SUMMARY OF MY 3 IPAC19 PAPERS

E. Métral

◆ 1) GALACTIC and GALACLIC: two Vlasov solvers for the transverse and longitudinal planes

◆ 2) Longitudinal Mode-Coupling Instability: GALACLIC Vlasov solver vs. macroparticle tracking simulations (with M. Migliorati)

◆ 3) A two-mode model to study the effect of space charge on TMCI in the "long-bunch" regime
1) GALACTIC and GALACLIC: two Vlasov solvers for the transverse and longitudinal planes
1) GALACTIC and GALACLIC: two Vlasov solvers for the transverse and longitudinal planes

- GALACTIC = GArnier-LAclare Coherent Transverse Instabilities Code => Was used for instance to shed light on the destabilising effect of resistive transverse dampers such as in the LHC (IPAC18)
1) GALACTIC and GALAQLIC: two Vlasov solvers for the transverse and longitudinal planes

- **GALACTIC = GArnier-LAclare Coherent Transverse Instabilities Code** => Was used for instance to shed light on the destabilising effect of resistive transverse dampers such as in the LHC (IPAC18)

- **GALAQLIC = GArnier-LAclare Coherent Longitudinal Instabilities Code** => Helped understanding the details of the mode-coupling behind some longitudinal microwave instabilities (see 2)
1) GALACTIC and GALACLIC: two Vlasov solvers for the transverse and longitudinal planes

- **GALACTIC** = GArnier-LAclare Coherent Transverse Instabilities Code => Was used for instance to shed light on the destabilising effect of resistive transverse dampers such as in the LHC (IPAC18)

- **GALACLIC** = GArnier-LAclare Coherent Longitudinal Instabilities Code => Helped understanding the details of the mode-coupling behind some longitudinal microwave instabilities (see 2)

- 2 similar approaches solving the linearised Vlasov equation
1) GALACTIC and GALACLIC: two Vlasov solvers for the transverse and longitudinal planes

- GALACTIC = GArnier-LAclare Coherent Transverse Instabilities Code => Was used for instance to shed light on the destabilising effect of resistive transverse dampers such as in the LHC (IPAC18)

- GALACLIC = GArnier-LAclare Coherent Longitudinal Instabilities Code => Helped understanding the details of the mode-coupling behind some longitudinal microwave instabilities (see 2)

- 2 similar approaches solving the linearised Vlasov equation
  - In the CAS from 1985 (CERN-87-03), Laclare obtained an eigenvalue system to solve but with the unknown frequency inside the matrix to be diagonalised
1) GALACTIC and GALACLIC: two Vlasov solvers for the transverse and longitudinal planes

- **GALACTIC** = GArnier-LAclare Coherent Transverse Instabilities Code => Was used for instance to shed light on the destabilising effect of resistive transverse dampers such as in the LHC (IPAC18)

- **GALACLIC** = GArnier-LAclare Coherent Longitudinal Instabilities Code => Helped understanding the details of the mode-coupling behind some longitudinal microwave instabilities (see 2)

- **2 similar approaches solving the linearised Vlasov equation**
  - In the CAS from 1985 (CERN-87-03), Laclare obtained an eigenvalue system to solve but with the unknown frequency inside the matrix to be diagonalised
  - In his PHD thesis in 1987, Garnier proposed to use a decomposition on the low-intensity eigenvectors to obtain an eigenvalue system with the unknown frequency outside the matrix to be diagonalised
1) GALACTIC and GALACLIC: two Vlasov solvers for the transverse and longitudinal planes

- **GALACTIC = GArnier-LAclare Coherent Transverse Instabilities Code** => Was used for instance to shed light on the destabilising effect of resistive transverse dampers such as in the LHC (IPAC18)

- **GALACLIC = GArnier-LAclare Coherent Longitudinal Instabilities Code** => Helped understanding the details of the mode-coupling behind some longitudinal microwave instabilities (see 2)

- **2 similar approaches solving the linearised Vlasov equation**
  - In the CAS from 1985 (CERN-87-03), Laclare obtained an eigenvalue system to solve but with the unknown frequency inside the matrix to be diagonalised
  - In his PHD thesis in 1987, Garnier proposed to use a decomposition on the low-intensity eigenvectors to obtain an eigenvalue system with the unknown frequency outside the matrix to be diagonalised

