Joint Snowmass-EUCARD/AccNet-HiLumi LHC meeting
Frontier capabilities for Hadron colliders

CERN, 22th February 2013

Flat-beam IR optics

José L. Abelleira, PhD candidate EPFL, CERN BE-ABP
Supervised by F. Zimmermann, CERN Beams dep.

Thanks to: O.Domínguez, S Russenchuck, D. Shatilov, M. Zobov
Contents

• Crab-waists collisions concept
• Flat beam optics for LHC
• CW for HE-LHC
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Crab-waist collisions (I)

An important limitation in hadron machines is beam-beam tune shift

\[ L \propto \frac{N \xi_y}{\beta_y}; \quad \xi_y \propto \frac{N \beta_y}{\sigma_x \sigma_y \sqrt{1 + \phi^2}}; \quad \xi_x \propto \frac{N}{\epsilon_x (1 + \phi^2)}; \quad \phi = \frac{\theta \sigma_z}{2 \sigma_x} \]

**A Large Piwinski Angle** $\Phi$ (LPA)

- reduces tune shift, allowing $N \uparrow$
- reduces the length of the collision section, allowing $\beta_y \downarrow$

*More luminosity*

**Length of the Collision section**

With Head-on collisions or small $\phi$

\[ l_{OA} \approx \sigma_z \]

But in LPA regime

\[ l_{OA} \approx \frac{2 \sigma_x}{\theta} \]

*For LHC* \[ \frac{2 \sigma_z}{\theta} \approx 1\text{cm} \]
Crab-waist collisions (II)

On the other hand, a LPA induces strong X-Y resonances

Suppressed by crab-waist scheme

Normal collision scheme  Crab-waist collision scheme

Condition for cw collisions

2 sextupoles spaced from the IP

\[ \Delta \mu_x \approx \pi m \]
\[ \Delta \mu_y \approx \pi \frac{1}{2}(2n+1) \]

\[ \sigma_x^*/\sigma_y^* \geq 10 \]
\[ \beta_x^*/\beta_y^* \geq 100 \]

Suitable for lepton machines
More challenging for hadron colliders

P. Raimondi, D. Shatilov, M. Zobov

Jose L. Abelleira
Flat beam optics for LHC

\[ \beta_x^*=1.5 \text{ m} \]
\[ \beta_y^*=1.5 \text{ cm} \]

<table>
<thead>
<tr>
<th>sext</th>
<th>( \Delta \mu_x )</th>
<th>( \Delta \mu_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>sext1</td>
<td>( \pi/2 )</td>
<td>( \pi/2 )</td>
</tr>
<tr>
<td>sext2</td>
<td>( \pi/2 )</td>
<td>( \pi/2 )</td>
</tr>
<tr>
<td>sext3</td>
<td>( 3\pi/2 )</td>
<td>( 3\pi/2 )</td>
</tr>
<tr>
<td>sext4</td>
<td>( 3\pi/2 )</td>
<td>( 3\pi/2 )</td>
</tr>
<tr>
<td>sext5</td>
<td>( 2\pi )</td>
<td>( 5\pi/2 )</td>
</tr>
</tbody>
</table>

Phase advance from IP

Local chromatic correction in both planes + crab-waist collisions

The extremely low \( \beta_y \) asks for a symmetric optics in the IR

Separation magnets

Chromatic correction
CRAB-WAIST SEXTUPOLE
Flat beam optics for LHC

\[ \frac{\sigma_x}{\sigma_y} = 10 \]

Minimum required according to beam-beam simulations.

Reference orbit

\[ \theta = 4 \text{mrad} \]
Crab-waist simulations

\[ CW = 0.5 \]

**Resonances**

**Frequency Map Analysis (FMA)**

Effective for the beam-beam resonance suppression.

Plot shown for \( \theta_c = 1.5 \) mrad

Dmitry Shatilov
Mikhail Zobov

Jose L. Abelleira
Luminosity evolution

\[ L = \frac{N(t)^2 n_b}{4\pi \sigma_x^*(t) \sigma_y^*(t) \sqrt{1 + \Phi(t)^2}} \quad \Phi(t) = \frac{\Theta \sigma_s(t)}{2 \sigma_x(t)} \]

During a run, \( N(t) \downarrow \)
But there is a significant decrease in, \( \sigma_x^* \), \( \sigma_y^* \), and in \( \Phi \)!
With low \( \Phi \), the limitation in the beam-beam tune shift obliges to introduce blow-up (longitudinal/horizontal).
With large \( \Phi \), the limitation is almost suppressed.
\[ \downarrow \text{we just have to adjust the parameters to have SR damping as a compensator for the burn off} \]

Beam lifetime due to burn off

\[ \tau = \frac{N_0}{L_0 \sigma_p n_{1P}} \]

LPA allows a bigger \( N_0 \) for the same \( L_0 \). Contribution to \( L_{\text{int}} \)
Symmetric optics

The lower $\beta_\gamma^*$ allowed by the LPA creates a large beam divergence
-> last quadrupole must be defocusing for the four cases: b1l, b1r, b2l, b2r.

IR optics is symmetric. Two options
– Match the sym. IR optics to the antisymmetric arc optics.
– Design a symmetric optics in the arcs.

In order to implement a symmetric optics in the IR, two options are proposed for the HE-LHC:
– $\theta=2\text{mrad}$. Use a double-half quadrupole, like in c-w LHC
– $\theta=8\text{mrad}$. Use a double aperture quadrupole with opposite sign.
Last quadrupole. $\theta = 2$ mrad

$B_y(x)$

$B_0 = -5.8 \text{ T}$

$g = 115 \text{ T/m}$

Double half quadrupole proposed for c-w LHC as a solution to have different polarized quadrupoles for the 2 beams in a same aperture.

