Overview of LHC Performance Linked to Collective Effects
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10/09/2008: LHC startup

Elias Métral

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Overview of LHC Performance Linked to Collective Effects

Elias Métral

10/09/2008: LHC startup

Run 1: 2010-2012
Overview of LHC Performance Linked to Collective Effects
Run 1: 2010-2012
Run 2: 2015-Now-2018

Future challenges

Overview of LHC Performance Linked to Collective Effects

10/09/2008: LHC startup

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http://emetral.web.cern.ch/emetral/
Duoplasmatron = Source @ 90 keV (kinetic energy)
LINAC2 = Linear accelerator @ 50 MeV
PS Booster = Proton Synchrotron Booster @ 1.4 GeV
PS = Proton Synchrotron @ 25 GeV
SPS = Super Proton Synchrotron @ 450 GeV
LHC = Large Hadron Collider @ 7 TeV
15 BBLR / IP side => 120 in total

=> PACMAN bunches
(# integrated beam-beam effect)
CONTENTS

◆ Brief history of the LHC

◆ Introduction

◆ Main messages

◆ Challenges and results linked to collective effects
  ▪ Past
  ▪ Current => E-cloud and Linear coupling
  ▪ Future
1983 (i.e. several years before LEP started): 1st ideas / estimates

2007: LHC was finished

2008: LHC commissioning & inauguration

30/03/2010: 1st collisions at 7 TeV (3.5 + 3.5)
A historical day : 4\textsuperscript{th} July 2012

=> Announcement of the discovery of a new particle ("Higgs-like" boson)

2013 Nobel prize in physics awarded to F. Englert and P. Higgs for their theoretical work on Higgs boson (1964)
INTRODUCTION

- Field in main magnets
- Proton beam intensity
- Beam transfer

To LHC clock-wise (Beam 1 - blue) or counter clock-wise (Beam 2 - red)

1.2 seconds
450 GeV
26 GeV
1.4 GeV
1.2 seconds
Time

SPS
PS
PSB

Courtesy of R. Steerenberg
INTRODUCTION

- = Field in main magnets
- = Beam 1 intensity
- = Beam 2 intensity

Time

450 GeV

Injection

Ramp

Squeeze & Adjust

Stable beams for physics

Dump & Ramp down

6.5 TeV (in 2016)

Courtesy of R. Steerenberg
### INTRODUCTION

- **Design peak luminosity:** $10^{34}$ cm$^{-2}$s$^{-1}$

<table>
<thead>
<tr>
<th>Parameter</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Number of particles per bunch</td>
<td>$N_b$</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>$M$</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>$f_{\text{rev}}$</td>
</tr>
<tr>
<td>Relativistic velocity factor</td>
<td>$\gamma_r$</td>
</tr>
<tr>
<td>$\beta$-function at the collision point</td>
<td>$\beta^*$</td>
</tr>
<tr>
<td>Normalised rms transverse beam emittance</td>
<td>$\epsilon_n$</td>
</tr>
<tr>
<td>Geometric reduction factor</td>
<td>$F$</td>
</tr>
</tbody>
</table>

- $N_b = 1.15 \times 10^{11}$
- $M = 2808$
- $f_{\text{rev}} = 11245$ Hz
- $\gamma_r = 7461$ ($\Rightarrow E = 7$ TeV)
- $\beta^* = 55$ cm
- $\epsilon_n = 3.75 \times 10^{-4}$ cm
- $F = 0.84$

\[ F = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}} \]

<table>
<thead>
<tr>
<th>Parameter</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Full crossing angle at the IP</td>
<td>$\theta_c$</td>
</tr>
<tr>
<td>Rms bunch length</td>
<td>$\sigma_z$</td>
</tr>
<tr>
<td>Transverse rms beam size at the IP</td>
<td>$\sigma^*$</td>
</tr>
</tbody>
</table>

- $\theta_c = 285$ $\mu$rad
- $\sigma_z = 7.55$ cm
- $\sigma^* = 16.7$ $\mu$m
MAIN MESSAGES