- I followed Garnier’s approach and obtained slightly different expressions, which I compared to Laclare => 4 Vlasov solvers discussed here (with Water-Bag for T & Parabolic Amplitude Density for L, but could be any longitudinal distribution)
GALACTIC vs. LACLARE (in black): constant inductive imped.
GALACTIC vs. LA克莱 (in black): constant inductive imped.

\[ x = \frac{\text{Im} \left[ Z_x(0) \right] e I_b}{4 \pi \gamma m_0 c Q_{x0} B \omega_s} \]
GALACTIC vs. LACLARE (in black): BB resonator imped. (2.8)
GALACLIC vs. LACLARE (in black): constant inductive imped.
WITHOUT PWD (i.e. normalising to $Q_s$)
GALACLIC vs. LACLARE (in black): constant inductive imped.

WITHOUT PWD (i.e. normalising to $Q_s$)

$$x = \frac{\text{Re}(Q)/Q_s}{\pi^2 B^3 \hat{V}_T h \cos \phi_s}$$
GALACLIC vs. LACLARE (in black): constant inductive imped. WITHOUT PWD (i.e. normalising to $Q_s$)
GALACLIC vs. LACLARE (in black): BB resonator imped. (2.8) WITHOUT PWD (i.e. normalising to $Q_s$)
GALAC LIC vs. LAC LAIRE (in black): BB resonator imped. (2.8)
WITHOUT PWD (i.e. normalising to \( Q_s \))
**GALACLIC: BB resonator imped. (2.8)**

**WITH PWD** (i.e. normalising to $Q_{s0}$)

\[
\frac{Q}{Q_{s0}} = \frac{Q}{Q_s} \times F_{PWD}
\]

\[
F_{PWD} = \frac{Q_s}{Q_{s0}} = \frac{1}{\sqrt{1 - \frac{4}{\pi} x}}
\]

Assuming here first the simplified case where the shape of the distribution is preserved

$x_{th} \approx -0.75$
2) Longitudinal Mode-Coupling Instability: GALACLIC Vlasov solver vs. macroparticle tracking simulations => For a “Parabolic Line Density” longitudinal distribution
2) Longitudinal Mode-Coupling Instability: GALA CLIC Vlasov solver vs. macroparticle tracking simulations \( \Rightarrow \) For a “Parabolic Line Density” longitudinal distribution

\[
F_{PWD} = \frac{Q_s}{Q_{s0}} = \frac{1}{\sqrt{1 - \frac{3}{4}x}}
\]
2) Longitudinal Mode-Coupling Instability: GALAACLIC Vlasov solver vs. macroparticle tracking simulations => For a “Parabolic Line Density” longitudinal distribution

\[ F_{PWD} = \frac{Q_s}{Q_{s0}} = \frac{1}{\sqrt{1 - \frac{3}{4} x}} \]

\[ f_r \tau_b = \begin{cases} 1) \text{Inf}; & 2) 2.7 \end{cases} \]

\[ f_0 = 43350.8 \text{ Hz} \quad B_0 = f_0 \tau_b = 1.17 \times 10^{-4} \]

\[ \left[ \frac{Z_l}{p} \right]_{p=0} = 8.67 \Omega \]

\[ \omega_{s0} = 889 \text{ rad/s} \]

\[ V_{RF} = 6 \text{ MV} \]

\[ h = 462 \]
2) Longitudinal Mode-Coupling Instability: GALACLIC Vlasov solver vs. macroparticle tracking simulations => For a “Parabolic Line Density” longitudinal distribution

\[ F_{PWD} = \frac{Q_s}{Q_{s0}} = \frac{1}{\sqrt{1 - \frac{3}{4} x}} \]

\[ f_r \tau_b = \begin{cases} 
\text{Inf} & \text{1) Inf} \\
2.7 & \text{2) 2.7} 
\end{cases} \]

\[ f_0 = 43350.8 \text{ Hz} \quad B_0 = f_0 \tau_b = 1.17 \times 10^{-4} \]

\[ \left[ \frac{Z_l}{p} \right]_{p=0} = 8.67 \Omega \]

\[ V_{RF} = 6 \text{ MV} \]

\[ \omega_{s0} = 889 \text{ rad/s} \]

\[ h = 462 \]

\[ f_r \tau_b = 2.7 \]
SBSC vs. GALA CLIC (in black): constant inductive imped.

