Effects of transverse damper, detuning impedance, linear coupling, chromaticity, Landau damping and space charge on TMCI

E. Métral

- Introduction
- 6 mechanisms modifying the TMCI intensity threshold (*beam-beam and e-cloud not considered here*)
- Conclusion
Introduction

- Let’s assume a single bunch with $Q' = 0$ interacting with a Broad-Band Resonator (BBR) impedance ($f_r, R_t, Q = 1$)
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- 3 regimes in general for the TMCI (Transverse Mode-Coupling Instability) => 2 important for us
  - “Very short-bunch” regime => Not discussed here
  - “Short-bunch” regime => TMCI between LOM (modes 0 and -1 as in LHC)
  - “Long-bunch” regime => TMCI between HOM (e.g. -2 and -3 as in SPS)
Introduction

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◆ Depending on the “bunch-length” regime, the different mechanisms can have different effects…
Introduction

“Very short-bunch”

“Short-bunch”

“Long-bunch”

$N_b^{th}$

$2 f_r \tau_b$

4 $\sigma$ bunch length

$\sigma_b$ bunch length
Introduction

"Very short-bunch"

"Long-bunch"

"Short-bunch"

\[ N_b^{th} \]

\[ \Delta t \approx \frac{1}{2f_r} \]

\[ 2f_r \tau_b \]

4 \( \sigma \) bunch length
Introduction

- Intensity threshold
Introduction

- Intensity threshold

“Short-bunch” regime: CERN LHC
Introduction

- Intensity threshold

"Short-bunch" regime: CERN LHC

\( N_{b}^{th} \) obtained when tune shift of mode 0 is "close to \( -Q_s \)"

\( Q' = 0 \)
No damper

D. Amorim (DELPHI Vlasov Solver)

\[ \frac{\Delta Q_{x}}{Q_s} \]

\[ C R / s^{-1} \]

\[ GF \ (\Delta Q_{x}/Q_s) \]

Intense, / \( 10^{11} \) p.p.b.

Mode 0

Mode -1

Most unstable

\[ \Rightarrow \] New low-impedance collimators to increase the intensity threshold for HL-LHC
Introduction

- Intensity threshold

“Short-bunch” regime: CERN LHC

“Long-bunch” regime: CERN SPS

\[ N_b^{th} \text{ obtained when tune shift of mode 0 is “close to } - Q_s \]

=> New low-impedance collimators to increase the intensity threshold for HL-LHC
**Intensity threshold**

"Short-bunch" regime: CERN LHC  

"Long-bunch" regime: CERN SPS

\[ N^{th}_b \] obtained when tune shift of mode 0 is "close to \( -Q_s \)"

\[ N^{th,y}_b \propto |\eta| Q_y \varepsilon_L \frac{f_r}{R_t} \]

=> Q20 (or Q22) optics (instead of Q26) to solve the problem in practice for LIU

=> New low-impedance collimators to increase the intensity threshold for HL-LHC
### Introduction

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**BENEFICIAL OR DETRIMENTAL?**
1) Transverse Damper
1) Transverse Damper

- Resistive and reactive Transverse Damper (TD)

\[ \Delta Q_{TD} = \frac{e^{j \phi}}{2 \pi d} \]
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- Resistive and reactive Transverse Damper (TD)

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- \( \phi \) = betatron phase advance between Pick-Up and Kicker
- \( d \) = damper damping time in machine turns (=2/G, G=gain)
1) Transverse Damper

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- If \( \phi = 90^\circ \) \( \Rightarrow \) TD is called "resistive": it is a conventional damper/feedback system, which damps the centre-of-charge motion of the beam

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1) Transverse Damper

- **Resistive and reactive Transverse Damper (TD)**

  - If $\phi = 90^\circ$ => TD is called “resistive”: it is a conventional damper/feedback system, which damps the centre-of-charge motion of the beam

  - If $\phi = 0^\circ$ => TD is called “reactive”: in this case, mode 0 is shifted (which can raise the intensity threshold in the presence of TMCI between modes 0 and -1)

$$\Delta Q_{TD} = \frac{e^{j \phi}}{2 \pi d}$$

- $\phi$ = betatron phase advance between Pick-Up and Kicker
- $d$ = damper damping time in machine turns (=2/G, G=gain)
1) Transverse Damper

“Long-bunch” regime:
~ CERN SPS \((f_r \tau_b = 2.8, Q' = 0)\)

No TD
Reactive TD

![Graph](image)
1) Transverse Damper

“Long-bunch” regime:
~ CERN SPS \((f_r \tau_b = 2.8, Q' = 0)\)

No TD
Reactive TD

No TD
Resistive TD

\[
\Re(\Delta Q)/Q, \quad \Im(\Delta Q)/Q
\]

UNSTABLE

~ CERN SPS \((f_r \tau_b = 2.8, Q' = 0)\)
1) Transverse Damper

“Long-bunch” regime:
~ CERN SPS \((f_r \tau_b = 2.8, Q' = 0)\)