◆ Collective effects
  ▪ Beam coupling impedance and related instabilities
  ▪ Mitigations: transverse damper + chromaticity + octupoles
  ▪ Space charge
  ▪ Electron cloud
  ▪ Beam beam => BBHO (Head On) and BBLR (Long Range)
MAIN MESSAGES

◆ Collective effects
  - Beam coupling impedance and related instabilities
  - Mitigations: transverse damper + chromaticity + octupoles
  - Space charge
  - Electron cloud
  - Beam beam => BBHO (Head On) and BBLR (Long Range)

◆ Relatively good understanding of the many collective effects (studied independently and in some cases interplays) and possible cures
MAIN MESSAGES

- Transverse instabilities are a concern based on the experience of the LHC Run 1 (2012 with 50 ns) and beginning of Run 2 (2015 with 25 ns)
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  - High chromaticities (~ +15 units)? A *known/predicted mechanism is e-cloud at injection*...
MAIN MESSAGES

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  - ~ Max current in the Landau octupoles (max = 550 A), i.e. much more (factor ~ 5) than predicted from impedance only?
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◆ We have identified 3 possible mechanisms (so far) which could explain a factor ~ 5 increase in the required current of the Landau octupoles
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  ▪ Noise => Already predicted by simulations but not measured yet. 1st BTF measurements and related Stability Diagram (SD) at injection made in 2015
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  - E-cloud => Already measured in MD but simulations still to come
  - Linear coupling between the transverse planes => Already predicted from simulations and measured in MD
MAIN MESSAGES

In a machine like the LHC, not only all the mechanisms have to be understood separately, but (ALL) the possible interplays between the different phenomena need to be analyzed in detail, including the
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- Beam-coupling impedance (with in particular all the necessary collimators to protect the machine but also new equipment such as crab cavities at large $\beta$-function)
- Linear and nonlinear chromaticity
- Landau octupoles (and other intrinsic nonlinearities)
- Transverse damper
- Space charge
- Beam-beam: BBLR (Long-Range) and BBHO (Head-On)
- Electron cloud
- Linear coupling strength
- Tune separation between the transverse planes (bunch by bunch)
- Tune split between the two beams (bunch by bunch)
- Transverse beam separation between the two beams
- Noise
- Etc.
### PAST CHALLENGES AND RESULTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td></td>
<td>7 TeV (4 in 2012)</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>( N_b )</td>
<td>1.15 (10^{11} ) (~ 1.6 in 2012)</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>( M )</td>
<td>2808 (1380 in 2012)</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>( \Delta t )</td>
<td>25 ns (50 in 2012)</td>
</tr>
<tr>
<td>Norm. rms. trans. emittance</td>
<td>( \varepsilon )</td>
<td>3.75 µm (~ 2.2 in 2012)</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>( f_0 )</td>
<td>11245 Hz</td>
</tr>
<tr>
<td>Rms bunch length</td>
<td>( \sigma_z )</td>
<td>7.5 cm (~ 10 in 2012)</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>( Q )</td>
<td>18.4 nC (25.6 in 2012)</td>
</tr>
<tr>
<td>Total beam current</td>
<td>( I_b )</td>
<td>0.58 A (~ 0.4 in 2012)</td>
</tr>
</tbody>
</table>

=> Bunch brightness reached: \(~ (1.6 / 1.15) \times (3.75 / 2.2) \sim 2.4\) times larger than nominal (at 4 TeV)!

=> Record peak luminosity: \(0.77 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\)
PAST CHALLENGES AND RESULTS

- Loss of longitudinal Landau damping during the first ramps when the longitudinal emittance was too small

Predicted $\frac{Z}{n} \sim 0.09 \Omega$ (with all collimators)

Elena Shaposhnikova et al.
PAST CHALLENGES AND RESULTS

- 1\textsuperscript{st} single-bunch head-tail instability $m = -1$ with neither octupoles nor damper (for $Q' \sim 6$) on flat-top

- Rise-time and Landau octupoles’ current for stability (between 10 and 20 A) within factor $\sim 2$ with predictions
PAST CHALLENGES AND RESULTS

- 1st TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)
  - Good agreement at 450 GeV
  - ~ 2-3 faster rise-times observed at 3.5 TeV (but uncertainty on chromaticities)
  - Landau octupoles’ current for stability at 3.5 TeV within factor ~ 2 with predictions (less than predicted!)
PAST CHALLENGES AND RESULTS

- 1st e-cloud studies in the LHC with 25 ns beam

\[ \delta_{\text{max}} \] has decreased from the initial 2.1 to 1.52 in the arcs!