New mode analysis implemented for the post-processing of the results obtained through macroparticle tracking simulations
SBSC vs. GALACLIC (in black): constant inductive imped.
SBSC vs. GALA CLIC (in black): BB resonator imped. (2.7)

Intensity threshold from slope of bunch length (SBSC sim., see slide 10)
SBSC vs. GALA CLIC (in black): BB resonator imped. (2.7)

Intensity threshold from slope of bunch length (SBSC sim., see slide 10)

M. Migliorati
Simple formula

\[
N_{th}^{b} = \frac{\left|x_{th}\right| \pi^2}{4} \frac{B_0^3 V_{RF} h}{e f_0 \left|\frac{Z_l(p)}{p}\right|_{p=0}} \frac{B_0}{B}
\]

\[
\left(\frac{B_0}{B}\right)_{PLD} = \left(1 - \frac{3}{4} x_{th}\right)^{-1/4}
\]

\[
x_{th} \approx -0.75 \Rightarrow N_{th}^{b} \approx 1.2 \times 10^{11} \text{ p/b}
\]
3) A two-mode model to study the effect of space charge on TMCI in the "long-bunch" regime
3) A two-mode model to study the effect of space charge on TMCI in the "long-bunch" regime

- A fast vertical single-bunch instability has been observed for many years in the SPS above a certain intensity threshold when the chromaticity is corrected => Latest review at ICAP’18 in Fall 2018
3) A two-mode model to study the effect of space charge on TMCI in the "long-bunch" regime

- A fast vertical single-bunch instability has been observed for many years in the SPS above a certain intensity threshold when the chromaticity is corrected => Latest review at ICAP’18 in Fall 2018
- A threshold close to the no-SC case was observed and therefore no (significant) stabilising effect from SC seemed to be observed, as opposed to most advanced theoretical predictions
3) A two-mode model to study the effect of space charge on TMCI in the "long-bunch" regime

- A fast vertical single-bunch instability has been observed for many years in the SPS above a certain intensity threshold when the chromaticity is corrected => Latest review at ICAP’18 in Fall 2018
- A threshold close to the no-SC case was observed and therefore no (significant) stabilising effect from SC seemed to be observed, as opposed to most advanced theoretical predictions
- Using a simplified “two-mode model”, no beneficial effect was expected (no effect for “very long” bunches and destabilising effect otherwise) => Discussed here
3) A two-mode model to study the effect of space charge on TMCI in the "long-bunch" regime

- A fast vertical single-bunch instability has been observed for many years in the SPS above a certain intensity threshold when the chromaticity is corrected => Latest review at ICAP’18 in Fall 2018
- A threshold close to the no-SC case was observed and therefore no (significant) stabilising effect from SC seemed to be observed, as opposed to most advanced theoretical predictions
- Using a simplified “two-mode model”, no beneficial effect was expected (no effect for “very long” bunches and destabilising effect otherwise) => Discussed here
- The fact that something seemed to be missing in the currently most advances theories was stressed again at the recent workshop at FNAL in Spring 2018 (https://indico.fnal.gov/event/16269/contribution/9/material/slides/1.pdf) => Since then a destabilising effect of SC was revealed: A. Burov, “Convective instabilities of bunched beams with space charge”
3) A two-mode model to study the effect of space charge on TMCI in the "long-bunch" regime

- A fast vertical single-bunch instability has been observed for many years in the SPS above a certain intensity threshold when the chromaticity is corrected => Latest review at ICAP’18 in Fall 2018
- A threshold close to the no-SC case was observed and therefore no (significant) stabilising effect from SC seemed to be observed, as opposed to most advanced theoretical predictions
- Using a simplified "two-mode model", no beneficial effect was expected (no effect for "very long" bunches and destabilising effect otherwise) => Discussed here
- The fact that something seemed to be missing in the currently most advances theories was stressed again at the recent workshop at FNAL in Spring 2018 (https://indico.fnal.gov/event/16269/contribution/9/material/slides/1.pdf) => Since then a destabilising effect of SC was revealed: A. Burov, “Convective instabilities of bunched beams with space charge”
- New simulations were then performed (A. Oeftiger) and analysed in detail (still ongoing), as well as new measurements in the SPS (A. Oeftiger & H. Bartosik) => Confirmed destabilising effect of SC
Reminder on 2-particle model from Y.H. Chin, A.W. Chao and M. Blaskiewicz => Extended to include also a ReaD

\[ \frac{\Delta \nu_{SC}}{\nu_s} = g_{\text{ReaD}} \frac{c^2}{\omega \beta \omega_s} \]

