Beam Transfer Function and Stability Diagram

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ICFA mini-Workshop on:
Mitigation of Coherent Beam Instability in particle accelerators

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Outline

• Introduction
• The fitting method and reconstruction of Stability Diagram
• BTF measurements on single beam:
  • Landau octupole scan
  • Impact of beam losses on Landau damping
  • Linear coupling and BTF response
• BTF measurements with beam-beam interaction
  • Crossing angle scan (long range interactions)
  • Parallel separation scan (head-on interactions)
• Limitations of BTF measurements:
  • Impact of impedance and chromaticity in BTF response
• Summary
Introduction: dispersion integral

Predictions of (transverse) instability thresholds in the LHC are based on computation of Landau damping by calculating the Stability Diagrams (SD) with all ingredients (octupoles, beam-beam…)[1-3]

\[
\text{SD}^{-1} \propto \int_0^\infty \int_0^\infty \frac{J_{x,y} \Psi_{x,y}(J_x, J_y)}{Q_0 - q_{x,y}(J_x, J_y)} \frac{dJ_x}{dJ_y} \frac{dJ_x}{dJ_y} \text{d}J_x \text{d}J_y
\]

- Modification of the tune spread (linear coupling) and/or particle distribution changes (beam losses due to resonance excitation, reduced DA…) modify Landau damping
- A factor 2 (w.r.t models) in Landau octupoles (tune spread) is required to stabilize the beams during operations

Which is the real Landau damping of the beams?
Beam Transfer Function to measure beam stability

**Beam Transfer Function** measurements are **direct** measurements of the dispersion integral:

\[
\text{BTF} \propto \int_0^\infty \int_0^\infty \frac{J_{x,y} d\Psi_{x,y}(J_x, J_y)}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y
\]

BTF can experimentally verify the stability

- **direct** measurements of SD!
- Tune (high resolution, operationally used at RHIC), chromaticity measurements
- Coherent mode observations
- **Sensitive to particle distribution changes**
- Tune spread of the beams

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![Image of Beam Transfer Function with graphs showing amplitude and phase variations with respect to \(q_x\).]
The Fitting Method for the BTF response

Uncalibrated system and dependency on measurements conditions: direct reconstruction of stability diagrams not possible → fitting method for quantitative comparisons with expectations [4]

BTF (complex response) [4]

\[ \text{Amplitude (Q)} \]
\[ \text{Phase (Q)} \]

\[ \text{SD} \propto \frac{1}{\text{BTF}} = A^{-1} e^{-i\varphi} \]

**Fitting method** allows to compare measurements respect to models *(reference case, i.e. octupoles)* [4]

\[ \varphi(Q_{\text{meas}}) = \varphi[p_0 + p_1 \cdot (Q_{\text{model}} - Q_0)] \]
\[ A(Q_{\text{meas}}) = \frac{p_2}{p_1} \cdot A_{\text{model}}(Q_{\text{model}}) \]

\[ p_0 = \text{Tune} \]
\[ p_1 = \text{Tune spread factor respect to a reference case independent from calibration factor, (phase slope)} \]
\[ p_2 = \text{Amplitude factor: calibration, proportionality constant} \]
Reconstruction of SD using fitting method

Example applied to simulations:
Well known case of linear detuning with amplitude: tune spread parameter $p_1 \sim 1$

\[
Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)
\]

\[
A_{fit} = \frac{p_2}{p_1} \cdot A_{analyt}
\]
Reconstruction of SD using fitting method

Simulations
Octupoles only

\[ Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0) \]
\[ A_{fit} = p_2 / p_1 \cdot A_{analyt} \]

Example applied to simulations:
Well known case of linear detuning with amplitude: tune spread parameter \( p_1 \sim 1 \)

Measurements

Tune spread \( p_1 = 1.71 \)
Landau Octupole scan

Tune spread given by Landau octupoles and lattice non linearities @ injection energy

For the largest octupole strength (26 A) larger spread measured in the horizontal plane than in the vertical plane.
Measured tune spread and beam losses

Beam losses observed during data acquisition correlated with octupole current changes

- Fitting method used to compare measurements and expectations from model (tune spread factor)
- Equivalent to 5 A octupole spread measured at 0 A octupole current
- Linear trend reproduced
- Deviation observed in the vertical plane
Measured tune spread and beam losses