Giovanni Iadarola, Giovanni Rumolo et al.

2011 scrubbing history of LHC arcs
PAST CHALLENGES AND RESULTS

- **Beam-beam**
  - PACMAN effects clearly visible

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G. Papotti, W. Herr et al.
PAST CHALLENGES AND RESULTS

PACMAN Orbit effects: calculation

W. Herr, R. Bartoldus et al.

Bunch-by-bunch orbit measurements variation of the vertex centroid in IP1
PAST CHALLENGES AND RESULTS

- Coherent beam-beam modes have been observed colliding 2 bunches (demonstrated by analysis of sum and difference of the measured positions of the 2 beams)
- Symmetry breaking suppresses modes as expected

- Without BB collisions

- With BB collisions

X. Buffat, T. Pieloni et al.
PAST CHALLENGES AND RESULTS

- Some instabilities observed during & at the end of the betatron squeeze (EOSI) pushed us to study in detail the interplay between the Landau octupoles and the BBLR
  - Decided to change the sign of the Landau octupoles (from – to + amplitude detuning => LOF > 0) in summer 2012
  - At the same time, both damper and chromaticity were increased
  - The EOSI could not be cured / understood yet => Still potential worry

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**FIG. 6.** Stability diagrams with both polarity of the octupoles for different long range contributions, corresponding to the configuration before the squeeze (None), after the squeeze, considering the most common bunch, i.e., largest long range contribution, and a PACMAN bunch with least long range contribution. The machine and beam parameters are those of 2012, neglecting the contribution of IP2 and 8.

**FIG. 7.** Comparison of the worst bunch at the end of the squeeze for each polarity of the octupole, in 2012 and nominal configurations.
PAST CHALLENGES AND RESULTS

FIG. 13. Comparison of footprints and corresponding stability diagrams generated by octupoles powered with $+500$ A, long range in IP1 and 5 or head-on in IP1 and 5. The machine and beam parameters are those of the nominal configuration.

FIG. 9. Example of tune footprint of a bunch colliding in IP1 with different separations in the horizontal plane. The machine and beam parameters are those of 2012 (Table I).

*Courtesy of X. Buffat*
PAST CHALLENGES AND RESULTS

- A possible mechanism which can lead to a loss of Landau damping (to try and explain the unexplained instabilities) => External noise, drilling holes in the stability diagram (still to be studied in detail)

(Courtesy of X. Buffat)
PAST CHALLENGES AND RESULTS

Nominal cycle 2011

6.5 TeV in 2015 and 2016

4 TeV in 2012

3.5 TeV in 2010 and 2011

Beam dump

Ramp down/precycle

Squeeze

Collide

Flat-top

Stable beams

Ramp

Some instabilities observed & Not cured

Injection

~30 mins

Some instabilities observed & cured

Ramp down

35 mins

Squeeze

8 mins

Some instabilities observed & cured

Injection

~30 mins

Ramp

17 mins

Collide

1 mins

Stable beams

0 – 30 hours

Some instabilities observed & cured

Some instabilities observed & cured

Some instabilities observed & cured
Conclusions

- Transverse instabilities are a concern based on the experience of the LHC Run 1 => Will we be able to stabilize the beam in the future?
PAST CHALLENGES AND RESULTS

◆ Conclusions

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- Beam-induced RF heating issues
PAST CHALLENGES AND RESULTS

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- UFOs (Unidentified Falling Objects) issues
PAST CHALLENGES AND RESULTS

- Conclusions

  - Transverse instabilities are a concern based on the experience of the LHC Run 1 => Will we be able to stabilize the beam in the future?