- \( \alpha \) Instability growth-rate
- \( \alpha \) Wake-field (constant)
Reminder on 2-particle model from Y.H. Chin, A.W. Chao and M. Blaskiewicz => Extended to include also a ReaD

- Conclusion: both SC and/or a reactive transverse damper (ReaD) would affect TMCI in a similar way and could suppress it
Reminder on 2-particle model from Y.H. Chin, A.W. Chao and M. Blaskiewicz => Extended to include also a ReaD

- Conclusion: both SC and/or a reactive transverse damper (ReaD) would affect TMCI in a similar way and could suppress it

=> Things are more involved with a bunched beam, where the “short-bunch” regime is different from the “long-bunch” regime…
SC only

- Blaskiewicz1998 (ABS model)

\[
\frac{\Delta Q}{Q_s} = -q_{sc} \pm \sqrt{q_{sc}^2 + m^2} \quad \quad q_{sc} = \frac{\Delta Q_{sc}}{2 Q_s}
\]
SC only

- Blaskiewicz1998 (ABS model)

\[
\frac{\Delta Q}{Q_s} = -q_{sc} \pm \sqrt{q_{sc}^2 + m^2} \quad q_{sc} = \frac{\Delta Q_{sc}}{2Q_s}
\]
“Short-bunch” regime without and with ReaD or SC

- Example from my IPAC18 paper on the “Destabilising effect of the LHC transverse damper” => Adding the effect of SC

\[
\begin{pmatrix}
F_{sc} x - \sqrt{1 + (F_{sc} x)^2} & -0.23 j x \\
-0.55 j x & -0.92 x + F_D
\end{pmatrix}
\]
“Short-bunch” regime without and with ReaD or SC

- Example from my IPAC18 paper on the “Destabilising effect of the LHC transverse damper” => Adding the effect of SC

\[
\begin{pmatrix}
F_{sc} x - \sqrt{1 + (F_{sc} x)^2} & -0.23 j x \\
-0.55 j x & -0.92 x + F_D
\end{pmatrix}
\]
“Long-bunch” regime with neither ReaD nor SC

- See also the previous IPAC18 paper (ReaD in red)

\[
f_r \tau_b = 0.8
\]

\[
f_r \tau_b = 2.8
\]
“Long-bunch” regime with neither ReaD nor SC

- A simple formula can be obtained by considering only the modes \( m \) and \( m + 1 \) overlapping the peak of the real part of the impedance (note that the eigenvectors / bunch modes are similar for the same radial mode number \( q = |m| + 2 k \))

\[
\begin{pmatrix}
Q - Q_y - m Q_s - \Delta Q_m \\
- \Delta Q_{m+1,m} \\
Q - Q_y - (m + 1) Q_s - \Delta Q_{m+1}
\end{pmatrix} = \begin{pmatrix}
0 \\
0 \\
0
\end{pmatrix}
\]
“Long-bunch” regime with neither ReaD nor SC

- **General solution**

\[
|Q_s + \Delta Q_{m+1} - \Delta Q_m| = 2 \left|\Delta Q_{m,m+1}\right|
\]

- **Approximate solution in our particular case**

\[
Q_s = 2 \left|\Delta Q_{m,m+1}\right|
\]

\[
=> N_b^{th} \propto |\eta| \varepsilon_l Q_y
\]
“Long-bunch” regime with ReaD

- As a ReaD modifies only the (main) mode 0 and not the others, it is expected to have no effect for the main mode-coupling
  => Confirmed by GALACTIC
  (ReaD in red)
“Long-bunch” regime with SC

