Crab-waist collisions. From lepton to hadron colliders

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Thanks to: R. de Maria, S.Russenschuck, F. Zimmermann (CERN), D.Shatilov (BINP SB RAS, Novosibirsk), C. Milardi, M. Zobov (INFN/LNF, Frascati (Roma))
Contents

• The LHC
• Flat beams
• Crab-waists collisions concept
• Crab-waist in DAΦNE
• A new IR for LHC
The Large Hadron Collider

collimators

experiments
Antisymmetric optics due to the opposite direction of the beams
Luminosity

The event rate for a process (number of collisions) is given by the cross section of the process times the luminosity.

\[
\frac{dR}{dt} = L\sigma_p
\]

Luminosity depends on by the beam parameters as follows.

\[
L = \frac{N^2 n_b f}{4\pi \sigma_x^* \sigma_y^*} \frac{1}{\sqrt{1 + \Phi^2}} \quad \Phi = \frac{\theta \sigma_z}{2\sigma_x^*}
\]

The values for nominal LHC are given

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N)</td>
<td>Particles per bunch.</td>
<td>1.15x10^{11}</td>
</tr>
<tr>
<td>(n_b)</td>
<td>Number of bunches.</td>
<td>2808</td>
</tr>
<tr>
<td>(f)</td>
<td>Revolution frequency</td>
<td>11.245 kHz</td>
</tr>
<tr>
<td>(\sigma_{x,y}^*)</td>
<td>Hor/vert beam size at IP*</td>
<td>16.7 (\mu)m</td>
</tr>
<tr>
<td>(\sigma_z^*)</td>
<td>bunch length</td>
<td>7.55 cm</td>
</tr>
<tr>
<td>(\theta)</td>
<td>Crossing angle*</td>
<td>285 (\mu)m</td>
</tr>
<tr>
<td>(\Phi)</td>
<td>Piwinski angle*</td>
<td>0.64</td>
</tr>
<tr>
<td>(L)</td>
<td>Luminosity*</td>
<td>(10^{34}) cm (^2) s(^{-1})</td>
</tr>
</tbody>
</table>

*For the experiments at IP1 and IP5.
A crossing angle is introduced to avoid parasitic collisions. Even though there are collisions only in the IP, there are long range interactions between the two beams. A measure of the interaction between the beams is the normalized separation.

\[
\Delta_{sep} = \frac{d_{sep}}{\sigma_x} \approx \frac{\theta}{\sigma_x'},
\]
Flat beams

$$\Delta_{sep} \approx \frac{\theta}{\sigma_x} \approx \frac{\theta}{\sqrt{\varepsilon/\beta^*_x}}$$

For the same section area $\sigma_x \sigma_y$
Flat beams increase $\Delta_{sep}$, for a given $\theta$
Less $\theta$ for the same $\Delta_{sep}$

$\beta_x = 1.20$ m  
$\beta_y = 1.20$ m

$\beta_x = 0.60$ m  
$\beta_y = 1.20$ m

$\beta_x = 1.20$ m  
$\beta_y = 0.60$ m

R. De Maria

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Hourglass effect

Beam size is given as \( \sigma = \sqrt{\varepsilon \beta} \).

\[
\beta(s) = \beta^* + \frac{s^2}{\beta^*}
\]

Especially important when the \( \beta \) function at the IP approaches the bunch length.

What is important is the length of the collision section.

**Length of the Collision section**

With Head-on collisions or small \( \phi \)