  - Beam-induced RF heating issues

  - UFOs (Unidentified Falling Objects) issues

  - Lessons learnt for the future (and future projects) => Better study of the interplays between (all) the different mechanisms…
CURRENT CHALLENGES AND RESULTS

- In 2015: 6.5 TeV (instead of 4 TeV in 2012), 25 ns bunch spacing (instead of 50 ns) and $\beta^* = 80$ cm (instead of 60 cm)
CURRENT CHALLENGES AND RESULTS

In 2015: 6.5 TeV (instead of 4 TeV in 2012), 25 ns bunch spacing (instead of 50 ns) and $\beta^* = 80$ cm (instead of 60 cm)

- **Pros**
  - ~ nominal bunch intensity and transverse emittance => ~ 2 times less critical compared to 2012
  - Smaller beam-beam effects
CURRENT CHALLENGES AND RESULTS

In 2015: 6.5 TeV (instead of 4 TeV in 2012), 25 ns bunch spacing (instead of 50 ns) and $\beta^* = 80$ cm (instead of 60 cm)

- **Pros**
  - $\approx$ nominal bunch intensity and transverse emittance $\Rightarrow \approx 2$ times less critical compared to 2012
  - Smaller beam-beam effects

- **Cons**
  - E-cloud
  - 2 times more BBLR
  - Landau octupoles less effective
CURRENT CHALLENGES AND RESULTS

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  • ~ nominal bunch intensity and transverse emittance => ~ 2 times less critical compared to 2012
  • Smaller beam-beam effects

- Cons
  • E-cloud
  • 2 times more BBLR
  • Landau octupoles less effective

◆ In 2016: $\beta^* = 40$ cm
CURRENT CHALLENGES AND RESULTS

- Transverse impedance and related instabilities: Single bunch

![Graphs showing transverse impedance predictions for different bunches with and without damper.]

DELPHI with perfect damper

BimBim with imperfect damper

Same predictions for many bunches with damper

Courtesy of L.R. Carver

Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016
CURRENT CHALLENGES AND RESULTS

- E-cloud effects
  - Scrubbing needed (as foreseen)

*Courtesy of G. Iadarola*
CURRENT CHALLENGES AND RESULTS

Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016

Courtesy of G. Iadarola
CURRENT CHALLENGES AND RESULTS

- Optimization of working point at injection

Octupole knob at -1.5
Q'\textsubscript{v}=15/20, 5 \times 10^{11} \text{ e/m}^{3}

Courtesy of A. Romano

Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016
CURRENT CHALLENGES AND RESULTS

QV = .297

QV = .305

Courtesy of A. Romano
CURRENT CHALLENGES AND RESULTS

Arc dip (450 GeV)

Only oct

Oct + Q’ 15/15

Only EC $\rightarrow$ 5e11 e/m$^3$

Combined effect

Courtesy of A. Romano
CURRENT CHALLENGES AND RESULTS

Arc quads (450 GeV)

Only oct

Oct + Q’ 15/15

Only EC → SEY 1.2

Combined effect

Courtesy of A. Romano
CURRENT CHALLENGES AND RESULTS

Forbidden by e-cloud + Q' + octupoles

Nominal

2016 2015

Can give stability issues if coupling is not fully corrected

Courtesy of G. Iadarola
CURRENT CHALLENGES AND RESULTS

- Instabilities observed at injection when Laslett tune shifts not corrected => Believed to be due to linear coupling (see later)

- Reminder from 2012

Closest tune approach
CURRENT CHALLENGES AND RESULTS

- Instabilities observed at high energy with a train of 72 bunches

![Graph showing instabilities with various parameters and annotations.](https://example.com/graph.png)

**DELPHI with perfect damper**

*After some scrubbing*

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Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016
CURRENT CHALLENGES AND RESULTS

- 72b w/25ns became unstable at 350A (unscaled) with presence of e-cloud (~0.8deg sync. phase shift) on 28/08.

- 72b w/25ns became unstable at currents consistent with single bunch measurements on 05/11. Sync. phase shift observed of ~0.3deg.