S. Russenchuck
Last quadrupole. $\theta=8$ mrad

Double aperture magnets with same polarity (as in LHC arc quadrupoles)

Gradient : 220 T/m

Double aperture magnets with same polarity for c-w HE-LHC

Gradient : 219 T/m

18.4 cm

S. Russenchuck

Jose L. Abelleira
Parameters (I)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. energy [TeV]</td>
<td>33</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>26.7</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>20</td>
</tr>
<tr>
<td>Dipole coil aperture [mm]</td>
<td>40</td>
</tr>
<tr>
<td>Beam half aperture [mm]</td>
<td>13</td>
</tr>
<tr>
<td>Injection energy [TeV]</td>
<td>&gt;1.0</td>
</tr>
<tr>
<td>Initial longitudinal emittance [eVs]</td>
<td>5.67</td>
</tr>
<tr>
<td>r.m.s. bunch length [cm]</td>
<td>7.7</td>
</tr>
<tr>
<td>peak luminosity [cm⁻² s⁻¹]</td>
<td>5x10³⁴</td>
</tr>
</tbody>
</table>

The initial beam size has been chosen to allow c-w from the beginning of a run

\[ \sigma_x^*/\sigma_y^* = 10 \]

Due to the fast emittance shrink

Initial luminosity ≠ peak luminosity
## Parameters (II)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \theta = 2 \text{ mrad} )</th>
<th>( \theta = 8 \text{ mrad} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial luminosity ([\text{cm}^{-2} \text{s}^{-1}])</td>
<td>2.3x10^{34}</td>
<td>2x10^{34}</td>
</tr>
<tr>
<td>(N_0[10^{11}])</td>
<td>2.45</td>
<td>3.05</td>
</tr>
<tr>
<td>Crossing angle [mrad]</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Technology for last quad.</td>
<td>Double-half quad.</td>
<td>Double aperture quad.</td>
</tr>
<tr>
<td>IP beta function ((\text{H/V}) [\text{m}])</td>
<td>3/0.03</td>
<td></td>
</tr>
<tr>
<td>Norm. initial emittance ((\text{H/V}) [\mu \text{m rad}])</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Initial beam size IP [\mu m]</td>
<td>19/1.9</td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1404</td>
<td></td>
</tr>
<tr>
<td>Crossing scheme</td>
<td>horizontal at the two IP</td>
<td></td>
</tr>
<tr>
<td>Initial Piwinski angle</td>
<td>4.1</td>
<td>16.3</td>
</tr>
<tr>
<td>Initial total tune shifts ([10^{-3}])</td>
<td>3.2/1.3</td>
<td>0.3/0.4</td>
</tr>
<tr>
<td>maximum total tune shifts</td>
<td>8.9/2.4</td>
<td>1.1/1.2</td>
</tr>
<tr>
<td>Beam separation [\sigma]</td>
<td>317</td>
<td>12680</td>
</tr>
</tbody>
</table>

O. Domínguez.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\theta = 2\text{ mrad}$</th>
<th>$\theta = 8\text{ mrad}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long. SR emittance damping time [h]</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>Transverse SR emittance damping time [h]</td>
<td>2.02</td>
<td></td>
</tr>
<tr>
<td>Initial horizontal IBS emittance rise time [h]</td>
<td>37.51</td>
<td>21.1</td>
</tr>
<tr>
<td>Initial vertical IBS emittance rise time [h]</td>
<td>72.02</td>
<td>42.2</td>
</tr>
<tr>
<td>Initial longitudinal IBS rise time [h]</td>
<td>72.45</td>
<td>40.7</td>
</tr>
<tr>
<td>Beam intensity lifetime [h]</td>
<td>14.6</td>
<td>29.9</td>
</tr>
<tr>
<td>Optimum run time [h]</td>
<td>6</td>
<td>8.5</td>
</tr>
<tr>
<td>Opt. av. Int. luminosity/day [fb$^{-1}$]</td>
<td>1.63</td>
<td>1.93</td>
</tr>
</tbody>
</table>

O. Domínguez.
Time evolution. $\theta=2$ mrad

- Emittance
- Total tune shifts
- Beam size ratio
- Transverse beam sizes
- Long. Beam size
- Piwinski angle
- Luminosity

Far below 0.01

C-w condition

O. Domínguez.
Time evolution. $\theta=8$ mrad

- Emittance
- Total tune shifts
- Beam size ratio
- Transverse beam sizes
- Long. Beam size
- Piwinski angle
- Luminosity ↑

O. Domínguez.
Luminosity evolution

\[ L \left[ 10^{34} \text{ cm}^{-2} \text{s}^{-1} \right] \]

O. Domínguez.
Conclusions

• An extremely-flat beam optics ($\beta_y^*/\beta_y^*=100$) is conceptual possible for LHC and HELHC
  – Large Piwinski angle, to reduce the collision area and allow for a lower $\beta_y^*$
  – Local chromatic correction
  – Possibility to have crab waist collisions that can increase luminosity and suppress resonances
  – Can accept higher brightness.

• With crab-waist collisions there is no tune shift limitation: no need for emittance blow up.
  – LPA allows for a higher brightness: increases beam lifetime
  – SR damping for the three planes increases luminosity
  – Significant increase in $L_{int}$

Jose L. Abelleira
Thank you...

...For your attention