Beam-beam and octupoles: stability analysis for HL-LHC operational scenarios

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D. Banfi, J. Barranco, X. Buffat

Acknowledges for discussion to: W. Herr, E. Metrial and M. Giovannozzi

HL-LHC WP2 Task Leader Meeting 27th March 2015
Contents

- Short introduction to Stability Diagrams

- ATS optics: footprint
  stability diagrams
  effects of sextupoles

- Optics effect study: footprint with different $\beta^*$ optics and beam-beam LR
  stability diagrams for different $\beta^*$ optics and LR

- Betatron: stability diagrams with LR+optics
  squeeze Nominal and PACMAN bunch comparison

- Can we avoid reductions of stability? How?

- BB head-on: footprint
  stability diagrams

- Summary and Outlook
Stability diagrams

Landau octupoles provide necessary tune spread to stabilize coherent modes from Impedence.

To be stable coherent modes must lie inside the stability diagrams area.

Tracking with MAD-X

Tune spread (footprint)

Pyssd Code (X.Buffat)

Stability Diagrams (SD)
Stability diagrams

Dispersion Integral:

\[ SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty J_{x,y} d\Psi_{x,y}(J_x, J_y) \left( \frac{dJ_{x,y}}{Q_0 - q_{x,y}(J_x, J_y)} - i\epsilon dJ_x dJ_y \right) \]

- "Landau Damping by Non-Linear Space-Charge Forces and Octupoles" D. Mohl & H. Schonauer
- Berg - Ruggiero
LR effects introduce non-linear detuning with amplitude → reducing or increasing SD
During squeeze LR becomes stronger
Hi-Lumi scenarios

$I = 2.2 \times 10^{11}$ ppb  $\varepsilon = 2.5 \mu m$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Luminosity cm$^{-2}$ s$^{-1}$</th>
<th>$\beta^*$ at collision</th>
<th>Long-range separation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$5 \times 10^{34}$</td>
<td>$\sim 65$ cm</td>
<td>30</td>
</tr>
<tr>
<td>Ultimate</td>
<td>$7.5 \times 10^{34}$</td>
<td>$\sim 40$ cm</td>
<td>24</td>
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<tr>
<td>Full Squeeze</td>
<td>---</td>
<td>15 cm</td>
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If $\beta^*$ levelling doesn’t work
Hi-Lumi Stability Diagrams

Extend the LHC studies for Hi-Lumi \[\rightarrow\] Different optics: ATS optics

A follow up of the previous studies presented at the HL-LHC WP2 Task 2.4 meeting

Now available optics files for different $\beta^*$
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- **BB head-on:** footprint
  stability diagrams

- **Summary and Outlook**
ATS optics

Reference paper on ATS optics:

*Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade*

Stéphane Fartoukh*

*CERN, CH 1211 Geneva 23, Switzerland*

(Received 26 July 2013; published 19 November 2013)
ATS: optics impact on footprint

Footprint comparisons: LHC and HL-LHC case

Negative LOF

Positive LOF

Strong impact for ATS optics with respect to LHC

opt_0150_0150thin.madx
ATS: optics impact on stability diagrams

HL-LHC vs LHC ($I = 2.2 \times 10^{11}$, $\varepsilon = 2.5 \mu m$)

Negative LOF

Positive LOF

Landau Damping, Dynamic Aperture and Octupoles in LHC

J. Gareyte, J.P. Koutchouk and F. Ruggiero

\[ \Delta Q_{\text{oct}} \propto \beta(s)^2 \]

\[ \beta(s)^2_{\text{HL-LHC}} / \beta(s)^2_{\text{LHC}} \approx 2.5 \text{ larger than the LHC case} \]
ATS optics: footprint

Full telescopic part for positive versus negative octupole polarities

Asymmetric footprint for the two polarities
ATS optics: stability diagrams

HL-LHC case (only octupoles)

For single beam, larger stability diagrams for negative polarity
Asymmetric stability diagrams for opposite LOF, why?
ATS optics: effect sextupoles

Not negligible tune spread due to the sextupoles typical of ATS. Can we reduce this spread since it reduces the spread for negative polarity?
ATS optics: effect of non-linearities

By removing the tune spread due to the sextupoles: pure octupole effect

Linear detuning of octupoles with fully telescopic part
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  stability diagrams

- Summary and Outlook
Effects of different optics: footprints

- Negative LOF

Round optics

![Graph showing effects of different optics](image-url)
Effects of different optics: footprints

- Negative LOF

Round optics

- $\beta = 6m$
- $\beta = 1.8m$
Effects of different optics: footprints

- Negative LOF

![Graph showing effects of different optics](image-url)
Effects of different optics: footprints