- Difference due to effect of scrubbing at FT.

- Different kind of instability observed between two cases. 2 nodes expected from simulation for H or V single bunch instabilities.

B1, 1x72b, 28/08

B2, 1x72b, 05/11

Courtesy of L.R. Carver

Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016
CURRENT CHALLENGES AND RESULTS

- To be further studied (from both simulations and measurements)
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- What will happen with many batches / full beam?
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- Will we succeed to remove all the e- from dipoles? Effect on beam stability?
CURRENT CHALLENGES AND RESULTS

- To be further studied (from both simulations and measurements)
- What will happen with many batches / full beam?
- Will we succeed to remove all the e- from dipoles? Effect on beam stability?
- What about the remaining e- in the quads (effect on tune footprint, beam stability, etc.)?
CURRENT CHALLENGES AND RESULTS

- Linear coupling can be beneficial or detrimental
CURRENT CHALLENGES AND RESULTS

- Linear coupling can be beneficial or detrimental
- Why could linear coupling be a problem for beam stability?
CURRENT CHALLENGES AND RESULTS

- Linear coupling can be beneficial or detrimental

- Why could linear coupling be a problem for beam stability?

- => Because the coherent tunes are shifted by linear coupling differently compared to the incoherent tunes (providing the Landau damping) due to the nonlinear fields (from octupoles to create the tune spread). Therefore in some cases a too strong coupling can be detrimental, leading to instabilities due to a loss of transverse Landau damping.
CURRENT CHALLENGES AND RESULTS

Proceedings of EPAC 2002, Paris, France

DESTABILISING EFFECT OF LINEAR COUPLING IN THE HERA PROTON RING

E. Métral, CERN, Geneva, Switzerland
G. Hoffstaetter, F. Willeke, DESY, Hamburg, Germany

Abstract

Since the first start-up of HERA in 1992, a transverse coherent instability has appeared from time to time at the beginning of the acceleration ramp. In this process, the emittance is blown up and the beam is partially or completely lost. Although the instability was found to be of the head-tail type, and the chromaticity and linear coupling between the transverse planes was recognized as essential for the instability to occur, the driving mechanism was never clarified. An explanation of the phenomenon is presented in this paper using the coupled Landau damping theory. It is predicted that a too strong coupling can be detrimental since it may shift the coherent tune outside the incoherent spectrum and thus prevent Landau damping. Due to these features, the name "coupled head-tail instability" is suggested for this instability in the HERA proton ring.

Simple model used (externally given elliptical spectrum...) => Detailed simulation study currently being performed for the LHC by L.R. Carver (see after)
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner

![Graph showing simulation results](image)

- $N_b = 3e11$, $E = 6.5$ TeV, $Q' = 7$, $\tau_d = 100$ turns, $\epsilon = 2.5$um

  - Green dots: Current threshold for $|C^-| = 0.001$
  - Red dots: Current threshold for $|C^-| = 0.005$
  - Blue dots: Current threshold for $|C^-| = 0.01$

Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

\[ |C^-| = 0 \]

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

\[ |C^-| = 0.002 \]

LOF > 0

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

\[ |C^-| = 0.004 \]

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

$|C^-| = 0.006$

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

\[ |C^-| = 0.008 \]

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

$$|C^-| = 0.01$$

LOF > 0

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner (LOF < 0)
- MADX with the real octupoles (LOF > 0, swapped tunes)

\[ |C^-| = 0 \]

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner (LOF < 0)
- MADX with the real octupoles (LOF > 0, swapped tunes)

$|C^-| = 0.002$

*Courtesy of L.R. Carver*
CURRENT CHALLENGES AND RESULTS

◆ pyHEADTAIL simulations with an octupole as detuner (LOF < 0)

◆ MADX with the real octupoles (LOF > 0, swapped tunes)

\[ |C^-| = 0.004 \]

Tune footprint for 3σ with \( i_{\text{act}} = 500 \) A, \( |C^-| = 0.004 \)

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner (LOF < 0)
- MADX with the real octupoles (LOF > 0, swapped tunes)

