Destabilising effect of resistive transverse dampers

E. Métral
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- Introduction
- Motivation
- New Vlasov solver: GALACTIC (and GALACLIC)
- Instability mechanism with $Q' = 0$
- Impact on Landau damping
- Comparison with PyHEADTAIL macroparticle tracking simulations
- Destabilising effect of Landau damping for TMCI
- Conclusion and outlook
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Many thanks to D. Amorim, S. Antipov, S. Arsenyev, N. Biancacci, X. Buffat, K. Li & A. Oeftiger

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Many thanks also to S. Berg for the very interesting breakfast discussion on Monday and for pointing me to his past work on the subject at EPAC98:

HEAD-TAIL MODE INSTABILITY CAUSED BY FEEDBACK
(http://accelconf.web.cern.ch/AccelConf/e98/PAPERS/THP10C.PDF)
Introduction

- Resistive and reactive Transverse Damper (TD)

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

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

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

- $\phi = 90^\circ$ => 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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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)
Introduction

- A resistive **TD** is needed for multi-bunch operation in a machine like LHC, and it is very efficient!

See talk from D. Valuch
“The LHC transverse damper: a multi-purpose system”
Introduction

- A resistive TD is needed for multi-bunch operation in a machine like LHC, and it is very efficient!

=> Example of LHC predictions in 2018 at 6.5 TeV
A resistive **TD** is needed for multi-bunch operation in a machine like LHC, and it is very efficient!

=> Example of LHC predictions in 2018 at 6.5 TeV

**With TD**
Introduction

- A resistive TD is needed for multi-bunch operation in a machine like LHC, and it is very efficient!

$\Rightarrow$ Example of LHC predictions in 2018 at 6.5 TeV

With TD

$Q' \sim 2$ was the initial recommendation for LHC operation
A resistive **TD** is needed for multi-bunch operation in a machine like LHC, and it is very efficient!

=> Example of LHC predictions in 2018 at 6.5 TeV

**With TD**

**Without TD**

Q’ ~ 2 was the initial recommendation for LHC operation
Introduction

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=> Example of LHC predictions in 2018 at 6.5 TeV

**With TD**

**Without TD**

\[ Q' \approx 2 \] was the initial recommendation for LHC operation

Limit of 550 A

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Introduction

- A better control of the machine has been achieved year after year, and at the end of Run 2 (2018), the following mitigation knobs were used at 6.5 TeV
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A better control of the machine has been achieved year after year, and at the end of Run 2 (2018), the following mitigation knobs were used at 6.5 TeV

- $Q'$: $\sim + 15$
- $TD$: $\sim 50$-$100$-turn damping time
- Landau Octupoles (LO) current: a factor $\sim 2$ higher than predicted (compared to factor $\sim 5$ at the end of Run 1)
Introduction

- Lessons learned from Run 1 and Run 2:

- TD to be included in beam stability analyses (also with Beam-Beam)
- LO (> 0 or < 0) with Beam-Beam effects (both Long-Range and Head-On)
- Destabilising effect of e-cloud
- Destabilising effect of linear coupling
- Destabilising effect of TD
- Destabilising effect of noise => Currently under study (demonstrated in 2018) as possible main contributor to the remaining factor ~ 2 in LO
Introduction

◆ Lessons learned from Run 1 and Run 2: 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 analysed in detail.
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Some observation in past studies such as KarlinerPopov2005

=> Referred to as “a sort of TMCI”, without detailed analysis
Motivation

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

$L.R. \ Carver \ et \ al.$
Motivation

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

Predictions \textit{(DELPHI)}

$L.R. \ Carver \ et \ al.$

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Motivation

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

Predictions

Measurements

L.R. Carver et al.
Motivation

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

Predictions

Measurements

=> 2 questions:

1) What is the (exact) predicted instability mechanism?

2) Is Landau damping well computed (stability diagram => 1-mode approach)?