- Negative LOF
Effects of different optics: footprints

- Negative LOF

Round optics
Effects of different optics: footprints

- Negative LOF

![Graph showing the effects of different optics on footprints](image-url)
Effects of different optics: footprints

- Negative LOF

Below $\beta^*=40$ cm, the beta function in the arc start to increase and accordingly the octupole spread thanks to ATS part!
Effects of different optics: footprints

- Positive LOF

Round optics

- $\beta=6\,\text{m}$
- $\beta=1.8\,\text{m}$
Effects of different optics: footprints

- Positive LOF

Round optics

![Graph showing the effects of different optics on footprints]
Effects of different optics: footprints

- Positive LOF

Round optics

![Graph showing footprints for different optics with annotations for different values of beta (\(\beta\)).]
Effects of different optics: footprints

- Positive LOF

![Round optics graph](image)
Effects of different optics: footprints

- Positive LOF

![Graph showing effects of different optics: footprints](image)

Legend:
- \( \beta=6 \text{m} \)
- \( \beta=1.8 \text{m} \)
- \( \beta=40 \text{cm} \)
- \( \beta=32 \text{cm} \)
- \( \beta=22 \text{cm} \)
- \( \beta=15 \text{cm} \)
Effects of different optics: footprints

- Positive LOF

![Diagram showing the effects of different optics on footprints.](image)
From $\beta^*=32\text{cm SD}$ start to increase due to the larger tune spread provided by the octupoles.
Effects of different optics + beam beam LR: footprints

- Negative LOF

IP1 and IP5 only crossing angle of 590 µrad
Effects of different optics + beam beam LR: footprints

- Negative LOF

IP1 and IP5 only crossing angle of 590 µrad

Beam-beam long range effects reduces the tune spread of octupoles during betatron squeeze (as also seen by S. Fartoukh for LHC run 1)
Effects of different optics + beam beam LR: footprints

- Negative LOF

IP1 and IP5 only crossing angle of 590 µrad
Effects of different optics + beam beam LR: footprints

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IP1 and IP5 only crossing angle of 590 µrad
Effects of different optics + beam beam LR: footprints

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IP1 and IP5 only crossing angle of 590 μrad
Effects of different optics + beam beam LR: footprints

- Negative LOF

IP1 and IP5 only crossing angle of 590 μrad

But it is not like for LHC case!
Effects of different optics + beam
beam LR: footprints

- Positive LOF

IP1 and IP5 only crossing angle of 590 µrad
Effects of different optics + beam beam LR: footprints

- Positive LOF

IP1 and IP5 only crossing angle of 590 𝜇rad
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- BB head-on: footprint vs beam intensity, stability diagrams
- Summary and Outlook
Evolution of the betatron squeeze with LR beam beam

**LR beam-beam in IP1 and IP5**

I=2.2e11 ppb  \( \varepsilon = 2.5 \, \mu m \)

Long range slightly reduce the SD

At 22\( \sigma \) the \( \beta \) in the arcs increases and compensates LR effects

The SD keep increasing below \( \beta^* = 32 \, cm \)
HL-LHC vs LHC

Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5

Negative LOF
Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5

LR add up to the octupoles contribution

At $22\sigma$ the $\beta$ in the arcs increase and add up with LR

$I = 2.2 \times 10^{11}$ ppb

$\varepsilon = 2.5 \, \mu m$

Positive LOF
HL-LHC vs LHC

Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5

As in LHC the SD increase during the squeeze
SD evolution during the $\beta$-squeeze

- Octupoles only, single beam

- Negative polarity preferred for single beam
SD evolution during the $\beta$-squeeze

LR beam-beam added

<table>
<thead>
<tr>
<th>$\beta$ [m]</th>
<th>Sep [$\sigma$]</th>
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SD evolution during the $\beta$-squeeze

LR beam beam added

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SD evolution during the $\beta$-squeeze

- At $22\sigma$ the ATS optics takes action and the SD starts to increase despite the LR contribution

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SD evolution during the $\beta$-squeeze

- LR beam beam added

- At $22\sigma$ equal SD for positive/negative LOF

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SD evolution during the $\beta$-squeeze

LR beam beam added
Betatron squeeze for HL-LHC optics: PACMAN bunches

Evolution of the betatron squeeze with LR beam beam for PACMAN bunches

$\beta^* = 1.8\text{m}$
$\beta^* = 40\text{cm}$
$\beta^* = 32\text{cm}$
$\beta^* = 15\text{cm}$
Stability Diagrams for PACMAN bunches

PACMAN bunches: greater SD in case of negative polarity
Stability Diagrams for PACMAN bunches

PACMAN bunches: greater SD in case of negative polarity
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PACMAN bunches: greater SD in case of negative polarity
Stability Diagrams for PACMAN bunches

PACMAN bunches: greater SD in case of negative polarity
Baseline scenario negative LOF preferred
Stability Diagrams for Ultimate scenario

Ultimate scenario negative LOF preferred/comparable to positive LOF
Can we compensate the reduction with stronger effect of Octupoles?