$|C^-| = 0.006

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- pyHEADTAIL simulations with an octupole as detuner (LOF < 0)
- MADX with the real octupoles (LOF > 0, swapped tunes)

\[ |C^-| = 0.008 \]

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- **pyHEADTAIL** simulations with an octupole as detuner (LOF < 0)

- **MADX** with the real octupoles (LOF > 0, swapped tunes)

\[ |C^-| = 0.01 \]

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- Physical mechanism => Simple model?

\[ J_x = 0 \text{ and } J_y = 1 \]
\[ J_x = 1 \text{ and } J_y = 0 \]
CURRENT CHALLENGES AND RESULTS

\[ Q_u = Q_x - \frac{|C^-|}{2} \tan \alpha \]

\[ Q_v = Q_y + \frac{|C^-|}{2} \tan \alpha \]

\[ \Delta = Q_y + l - Q_x = q_y - q_x = Q_{sep} \]

\[ \tan(2\alpha) = \frac{|C^-|}{\Delta} \]
Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016

CURRENT CHALLENGES AND RESULTS

\[ Q_y - Q_y = \frac{1}{2} \left( -\Delta + \sqrt{\Delta^2 + |C^-|^2} \right) \]

\[ Q_u - Q_x = -\frac{1}{2} \left( -\Delta + \sqrt{\Delta^2 + |C^-|^2} \right) \]
CURRENT CHALLENGES AND RESULTS

- Similar (but much smaller) behaviour seen
- Another ingredient is needed
  \[ \text{Amplitude-dependent } C^- \]
  - Example found empirically:
  \[ |C^-| \times \left[ 1 + 0.15 \left( J_x - J_y \right) \right] \]
CURRENT CHALLENGES AND RESULTS

- Similar (but much smaller) behaviour seen
- Another ingredient is needed

\[ |C^-| \times \left[ 1 + 0.15 \left( J_x - J_y \right) \right] \]
CURRENT CHALLENGES AND RESULTS

\[ |C^-| \times \left[ 1 - 0.15 \left( J_x - J_y \right) \right] \]

- \( |C^-| = 0.02 \)
- \( |C^-| = 0.01 \)
- \( |C^-| = 0.005 \)
- \( |C^-| = 0 \)
CURRENT CHALLENGES AND RESULTS

\[ |C^-| = 0.008 \]

\[ |C^-| \times [1 - 0.15 (J_x - J_y)] \]

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CURRENT CHALLENGES AND RESULTS

- See also R. Tomas et al., “Amplitude dependent closest tune approach” (submitted to PRAB) => However, the amplitude-dependent $C^*$ discussed before is not the same as the one in the paper and has been deduced empirically => To be continued...
CURRENT CHALLENGES AND RESULTS

- Dedicated instability measurements in the LHC on 16/04/2016
  - 1) During the betatron squeeze
  - 2) At top energy (before the betatron squeeze)
CURRENT CHALLENGES AND RESULTS

1) During the betatron squeeze: ADT on, $Q' \sim 9$ and $LOF = +285$ A
CURRENT CHALLENGES AND RESULTS

1) During the betatron squeeze: ADT on, $Q' \sim 9$ and $LOF = +285$ A

$|C^-| \sim 0.008$
CURRENT CHALLENGES AND RESULTS

1) During the betatron squeeze: ADT on, $Q' \sim 9$ and $\text{LOF} = +285 \text{ A}$

- $|C| \sim 0.008$
- $Q_1/Q_2$ kept at $0.31/0.32$ (tune feedback) => $Q_x \sim 0.312$ and $Q_y \sim 0.318$ => $Q_y - Q_x \sim 0.006$ (i.e. tune feedback is amplifying the coupling effect!)
CURRENT CHALLENGES AND RESULTS

1) During the betatron squeeze: ADT on, $Q' \sim 9$ and LOF = + 285 A

- $|C| \sim 0.008$
- $Q_1/Q_2$ kept at 0.31/0.32 (tune feedback) $\Rightarrow Q_x \sim 0.312$ and $Q_y \sim 0.318 \Rightarrow Q_y - Q_x \sim 0.006$ (i.e. tune feedback is amplifying the coupling effect!)
- Instability observed with LOF = + 285 A, i.e. ~ 4 times higher octupole current than uncoupled threshold
CURRENT CHALLENGES AND RESULTS