- Fitting method used to compare measurements and expectations from model (tune spread factor)
- Equivalent to 5 A octupole spread measured at 0 A octupole current
- Linear trend reproduced
- Deviation observed in the vertical plane

Simulated particle losses show that in the vertical plane a reduction up to 40% is observed for amplitudes < 4 \( \sigma \)

→ Increasing the tune spread is not beneficial for Landau damping if particle losses are present
The transverse linear coupling might cause destabilizing effects [5-7] due to a reduction of the Landau damping of the beams (talk by L. Carver):

- **reduced Landau damping in both planes**
- **asymmetric H-V frequency** distribution (tune spread)
- **stronger effect in the V-plane** (smaller tune spread w.r.t. H-plane)

**Simulated BTF response**

- **Horizontal plane**
- **Vertical plane**
Measurements in the presence of linear coupling

![Graphs showing measurements in horizontal and vertical planes with and without coupling.]

Fitting function method applied to measure tune spread from BTFs (w.r.t to an analytical reference case of SD with 4 A octupole current)

Quantitative comparison w.r.t to expectations (MAD-X + PySSD with and without linear coupling)

→ BTF measurements well agree with expectations!
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Crossing angle scan performed to measure tune spread as a function of the LR separation:

- Asymmetric tune spread and shifts in horizontal/vertical planes
- Tune shifts are comparable with measured tune shifts from Long Range beam-beam

Measured LR contribution on the stability diagram as a function of bb LR separation w.r.t. exceptions at EOS (octupoles + BB)

- Dependence on working point
- Not expected from models, it may have strong impact on SD

→ Other mechanisms should play a role
Parallel separation scan (head-on interactions)

- The biggest tune spread is observed with full Head-on collision (as expected)
Parallel separation scan (head-on interactions)

- Tune spread is reduced when a small parallel separation is applied
Parallel separation scan (head-on interactions)

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Parallel separation scan (head-on interactions)

Narrowest peak

- Smallest tune spread observed at ~1.5 σ (expected minimum of stability [3, 8])
Parallel separation scan (head-on interactions)

- Tune spread increases again when separating the beams
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- At 6 σ separation the tune spread slightly decreases
Parallel separation scan (head-on interactions)

• At 6 σ separation the tune spread slightly decreases

Head-on tune shifts as a function of offset sep.

Head-on tune shifts compared to MADx considering ±10% emittance, crossing angle, separation
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Chromaticity impact on BTF and SD

In the presence of chromaticity synchrotron sidebands appear in the BTF amplitude and phase jumps (at $\pm n \cdot Q_s$ from tune)

When synchrotron sidebands are close enough to coherent beam response the stability diagram is deformed by the bumps produced by the chromaticity effect in the transverse plane

There is no analytical formula to characterize this effect

Does the new area contribute to stabilize the beam or is it just an artifact on BTF response?
Triggering of instabilities with BTF

Single bunch (I~0.95 × 10^{11} p/bunch)

Q’ ~ 10 units, Oct. current 510 A

Measurements at top energy in 2017: Instability triggered by BTF due to the impedance increase in 2017

Higher stability thresholds (octupoles) are required in the presence of small external excitation (2 · 10^{-4} σ) [9]

- A gated system has been installed to measure multiple bunches
- Setup of the BTF excitations amplitude needed according to machine conditions (flat top, impedance)
Measurements at top energy (2018)

Tune shift observed in BTF response (asymmetric sidebands w.r.t. tune peak )

\[ \Delta Q_{coh} \approx -3.5 \times 10^{-4} \]

(Int= 8.23 E10)
Measurements at top energy (2018)

-\(Q_s\) (Int= 8.23 E10 ) +\(Q_s\)

\[\Delta Q_{coh} \sim -3.5 \times 10^{-4}\]

Fitting function is not giving satisfactory results:
the BTF shape is not equal to the analytical one (octupoles)
→ other unexpected effects in the BTF response
IMPEDANCE contribution!