L.R. Carver et al.
New Vlasov solver: GALACTIC (and GALACLIC)


- GALACLIC = GArnier-LAclare Coherent Longitudinal Instabilities Code => Helped to understand the details of the mode-coupling behind some longitudinal microwave instabilities (IPAC19: https://ipac2019.vrws.de/papers/mopgw089.pdf)
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Results in black are from Laclare (only real parts)

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New Vlasov solver: GALACTIC (and GALACLIC)

TIC (BB Resonator, $f_r \tau_b = 2.8$)

LIC (similar BBR) without PWD

LIC (similar BBR) with PWD

Results in black are from Laclare (only real parts)
New Vlasov solver: GALACTIC (and GALACLIC)

TIC (BB Resonator, $f_r \tau_b = 2.8$)

LIC (similar BBR) without PWD

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With simplest model of PWD (Potential-Well Distortion)
New Vlasov solver: GALACTIC (and GALACLIC)

PyHEADTAIL\( (f_r \tau_b = 2.7) \)

SBSC\( (f_r \tau_b = 2.7) \)

PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)
New Vlasov solver: GALACTIC (and GALACLIC)

PyHEADTAIL\( (f_r \tau_b = 2.7) \) vs. GALACTIC (in black)

SBSC\( (f_r \tau_b = 2.7) \) vs. GALACLIC (in black)

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PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)
New Vlasov solver: GALACTIC (and GALACPLIC)

**PyHEADTAIL** ($f_r \tau_b = 2.7$) vs. GALACTIC (in black)

**SBSC** ($f_r \tau_b = 2.7$) vs. GALACPLIC (in black)

*With simplest model of PWD (Potential-Well Distortion)*

*PyHEADTAIL and SBSC tracking simulations from M. Migliorati (with new mode analysis)*

*Full convergence study not done...*
Instability mechanism with $Q' = 0$

Long-bunch regime: $\sim$ CERN SPS

$(f_r\tau_b = 2.8)$
Instability mechanism with $Q' = 0$

Long-bunch regime: $\sim$ CERN SPS

$(f_r \tau_b = 2.8)$

No TD
Reactive TD

Resistive TD

UNSTABLE

Long-bunch regime: $\sim$ CERN SPS

$(f_r \tau_b = 2.8)$

No TD
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UNSTABLE
Instability mechanism with $Q' = 0$

Long-bunch regime: ~ CERN SPS

$\left(f_r \tau_b = 2.8\right)$

Short-bunch regime: ~ CERN LHC

$\left(f_r \tau_b = 0.8\right)$

No TD

Reactive TD

Resistive TD
Instability mechanism with $Q' = 0$

Long-bunch regime: ~ CERN SPS  
$(f_r \tau_b = 2.8)$

Short-bunch regime: ~ CERN LHC  
$(f_r \tau_b = 0.8)$

No TD  
Reactive TD

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Resistive TD

UNSTABLE

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UNSTABLE

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Instability mechanism with $Q' = 0$

- Approximated model for the LHC without TD

$$\begin{pmatrix}
-1 & -0.23 j x \\
-0.55 j x & -0.92 x
\end{pmatrix}$$

Normally, $(\Delta Q/Q_s)_{0,-1} = -(\Delta Q/Q_s)_{-1,0}$ and real, but it can also be presented like this (was solved numerically here...).
Instability mechanism with $Q' = 0$

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E. Métral, MCBI2019 workshop, Zermatt, Switzerland, 23-27/09/2019
Instability mechanism with $Q' = 0$

- Approximated model for the LHC with TD ($d = 100$ turns)

$$
\begin{pmatrix}
-1 & -0.23 j x \\
-0.55 j x & -0.92 x + 0.48 j
\end{pmatrix}
$$

$$= \frac{j}{2 \pi d Q_s}$$

$$\text{Re} \left( \Delta \phi_Q \right) / Q_s$$
Instability mechanism with $Q' = 0$

- Approximated model for the LHC with TD ($d = 100$ turns)

\[
\begin{pmatrix}
-1 & -0.23 j x \\
-0.55 j x & -0.92 x + 0.48 j
\end{pmatrix}
\]

\[
= \frac{j}{2 \pi d Q_s}
\]

\[
\begin{array}{c}
\text{Re} \left( \frac{\Delta Q}{Q_s} \right) \\
\text{Im} \left( \frac{\Delta Q}{Q_s} \right)
\end{array}
\]
Instability mechanism with $Q' = 0$

- Approximated model for the LHC with TD ($d = 100$ turns)

\[
\begin{pmatrix}
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\end{pmatrix}
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\[
\frac{j}{2 \pi d Q_s} = \frac{j}{2 \pi d Q_s}
\]

 ISR instability (Imaginary tune Split & Repulsion)
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time => $+ 0.00 \, j$