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

But in Large Piwikinski Angle (LPA) regime

\[
l_{OA} \approx \frac{2\sigma_x}{\theta}
\]
Crab-waist collisions

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

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

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

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

Suppressed by crab-waist scheme
With LPA. The Collision Point (CP) for each particle ≠ Interaction Point (IP), (minimum of $\beta_Y$).
C-W scheme corrects this effect and brings for each particle the IP to the CP.
Crab-waist collisions

\[
\hat{M}_y = D^{-1} M_y S = \begin{pmatrix} 1 & \Delta l \end{pmatrix}^{-1} \begin{pmatrix} \pm \alpha_{CP} \sqrt{\frac{\beta_{y}^*}{\beta_{y,cs}}} & \pm \sqrt{\beta_{y,cs} \beta_{y}^*} \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ -1/f \end{pmatrix}
\]

\[
\Delta l = \frac{x_{IP}}{\theta}
\]

\[
f = \frac{1}{k_{s1} x_{cs}}
\]
Crab-waist collisions

Conditions for the crab-waist sextupole

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

Sextupole strength

\[
k l_s = \sqrt[ \theta \beta_y^* \beta_y^* ]{ \beta_x^* / \beta_x^* }
\]

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

Suitable for lepton machines (\(\varepsilon_x \neq \varepsilon_y\))

More challenging for hadron colliders
Crab waist collisions in DAΦNE

Start of switching off the CW sextupoles in both rings: 200 A → 0 A

900 mA x 500 mA

C. Milardi
M. Zobov

José L. Abelleira
Crab waist collisions in DAΦNE

Minimum luminosity, highest background when the sextupoles are OFF

KLOE background

KLOE luminosity monitor

DAFNE luminosity monitor

C. Milardi
M. Zobov

José L. Abelleira
C-W collisions for hadron colliders

There are several facts that make difficult the implementation of crab-waist collisions in LHC:

- Same charge of particles
- Large $L^*$
- Large energy
- Same emittance in the two planes

A new IR for HL-LHC is presented with the following ingredients:

- Large Piwinski Angle
- Flat beams
- Local chromatic correction?
- Crab-waists
A new IR for LHC

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

Local chromatic correction in both planes + crab-waist collisions

<table>
<thead>
<tr>
<th>Sextupole</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>

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

\[ s = 0.05 \]
A new IR for LHC

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A new IR for LHC
A new IR for LHC
A new IR for LHC
A new IR for LHC
A new IR for LHC
A new IR for LHC
A new IR for LHC
A new IR for LHC

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A new IR for LHC
A new IR for LHC

\[ \sigma^*_x / \sigma^*_y = 10 \] Minimum required according to beam-beam simulations.
A new IR for LHC

Present IR LHC

Proposed IR

final-focus Q1-Q3

What is this element?
Last quadrupole

_by(x)_

$B_0 = -5.8 \, \text{T}$

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

Double half quadrupole

solution to have different quadrupole sign for the 2 beams in the same aperture

Dipolar component and sextupolar component

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S. Russenchuck
Kick due to the dipolar term
Crab-waist simulations

**CW = 0**

Resonances

**CW = 0.5**

Resonances suppressed

Frequency Map Analysis (FMA)
Effective for the beam-beam resonance suppression.
Plot shown for $\theta_c = 1.5$ mrad

Dmitry Shatilov
Mikhail Zobov

José L. Abelleira
Work on progress

• Chromatic correction and sextupole compensation

• Plan B

\[ \beta_x^* = 1.5 \text{ m} \]
\[ \beta_y^* = 1.5 \text{ cm} \]
\[ \theta = 4 \text{ mrad} \]

\[ \beta_x^* = 3.5 \text{ m} \]
\[ \beta_y^* = 3.5 \text{ cm} \]
\[ \theta = 2.6 \text{ mrad} \]
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.
• W. Herr and B. Muratori. *Concept of luminosity.*

• P. Raimondi¹, D. Shatilov, M. Zobov, *Beam-beam issues for colliding schemes with large Piwinski angle and crabbed waist.*


• J.L. Abelleira, ”Flat beam IR optics”, *Joint Snowmass-EUCARD/AccNet-HiLumi LHC meeting Frontier capabilities for Hadron colliders. February 22-23; 2013, CERN, Switzerland*

• J.L. Abelleira, ”Towards an extremely-flat beam optics with large crossing angle for the LHC”, *EUCARD Annual Meeting, April 25-27, 2012, Warsaw, Poland.*
Thank you...

...For your attention