- 2) At top energy (before the betatron squeeze)

|C-| \(\sim 0.001\) and \(Q_{\text{sep}} = 0.03\):

\[\Rightarrow \text{Stability for LOF} = +71\ A\]

\[|C-| \sim 0.01\] and \(\text{LOF} = +310\ A\)

\[\Rightarrow \text{Instability for } Q_{\text{sep}} \sim 0.018\]

Courtesy of L.R. Carver
CURRENT CHALLENGES AND RESULTS

- This gives a factor $\frac{310}{71} = 4.4$ increase in Landau octupoles current compared to the uncoupled case.

![Graph showing current threshold for different values of $Q_{sep}$]

*Courtesy of L.R. Carver*
FUTURE CHALLENGES

- Reach design luminosity (hopefully soon…)

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FUTURE CHALLENGES

• Reach design luminosity (hopefully soon…)

• Continue to try and understand why we need such high values of chromaticities and octupoles as we need to prepare for HL-LHC where we will more than double the beam brightness
FUTURE CHALLENGES

- Reach design luminosity (hopefully soon…)

- Continue to try and understand why we need such high values of chromaticities and octupoles as we need to prepare for HL-LHC where we will more than double the beam brightness

Courtesy of T. Pieloni

LHC

HL-LHC

Octupoles reduce DA
High Q’ reduces DA Worse case LOF Pos and High Chroma
Lower Q’ is BETTER!
FUTURE CHALLENGES

- Understand also all the incoherent effects (noise issues etc.) leading to slow emittance growths and/or beam losses => Many thanks to Ji for all his help!

- Etc.
FUTURE CHALLENGES

- Understand also all the incoherent effects (noise issues etc.) leading to slow emittance growths and/or beam losses => Many thanks to Ji for all his help!

- Etc.
FUTURE CHALLENGES

The goal for Run 2 luminosity is $1.3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ and operation with 25 ns bunch spacing (2800 bunches), giving an estimated pile-up of 40 events per bunch crossing.

“A maximum pileup of ~50 is considered to be acceptable for ATLAS and CMS”

Run2: $\sim 100$–$120$ fb$^{-1}$
(better estimation by end of 2015)

