue?**

<table>
<thead>
<tr>
<th>Collider</th>
<th>Atomic number</th>
<th>Mass number</th>
<th>Energy / nucleon GeV/u</th>
<th>Circumference m</th>
<th>Number of Bunches</th>
<th>Number part. / Bunch $10^7$</th>
<th>stored energy / beam MJ</th>
<th>instantaneous beam power GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-LHC</td>
<td>1</td>
<td>1</td>
<td>7000</td>
<td>26659</td>
<td>2808</td>
<td>11500</td>
<td>362.1</td>
<td>4075</td>
</tr>
<tr>
<td>I-LHC</td>
<td>82</td>
<td>208</td>
<td>2760</td>
<td>26659</td>
<td>592</td>
<td>7</td>
<td>3.8</td>
<td>43</td>
</tr>
<tr>
<td>I-LHC early scheme</td>
<td>82</td>
<td>208</td>
<td>2760</td>
<td>26659</td>
<td>62</td>
<td>7</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>p-HERA</td>
<td>1</td>
<td>1</td>
<td>920</td>
<td>6336</td>
<td>180</td>
<td>7000</td>
<td>1.9</td>
<td>88</td>
</tr>
<tr>
<td>TEVATRON</td>
<td>1</td>
<td>1</td>
<td>980</td>
<td>6280</td>
<td>36</td>
<td>24000</td>
<td>1.4</td>
<td>65</td>
</tr>
<tr>
<td>I-RHIC</td>
<td>79</td>
<td>183</td>
<td>99</td>
<td>3834</td>
<td>60</td>
<td>110</td>
<td>0.2</td>
<td>14</td>
</tr>
<tr>
<td>p-RHIC</td>
<td>1</td>
<td>1</td>
<td>230</td>
<td>3834</td>
<td>28</td>
<td>17000</td>
<td>0.2</td>
<td>14</td>
</tr>
</tbody>
</table>

**LHC Proton collimation difficult because collimation efficiency $\eta \approx 10^{-5}$ required, but proposed scheme fulfills requirements in simulations and SPS prototype tests.**

**I-LHC beam has only 1/100 of the proton beam power, so only collimation efficiency $\eta \approx 10^{-3}$ required. Where is the problem?**
Criteria for two stage betatron collimation

Necessary condition:

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

scattering at primary collimator \( \delta x' \) is mainly due to multiple Coulomb scattering with \( <\delta x'^2> \sim L \)

But:
if required \( L > L_{INT} \) particle undergoes nuclear reaction before secondary collimator is reached!
The interactions of $^{208}$Pb-ion/matter in comparison with proton/matter interactions (values are for particle impact on graphite).

<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>Ionisation 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 r.m.s.</td>
<td>73.5 µrad/m$^{1/2}$</td>
<td>4.72 µrad/m$^{1/2}$</td>
<td>73.5 µrad/m$^{1/2}$</td>
<td>4.72 µrad/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 cm</td>
<td>19.0 cm</td>
</tr>
</tbody>
</table>
Computation of cross-sections by Igor Pshenichnov (INR, Moscow)
Nuclear fragmentation and dissociation lead to a variety of daughter nuclei.

Typical transverse momentum $\approx 1 \text{ MeV/c/u}$, transverse momentum due to emittance $\approx 10 \text{ MeV/c/u}$

First impacts of halo ions on primary collimators is usually grazing, small effective length of collimator.

- high probability of conversion in neighbouring isotopes without change of momentum vector
- isotopes miss secondary collimator and are lost in downstream SC magnets because of wrong $B\rho$ value
Effective momentum error of daughter nuclei

\[ \frac{\Delta P}{P}_{\text{EFF.}} = \frac{Z_1}{A_1} \frac{A_2}{Z_2} - 1 \]

Energy acceptance LHC arcs \( \approx \pm 1\% \)

Energy acceptance energy cleaning IR3 \( \approx \pm 0.2\% \)
Computing tools for ILHC collimation

MAD-X generates twiss function and aperture tables (John Jowett)

ICOSIM
- reads MAD-X tables
- generates initial impact distribution on collimator
- simulates ion/matter interactions in collimator
- computes trajectories and impact sites of ions in LHC lattice

ICOSIM output
- Loss patterns
- Collimation efficiencies

RELDIS & ABRATION/ABLATION
(programs of Igor Pshenichnov)
generates cross section tables for fragmentation processes