Tune shift observed in BTF response (asymmetric sidebands)

Int = 8.23 \times 10^{10}
Impedance contribution in the BTF response

- The coherent tune shift increases with the bunch intensity
- BTF response is distorted increasing beam intensity (impedance)

Bunch Intensity scan (simulations)

546 A, Q’=2.5 units, Q_s=0.002
Impedance contribution in the BTF response

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- The coherent tune shift increases with the bunch intensity
- BTF response is distorted increasing beam intensity (impedance)

For low intensity bunches (lower impedance) the fitting method still works
Impedance contribution in the BTF response

Bunch Intensity scan (simulations)

546 A, Q′=2.5 units, Q_s=0.002

- The coherent tune shift increases with the bunch intensity
- BTF response is distorted increasing beam intensity (impedance)

Simulated BTF response

For stronger impedance the fitting function method cannot be applied anymore!
In order to reproduce the observed tune shift $N_{\text{bunch}} \sim 1.2 \times 10^{11}$ factor 1.5 more impedance needed consistent with other independent measurements [10].
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Summary

• The transverse BTF system was installed in the LHC in order to measure Landau damping of the beams and explore possible mechanisms that could explain loss of Landau damping observed in the LHC.

• A **fitting method was successfully** used and applied for:
  
  - reconstruction of stability diagram
  - comparison of the measured **tune spread w.r.t. models**
  - measurements of the **tunes with a resolution of 10^{-4}**

• The effects of the linear coupling resonance on the tune spread of the beams have been measured and quantified by BTF measurements at injection energy → **measurements well reproduce expectations**

• **Beam losses** due to a reduced DA **reduce Landau damping** of the beams → **experimentally observed** for the first time in the LHC.

• Measurements with LR beam-beam interactions:
  
  - **unexpected behaviors observed from measured tune spread** → other mechanisms should play a role such as linear coupling / particle redistributions
  
  - Tune shifts measured from BTF were used in 2016 operations to increase beam lifetimes [11]

• Measurements with Head-on interactions:
  
  - **tune shifts reproduced with MADx** (in within error bars)
  
  - Minimum of stability observed in the width of the BTF response
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- Measurements with Head-on interactions:
  - tune shifts reproduced with MADx (within error bars)
  - Minimum of stability observed in the width of the BTF response

The BTF system and fitting method presents some limitations:

- The fitting method relies on an approximation of the tune spread when unknown nonlinear effects are present and the beam distribution is considered as Gaussian

- the effect of the chromaticity in the BTF response causes distortion in the reconstruction of the stability diagrams (reducing too much chromaticity dangerous for stability especially at flat top energy at the LHC)

- **when the impedance is strong it is not possible to apply the fitting method** to extrapolate the tune spread from the measurements and reconstruct SD
Thanks for your attention!
References

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(2) J. Gareyte et al., Landau Damping, Dynamic Aperture and Octupoles in LHC, LHC Project Report 91 (CERN, Geneva, Switzerland)
(3) Buffat, W. Herr, N. Mounet, T. Pieloni, and S. White, Phys. Rev. ST Accel. Beams 17, 111002
(9) C. Tambasco Triggering of instabilities by BTF measurements LBOC 27/03/2018
(10) D. Amorim et al. https://indico.cern.ch/event/743627/
(11) B. Salvachua et al. Presentation at LBOC Meeting on October 2016
Introduction: Dispersion Integral

Landau damping of head-tail instabilities can be quantified by the dispersion integral [1 - 3]:

\[ \text{SD}^{-1} \propto \int_0^\infty \int_0^\infty \frac{J_{x,y} \, d\Psi_{x,y}(J_x,J_y)}{Q_0 - q_{x,y}(J_x,J_y) - i\epsilon} \, dJ_x \, dJ_y \]

Tune spread

Octupoles + beam-beam (any non-linearities)

Gaussian particle distribution

\[ Q_x, Q_y \]

\[ -1.5 \leq \text{Re}(\Delta Q) \leq 1.5, -1.5 \leq \text{Im}(\Delta Q) \leq 1.5 \]

\[ 10^{-3} \leq |\Delta Q| \leq 2.5 \times 10^{-4} \]
Incoherent effects on SD

If we consider a Gaussian particle distribution with reduced DA. DA < 5 σ reduces Landau damping
Incoherent effects on SD

If we consider a Gaussian particle distribution with reduced DA. DA < 5σ reduces Landau damping.

Diffusive mechanisms and/or reduced dynamic aperture with particle losses (or redistribution) → Coherent stability modified.
BTF amplitude dependency on tune spread

![Graph showing BTF amplitude dependency on tune spread. The graph plots Octupole current [A] on the x-axis and $A_{BTF} (\text{max})$ [a.u.] on the y-axis. Two data sets are shown: Data set 1 (COMBI) with blue dots and Data set 2 (COMBI) with green dots. Additionally, a dashed line represents the fit $a/\Delta q$.](image)