We increase current in Octupoles

\[ \Delta Q_x = \left[ \frac{3}{8\pi} \int \frac{\beta_x^2 O_3}{B \rho} \, ds \right] J_x - \left[ \frac{3}{8\pi} \int \frac{2\beta_x \beta_y O_3}{B \rho} \, ds \right] J_y, \]

Landau Damping, Dynamic Aperture and Octupoles in LHC

J. Gareyte, J.P. Koutchouk and F. Ruggiero
Can we compensate the reduction with stronger effect of Octupoles?

To reduce differences in Octupole spread to $10^{-4}$ we will need a factor 17% more in current 690 A → **8% more betas in arcs at 40 cm** (should arrive linearly from 70 cm beta*). Is this feasible?
Can we compensate the reduction with weaker LRs?

To reduce differences in Octupole spread to $10^{-4}$ we will need a factor 17% more in current 690 A $\rightarrow$ 8% more betas in arcs at 40 cm.
Can we compensate the reduction with weaker LRs?

Less effective (acts only on LRs close to IP) but still can help. We can reduce to half the variation with a half separation of 2mm at 40 cm beta*. Is this feasible?
Full squeeze positive LOF preferred
Crab crossing head-on: footprint

- Negative LOF

$\beta^* = 15 \text{cm optics}$

1 H-0 $l=2.2\text{e}11$ ppb

2 H-0 $l=2.2\text{e}11$ ppb
Crab crossing head-on: footprint

- Positive LOF

\[ \beta^* = 15\text{cm optics} \]

Graphs showing Crab crossing head-on footprint for different values of beta and momentum.
Crab crossing head-on: stability diagrams

$\beta^*=15\text{cm optics}$

1 H-O $l=2.2\times10^{11}$ ppb

2 H-O $l=2.2\times10^{11}$ ppb

Ongoing work, to study SD H-O collision for different ATS optics (octupoles contribution)
Summary and Outlook

- **At flat top** (single beam) **negative polarity preferred** to positive for optic with $\beta^*=60\text{cm}$

- **ATS optics** $\beta^*=15\text{cm}$ gives **larger SD** thanks to large $\beta$ function in the arcs
  - SD gets larger for $\beta^*<40\text{cm}$
  - Sextupole non-linearities adds to positive polarity creating asymmetry positive-negative LOF: **can we reduce this contribution?**

- **BB LR:**
  - Negative LOF reduces SD till $\beta^*>40\text{cm}$
  - Positive LOF increases SD at any $\beta^*$

- **For Negative LOF** larger $\beta$ in the arcs compensates LR reduction increasing SD for $\beta^*<40\text{cm}$.
  - **Can we have larger betas in arcs to compensate reduction?**

- Positive polarity of Octupoles reduces by $2\,\sigma\,\text{DA}$ → presentation after Easter on chromaticity and octupoles effect
<table>
<thead>
<tr>
<th>Summary</th>
<th>Positive LOF</th>
<th>Negative LOF</th>
</tr>
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<tbody>
<tr>
<td>HL-LHC V1.0 optics</td>
<td></td>
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<tr>
<td>Single beam $\beta^*=6m$</td>
<td>Smaller SD than Negative</td>
<td>Preferred</td>
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<tr>
<td>Baseline scenario ~65 cm $\beta^*$</td>
<td>Smaller SD than Negative</td>
<td>Preferred</td>
</tr>
<tr>
<td>Ultimate scenario ~40 cm $\beta^*$</td>
<td>Smaller SD than Negative</td>
<td>Preferred Reduction can be solved with 8% more betas in arc (and/or larger sep)</td>
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<tr>
<td>Full squeeze ~15 cm $\beta^*$</td>
<td>SD increases during the full squeeze</td>
<td>To avoid reduction collide needed at ~70 cm or apply larger betas and or sep</td>
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</table>
Backup slide
Effects of different optics+beam beam LR: stability diagrams

- **Negative LOF**
- **Positive LOF**

For 2m $\beta$ * the crossing angle was set to 80$\mu$rad in the optics file
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Negative LOF

Positive LOF