LHC optics files

MAD-X generates twiss function and aperture tables (John Jowett)
Beam 1 with tertiary collimators, $\tau_{beam} = 12\text{min}$

**Collimator load distribution**

**Lossmap**

**Time development after first impact on collimator**

Legend:
- Red: particles lost on collimators
- Green: particles lost elsewhere
- Blue: particles in beam
Beam 1 with tertiary collimators, $\tau_{\text{BEAM}}=12\text{min}$, without TCP.A6L7.B1
Beam 1 without tertiary collimators

Beam 1 with tertiary collimators
Beam 2 without tertiary collimators

Beam 2 with tertiary collimators
Nominal Ion beam 1 with collision optics and collimator settings

Quench limit
According to a discussion of John J. with Daniel Leroy permissible losses in LHC MB’s can be increased by factor 2

Ion collimation problems almost solved

Somewhat more official agreement on acceptable loss rates desirable.
Benchmarking of ICOSIM with RHIC data
Is the ratio of heat deposition in SC coils to BLM signals the same for Protons and Ions?

FLUKA calculations by Roderik Bruce

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[Graph showing longitudinal energy deposition in main bend at collision energy for Protons in SC coil, Protons in BLM, $^{208}$Pb in SC coil, scaled with 1/Z, and $^{208}$Pb in BLM, scaled with 1/Z.]
Robustness of collimator against mishaps

**FLUKA calculations from Vasilis Vlachoudis**
for dump kicker single module prefire

The higher ionisation loss makes the energy deposition at the impact side almost equal to proton case, despite of 100 times less beam power.
Energy Loss by High Energy Ions in Matter

Alfredo Ferrari and George Smirnov (JINR, Dubna) and

\( \frac{dE}{dx} \) of heavy ions deviates from Bethe-Bloch formula at high energies
- Higher order corrections
- Finite nuclear size effects
- Pair production

Consequences for local energy deposition of impacting beams and for collimation efficiency needs to be understood.
Implementation of all relevant effects in FLUKA code underway.

**Finite size effects**

**Pair production**
**Remedies?**

Optimising the material primary collimator material

The important ion/matter interactions for ions in this context are

- hadronic fragmentation \( \sigma_{\text{HAD}} \sim (A_{\text{PROJ}}^{1/3} + A_{\text{COLL}}^{1/3})^2 \)
- electromagnetic dissociation \( \sigma_{\text{EMD}} \sim Z_{\text{COLL}}^2 \)
- Multiple scattering \( <\delta x'^2>^{1/2} \sim Z_{\text{COLL}} \)
- Ionisation energy loss \( dE/dx \sim Z_{\text{COLL}} \)

remark:

angle deflection for hadronic fragmentation and electromagnetic dissociation are negligibly small for LHC conditions

figure of merit for collimator material

\[
\sqrt{\left\langle \delta x'^2 \right\rangle}_{L=L_{\text{INT}}} = \frac{A_{\text{COLL}}}{N_A \rho (\sigma_{\text{HAD}} + \sigma_{\text{EMD}})}
\]

\( z_{\text{Pb}} \) Pb beam in LHC
Condition
\[ \delta x' \gg \sqrt{\left( N_2^2 - N_1^2 \right) \varepsilon_N} \gamma_{REL.} \beta_{TWISS} \]

can be used to define boundaries in \( Z - \beta_{TWISS} \) plane

High Z scrapers (already foreseen behind primary collimator) may give some improvement. Needs further study.
Only particles with effective $\Delta P/P>3\%$ can be intercepted with secondary collimators.
Trivial (and impossible) solution:
Increase strength of dogleg magnets by factor 4
Perhaps a different IR7 optics could give some improvement. Needs further study.
Conclusions

- Present 2 stage collimation of LHC gives insufficient protection of s.c. magnets against heavy ion fragments.
  Collimation system acts almost like a single stage system.
  \[ \Rightarrow \text{particle losses in SC magnets exceeds permissible values by a factor } \sim 2 \]
  for nominal ion beams at collision energy.
  Calculations have considerable accumulated errors!

- This is a soft limitation depending on 12min lifetime requirement.

- Early Ion scheme and losses at injection seem to be ok

- Collimator robustness sufficient for kicker accidents with ion beams

- FLUKA simulations indicate that BLM thresholds for beam abort are comparable for protons and ions.

- Inventory of nuclear physics relevant for collimation efficiency and energy deposition has been established. Presently partially implemented in FLUKA code. Complete implementation progress.

- No solution for nominal beam found yet