300 fb$^{-1}$ before LS3

Goal of 3’000 fb-1 by mid 2030ies

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal LHC (design report)</th>
<th>HL-LHC 25ns (standard)</th>
<th>HL-LHC 25ns (BCMS)</th>
<th>HL-LHC 50ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Nb</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
<td>2.2E+11</td>
<td>3.5E+11</td>
</tr>
<tr>
<td>( n_b )</td>
<td>2808</td>
<td>2748</td>
<td>2604</td>
<td>1374</td>
</tr>
<tr>
<td>Number of collisions in IP1 and IP5 (^1)</td>
<td>2808</td>
<td>2736</td>
<td>2592</td>
<td>1368</td>
</tr>
<tr>
<td>Ntot</td>
<td>3.2E+14</td>
<td>6.0E+14</td>
<td>5.7E+14</td>
<td>4.9E+14</td>
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<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td>1.09</td>
<td>1.03</td>
<td>0.89</td>
</tr>
<tr>
<td>x-ing angle [( \mu rad )]</td>
<td>285</td>
<td>590</td>
<td>590</td>
<td>590</td>
</tr>
<tr>
<td>beam separation [( \sigma )]</td>
<td>9.4</td>
<td>12.5</td>
<td>11.4</td>
<td>11.4</td>
</tr>
<tr>
<td>( \beta ) [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>( \epsilon_b ) [( \mu \mbox{m} )]</td>
<td>3.75</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>( \epsilon_L ) [eVs]</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>r.m.s. energy spread</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
</tr>
<tr>
<td>r.m.s. bunch length [m]</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
</tr>
<tr>
<td>IB S horizontal [h]</td>
<td>80 -&gt; 106</td>
<td>18.5</td>
<td>18.5</td>
<td>17.2</td>
</tr>
<tr>
<td>IB S longitudinal [h]</td>
<td>61 -&gt; 60</td>
<td>20.4</td>
<td>20.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>0.65</td>
<td>3.14</td>
<td>3.14</td>
<td>2.87</td>
</tr>
<tr>
<td>Total loss factor R0 without crab-cavity</td>
<td>0.836</td>
<td>0.305</td>
<td>0.305</td>
<td>0.331</td>
</tr>
<tr>
<td>Total loss factor R1 with crab-cavity</td>
<td>(0.981)</td>
<td>0.829</td>
<td>0.829</td>
<td>0.883</td>
</tr>
<tr>
<td>beam-beam / IP without Crab Cavity</td>
<td>3.1E-03</td>
<td>3.3E-03</td>
<td>3.3E-03</td>
<td>4.7E-03</td>
</tr>
<tr>
<td>beam-beam / IP with Crab cavity</td>
<td>3.8E-03</td>
<td>1.1E-02</td>
<td>1.1E-02</td>
<td>1.4E-02</td>
</tr>
<tr>
<td>Peak Luminosity without crab-cavity [cm(^2) s(^{-1})]</td>
<td>1.00E+34</td>
<td>7.18E+34</td>
<td>6.80E+34</td>
<td>8.44E+34</td>
</tr>
<tr>
<td>Virtual Luminosity with crab-cavity: ( \text{Lpeak} \times \text{R1/R0} ) [cm(^2) s(^{-1})]</td>
<td>(1.18E+34)</td>
<td>19.54E+34</td>
<td>18.52E+34</td>
<td>21.38E+34</td>
</tr>
<tr>
<td>Events / crossing without levelling and without crab-cavity</td>
<td>27</td>
<td>198</td>
<td>198</td>
<td>454</td>
</tr>
<tr>
<td>Levelled Luminosity [cm(^2) s(^{-1})]</td>
<td>-</td>
<td>5.00E+34 (^5)</td>
<td>5.00E+34</td>
<td>2.50E+34</td>
</tr>
<tr>
<td>Events / crossing (with leveling and crab-cavities for HL-LHC) (^8)</td>
<td>27</td>
<td>138</td>
<td>146</td>
<td>135</td>
</tr>
<tr>
<td>Peak line density of pile up event [event/mm] (max over stable beams)</td>
<td>0.21</td>
<td>1.25</td>
<td>1.31</td>
<td>1.20</td>
</tr>
<tr>
<td>Leveling time [h] (assuming no emittance growth) (^8)</td>
<td>-</td>
<td>8.3</td>
<td>7.6</td>
<td>18.0</td>
</tr>
<tr>
<td>Number of collisions in IP2/IP8</td>
<td>2808</td>
<td>2452/2524 (^7)</td>
<td>2288/2396</td>
<td>0(^4)/1262</td>
</tr>
<tr>
<td>( n_b ) at LHC Injection (^2)</td>
<td>1.20E+11</td>
<td>2.30E+11</td>
<td>2.30E+11</td>
<td>3.68E+11</td>
</tr>
<tr>
<td>( n_b / ) injection</td>
<td>288</td>
<td>288</td>
<td>288</td>
<td>144</td>
</tr>
<tr>
<td>( \epsilon_n ) at SPS extraction [( \mu \mbox{m} )] (^3)</td>
<td>3.40</td>
<td>2.00</td>
<td>&lt; 2.00 (^6)</td>
<td>2.30</td>
</tr>
</tbody>
</table>

\(^1\) Parameters and Layout Committee
\(^2\) Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016
\(^3\) HL-LHC parameters page as of 16/12/2014
\(^4\) Parameters and Layout Committee
\(^5\) Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016
\(^6\) HL-LHC parameters page as of 16/12/2014
\(^7\) Parameters and Layout Committee
\(^8\) Elias Métral, seminar @ LBNL, Berkeley, USA, 23/05/2016

8.1 cm
1.08E-4
Thank you for your attention!