“Short-bunch” regime:
~ CERN LHC \((f_r \tau_b = 0.8, Q' = 0)\)

---

No TD

Reactive TD

No TD

Resistive TD

---

No TD

Reactive TD

---

No TD

Reactive TD

---

No TD

Resistive TD
1) Transverse Damper

“Long-bunch” regime:
~ CERN SPS \((f_r \tau_b = 2.8, Q' = 0)\)

“Short-bunch” regime:
~ CERN LHC \((f_r \tau_b = 0.8, Q' = 0)\)
“Short-bunch” regime without resistive TD

1) Transverse Damper
1) Transverse Damper

- “Short-bunch” regime with resistive TD
1) Transverse Damper

◆ “Short-bunch” regime with resistive TD
1) Transverse Damper

- “Short-bunch” regime with resistive TD

ISR instability (Imaginary tune Split & Repulsion)
1) Transverse Damper

“Short-bunch” regime with resistive TD

Required tune spread (normalised by $Q_s$) for Landau damping
2) Detuning impedance

- Extending Burov-Danilov_1998 (“air-bag” model) with a constant wake and considering first only 2 modes (0 and -1), the system is fully described by the following matrix to be diagonalized:

\[
\begin{pmatrix}
-1 + \frac{\kappa}{2} I_{\text{norm}} & \frac{2 I_{\text{norm}}}{\pi^2} (1 - \kappa) \\
\frac{2 I_{\text{norm}}}{\pi^2} (-1 - \kappa) & \frac{I_{\text{norm}}}{2} (-1 + \kappa)
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\end{pmatrix}
\]

\[
I_{\text{norm}} = \frac{Ne^2}{2\gamma m_0 \omega \beta \omega_s C} \times \frac{\omega_r^2 R_t}{Q \omega_r}
\]

\[
\kappa = D(z)/W_x(z)
\]

+ 1 in \(x\) for CRW flat chamber
- 1/2 in \(y\) for CRW flat chamber
2) Detuning impedance

[Graph showing the increase factor from detuning impedance against \( k \) with data points indicating a non-linear relationship.]
2) Detuning impedance

- 1/2 in y for CRW flat chamber
- + 1 in x for CRW flat chamber
2) Detuning impedance: $\kappa = 0.0$
2) Detuning impedance: $\kappa = 0.1$
2) Detuning impedance: $\kappa = 0.2$
2) Detuning impedance: \( \kappa = 0.3 \)
2) Detuning impedance: $\kappa = 0.4$
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2) Detuning impedance

- These results are in good agreement with the results from G. Rumolo who extended the 2-particle model (CERN HSC section meeting, 12/08/19)

2) Detuning impedance

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![Graphs showing detuning impedance](https://indico.cern.ch/event/832772/contributions/3523440/attachments/1892401/3121154/HSC-20190812.pdf)
2) Detuning impedance

- Considering now a BBR and many azimuthal modes (but still 1 radial mode), a good agreement is also obtained between theory and simulation.
2) Detuning impedance

- Considering now a BBR and many azimuthal modes (but still 1 radial mode), a good agreement is also obtained between theory and simulation.

![Graph showing detuning impedance comparison between theory and simulation.](https://indico.cern.ch/event/840690/contributions/3528490/attachments/1892682/3125100/BenchmarkDetuningImpedWithCirculantMatrix_EM_19-08-2019.pdf)
2) Detuning impedance

\[ f_r \tau_b = 2.8 \quad \kappa = 0 \]

Circulant Matrix (XavierB)
2) Detuning impedance

\[ f_r \tau_b = 2.8 \quad \kappa = -1 \]

Circulant Matrix (XavierB)
2) Detuning impedance

\( f_r \tau_b = 2.8 \)  \( \kappa = 1 \)

Circulant Matrix (XavierB)
2) Detuning impedance

- Considering now also many radial modes, similar results as with past HEADTAIL simulations are obtained (simulation by X. Buffat)
2) Detuning impedance

- Considering now also many radial modes, similar results as with past HEADTAIL simulations are obtained (simulation by X. Buffat)

\[ f_r \tau_b = 2.8 \]

\[
\frac{N_{b}^{th,x}}{N_{b}^{th,round}} \approx 2 \quad \frac{N_{b}^{th,y}}{N_{b}^{th,round}} \approx 1
\]

B. Salvant (PHD thesis)
3) Linear coupling

- Considering the case of the SPS with a BBR (and a flat chamber)
3) Linear coupling

- Considering the case of the SPS with a BBR (and a flat chamber)

\[ Q_x = 26.180 \quad Q_y = 26.185 \quad \xi_{x,y} = 0 \]

\[ K_{skew}^{\text{HEADTAIL}} = 0.005 \text{ m}^{-1} \]

\[ \Rightarrow \text{The vertical intensity threshold is increased from } \sim 3.3 \times 10^{10} \text{ p/b} \]
\[ \text{to } \sim 4.5 \times 10^{10} \text{ p/b, i.e. an increase of 36%, in good agreement with a previous theoretical prediction of 33%} \]
3) Linear coupling