![Graph showing instability mechanism with Q' = 0](image.png)
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow + 0.03 j$ (obtained e.g. with $d=50$ & $Q_s=0.1$)

$$= \frac{j}{2\pi d Q_s}$$
Scan vs. TD damping time => + 0.03j (obtained e.g. with d=50 & $Q_s=0.1$)

$\frac{j}{2\pi d Q_s}$

=> Explains in particular why TD not very effective for machines with large $Q_s$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow + 0.08 \, j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow + 0.18 j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time => $+ 0.28j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time => $+ 0.38 j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow + 0.48 \, j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow + 0.58j$

![Graph showing instability mechanism with $Q' = 0$.](image-url)
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time => $+ 0.68j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow +0.78\,j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow + 0.88 j$
Instability mechanism with $Q' = 0$

- Scan vs. TD damping time $\Rightarrow + 0.98 \, j$

![Graph showing instabilities with $Q'$ = 0]
Impact on Landau damping

- Approximated model for the LHC with TD ($d = 100$ turns) and Landau damping

\[
\begin{vmatrix}
I_{m=-1}^{-1} & 0.23 j x \\
0.55 j x & I_{m=0}^{-1} + 0.92 x - 0.48 j
\end{vmatrix} = 0
\]

Dispersion integral
=> Solved for an externally given elliptical tune spread
Impact on Landau damping

- Approximated model for the LHC with TD ($d = 100$ turns) and Landau damping

\[
\begin{bmatrix}
I_{m=-1}^{-1} & 0.23 j x \\
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\]

Dispersion integral => Solved for an externally given elliptical tune spread

Required tune spread (normalised by $Q_s$) for Landau damping
Comparison with PyHEADTAIL
macroparticle tracking simulations

Stability threshold for $I_{LOF} < 0$ for PyHEADTAIL (x-plane)

- SD prediction from $I_{LOF} = 0$ simulation (damper, linear synchrotron motion)
- 2nd degree fit (damper simulation)
- no-damper simulation with octupole
- damper simulation with octupole

Threshold octupole current LOF [A]

0 1000 2000 3000 4000 5000 6000 7000

0.2 0.4 0.6 0.8 1.0 1.2 1.4

Intensity $N$ [10$^{11}$ ppb]

**TMCI intensity threshold without TD**

**Required tune spread (normalised by $Q_s$) for Landau damping**

A. Oeftiger

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Destabilising effect of Landau damping for TMCI (without TD)

- Scan vs. $\Delta q$

$\Delta q = 0.0$

Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.1 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.2 \]
Destabilising effect of Landau damping for TMCI (without TD)

$\Delta q = 0.3$
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.4 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.5 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.6 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.7 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.8 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 0.9 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 1.0 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 1.2 \]
Destabilising effect of Landau damping for TMCI (without TD)

$\Delta q = 1.4$
Destabilising effect of Landau damping for TMCI (without TD)

$$\Delta q = 1.6$$
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 1.8 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 2.0 \]
Destabilising effect of Landau damping for TMCI (without TD)

\[ \Delta q = 3.0 \]

Some benchmarks with PyHEADTAIL macroparticle tracking simulations started (N. Mounet) but need to be finalised.
Conclusion and outlook

- Instability mechanism for $Q' = 0$ in presence of resistive TD, which is needed for multi-bunch operation in a machine like LHC
  => ISR (Imaginary tune Split & Repulsion) instability (instead of TMCI)
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- Confirmed by 2 other Vlasov solvers: DELPHI (D. Amorim) and NHTVS (S. Antipov)

Detrimental effect of TD below TMCI intensity threshold
Beneficial effect of TD above TMCI intensity threshold

Another mechanism is needed to explain the LHC observations at low chromaticity, such as e.g. a modification of the longitudinal distribution (studied by A. Oeftiger) => To be finalised. Effect of noise? Others?
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- Another mechanism is needed to explain the LHC observations at low chromaticity, such as a modification of the longitudinal distribution (A. Oeftiger) => To be finalised. Effect of noise? Others?
Thank you for your attention!

(hoping that you are enjoying the workshop as we are doing. Many thanks to all!)
APPENDIX
Resistive TD

+ 0.48 j

- 0.48 j
½ resistive and ½ reactive TD

\[ +0.48 \, (j+1) \]

\[ -0.48 \, (j+1) \]
Reactive TD

\[ \text{Re} \left( \frac{\Delta Q}{Q_s} \right) \]

\[ \text{Im} \left( \frac{\Delta Q}{Q_s} \right) \]

+0.48

-0.48