- General solution

\[ |Q_s + \Delta Q_{m+1} - \Delta Q_m| = 2 |\Delta Q_{m,m+1}| \]

\[ \Rightarrow Q_s R_{SC} = 2 |\Delta Q_{m,m+1}| \]

\[ \Rightarrow N_b^{th} \propto |\eta| \varepsilon_l Q_y R_{SC} \]

\[ R_{SC} = \left[ \sqrt{q_{sc}^2 + (m + 1)^2} - \sqrt{q_{sc}^2 + m^2} \right] \]

Reduction factor from SC
“Long-bunch” regime with SC

- **General solution**
  \[ |Q_s + \Delta Q_{m+1} - \Delta Q_m| = 2 |\Delta Q_{m,m+1}| \]

  \[ \Rightarrow Q_s R_{SC} = 2 |\Delta Q_{m,m+1}| \]

  \[ \Rightarrow N_b^{th} \propto |\eta| \varepsilon_l Q_y R_{SC} \]

  \[ R_{SC} = \left[ \frac{1}{q_{sc}^2 + (m + 1)^2} - \frac{1}{q_{sc}^2 + m^2} \right] \]

Reduction factor from SC

\[ q = |m| + 2k \]
“Long-bunch” regime with SC

- **General solution**
  
  \[
  |Q_s + \Delta Q_{m+1} - \Delta Q_m| = 2 \left| \Delta Q_{m,m+1} \right|
  \]

  \[
  \Rightarrow Q_s R_{SC} = 2 \left| \Delta Q_{m,m+1} \right|
  \]

  \[
  \Rightarrow N_b^{th} \propto |\eta| \varepsilon_l Q_y R_{SC}
  \]

- **Reduction factor from SC**
  
  \[
  R_{SC} = \left[ \sqrt{q_{sc}^2 + (m + 1)^2} - \sqrt{q_{sc}^2 + m^2} \right]
  \]

- **Towards “Beam Break-Up” Instabilities…**
“Long-bunch” regime with SC

- **General solution**  
  \[ |Q_s + \Delta Q_{m+1} - \Delta Q_m| = 2 |\Delta Q_{m,m+1}| \]

  \[ \Rightarrow Q_s R_{SC} = 2 |\Delta Q_{m,m+1}| \]

  \[ \Rightarrow N_b^{th} \propto |\eta| \varepsilon_l Q_y R_{SC} \]

\[ R_{SC} = \left[ \sqrt{q_{sc}^2 + (m + 1)^2} - \sqrt{q_{sc}^2 + m^2} \right] \]

**Reduction factor from SC**

\[ q = |m| + 2k \]
Some simulations from A. Oeftiger with pyHEADTAIL (detailed analyses ongoing)
Some simulations from A. Oeftiger with pyHEADTAIL
(detailed analyses ongoing)

\[ Q'_{x,y} = 0, \quad R_{BBR} = 10 \text{ M}\Omega/m, \quad q_{26} = 27 \]

- no SC: original seed
- with SC: original seed
- with SC: diff. seed 1
- with SC: diff. seed 2

TMCI threshold without SC
Some simulations from A. Oeftiger with pyHEADTAIL (detailed analyses ongoing)

Q26 case @ 0.2e11 ppb

- $Q'_{x,y} = 0$, $R_{BBR} = 10 \text{ M}\Omega/m$, $q_{SC} = 27$
- no SC: original seed
- with SC: original seed
- with SC: diff. seed 1
- with SC: diff. seed 2

TMCI threshold without SC
Some simulations from A. Oeftiger with pyHEADTAIL (detailed analyses ongoing)

Q26 case @ 0.2e11 ppb

Without SC => STABLE

TMCI threshold without SC
Some simulations from A. Oeftiger with pyHEADTAIL (detailed analyses ongoing)

Q26 case @ 0.2e11 ppb

Without SC => STABLE

With SC => UNSTABLE

TMCI threshold without SC
Some simulations from A. Oeftiger with pyHEADTAIL (detailed analyses ongoing)

Q26 case @ 0.2e11 ppb

Without SC => STABLE

With SC => UNSTABLE

=> Instability with SC still to be fully characterized… + Understand why ~ no-SC intensity threshold seems to be observed in SPS (effect of nonlinearities, etc.)…

TMCI threshold without SC