- This result was checked/confirmed by B. Salvant (PHD thesis), simulating more (10,000) turns
3) Linear coupling

- This result was checked/confirmed by B. Salvant (PHD thesis), simulating more (10 000) turns
4) Chromaticity

- Considering the case of the SPS with a BBR
4) Chromaticity

- Considering the case of the SPS with a BBR

\[
\begin{align*}
\text{Re}\left(\frac{\Delta Q}{Q_s}\right) & = 0 & \text{Re}\left(\frac{\Delta Q}{Q_s}\right) & = +7 & \text{Re}\left(\frac{\Delta Q}{Q_s}\right) & = -7 \\
\text{Im}\left(\frac{\Delta Q}{Q_s}\right) & = 0 & \text{Im}\left(\frac{\Delta Q}{Q_s}\right) & = +7 & \text{Im}\left(\frac{\Delta Q}{Q_s}\right) & = -7
\end{align*}
\]
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 0.0 \]
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 0.1 \]
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 0.2 \]
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 0.3 \]
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 0.4 \]
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 0.5 \]
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- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 0.6 \]
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\[ \Delta q = 0.8 \]
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\[ \Delta q = 0.9 \]
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\[ \Delta q = 1.0 \]
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- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 1.2 \]
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- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes $0$ and $-1$ and an externally given elliptical tune spread

$$\Delta q = 1.4$$
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- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 1.6 \]
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\[ \Delta q = 1.8 \]
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- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

\[ \Delta q = 2.0 \]
5) Landau damping

- Considering the case of the LHC with a BBR, assuming only the 2 azimuthal modes 0 and -1 and an externally given elliptical tune spread

$$\Delta q = 3.0$$
6) Space charge

\[ q_{sc} = \frac{\Delta Q_{sc}}{2Q_s} \]
6) Space charge

With a “simple 2-mode model”, 2 effects predicted

- “Short-bunch” regime => Beneficial
- “Long-bunch” regime => Detrimental

\[ q_{sc} = \frac{\Delta Q_{sc}}{2 Q_s} \]

6) Space charge

- Considering the case of the LHC ("Short-bunch" regime)
6) Space charge

- Considering the case of the LHC ("Short-bunch" regime)

![Mode spectral power (vertical)]

- WITHOUT SC
- WITH SC

- No instability anymore with SC

A. Oeftiger (pyHT)
6) Space charge

- Considering the case of the SPS ("Long-bunch" regime)
6) Space charge

- Considering the case of the SPS ("Long-bunch" regime)
6) Space charge

◆ Considering the case of the SPS ("Long-bunch" regime)

Q26 case @ 0.2e11 ppb

Without SC => STABLE
With SC => UNSTABLE

TMCI threshold without SC

A. Oeftiger (pyHT)
6) Space charge

- Considering the case of the SPS ("Long-bunch" regime)

=> Clear detrimental effect of space charge for both "high SC" and "low SC" regimes, **BUT** still lot of work to understand clearly the instability and define correctly the instability growth rates...

A. Oeftiger (pyHT)

=> Corresponding to Q20
6) Space charge

- Considering the case of the SPS ("Long-bunch" regime)

=> Clear detrimental effect of space charge for both "high SC" and "low SC" regimes, BUT still lot of work to understand clearly the instability and define correctly the instability growth rates...

E. Métiral, Space charge workshop, CERN, 05/11/2019
6) Space charge

![Graph of resonator wake with different Q_s/Q_sc values: Q_s/Q_sc = 1, Q_s/Q_sc = 0.2, Q_s/Q_sc = 0.02, Q_s/Q_sc = 0.05.](image)

Y. Alexahin  
(MCBI 2019)
6) Space charge

The TMCI threshold defined as \( \text{Im } \nu/Q_s > 0.1 \) vs the space charge tuneshift.

Y. Alexahin
(MCBI 2019)
6) Space charge

Smaller beneficial effect than predicted in the past by some theories.

The TMCI threshold defined as $\text{Im } \nu/Q_s > 0.1$ vs the space charge tuneshift.

Y. Alexahin
(MCBI 2019)
6) Space charge

Is there really a beneficial effect?

Smaller beneficial effect than predicted in the past by some theories

The TMCI threshold defined as $\text{Im } v/Q_s > 0.1$ vs the space charge tuneshift.

Y. Alexahin
(MCBI 2019)
Conclusion

- Many mechanisms influencing the TMCI are relatively well understood
Conclusion

- Many mechanisms influencing the TMCI are relatively well understood.
- Still some work needed to understand better the effect of space charge, in particular in the “long-bunch” regime (with recent improvements in both simulation and theory) => To be continued/finalised.
## Conclusion

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### “Long-bunch” regime

| | Reactive or resistive: no effect for main TMCI |

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E. Métral, Space charge workshop, CERN, 05/11/2019
## Conclusion

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