FUTURE CIRCULAR COLLIDER

FCCee High Energy Booster

Updates on collective effects studies

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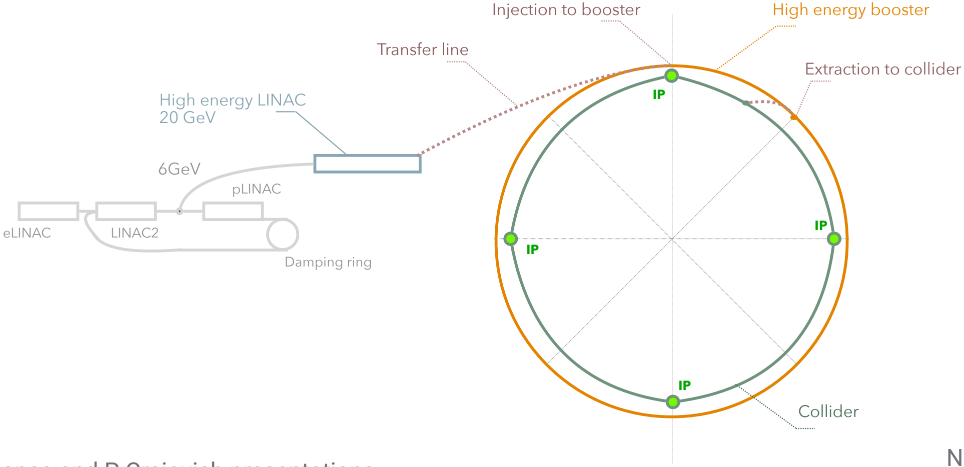
Outline

Context

Introduction

PA31.3 baseline Layout (2024)

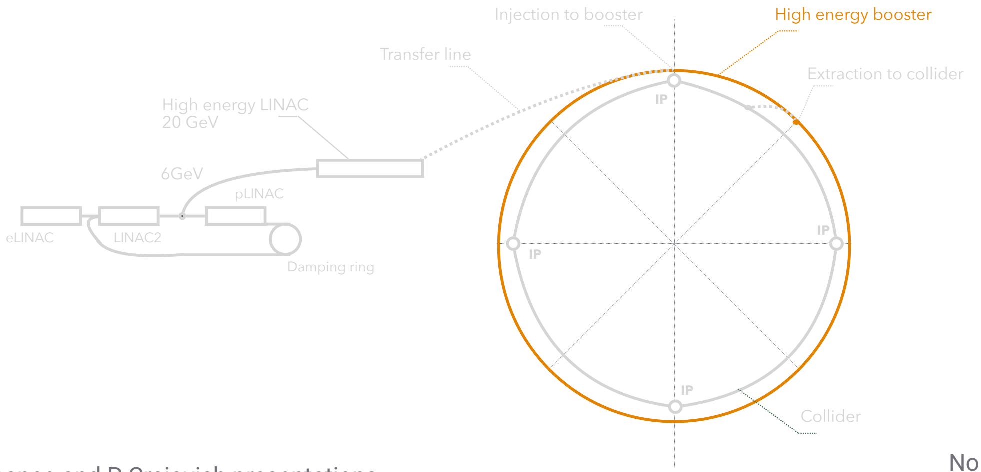


No to scale

See A Chance and P Craiovich presentations

Introduction

PA31.3 baseline Layout (2024)



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See A Chance and P Craiovich presentations

Purpose

- Investigate collective effects instabilities in the booster ;
  → See previous booster collective effects studies[1].
- Perform parametric analysis ;
- Investigate mitigation strategies if needed ;
- Give feedback to appropriate working groups : collider, RF, vacuum, costing, . . .

[1] FCCIS WP2 Workshop (2023) ; Booster parameters workshop (2024)

Baseline

Assumptions

- Only resistive wall effects taken into account (round vacuum pipe);
- Baseline PA31 optics including booster updates [a] ;
- Longitudinal impedance and wake potential of a 0.4 mm Gaussian bunch used as Green function in beam dynamics simulations ;
- Studies of instabilities at injection energy.

[a] see A Chance prsentation

Usage

→ to source codes and in-puts/outputs ;

→ access to corresponding wiki entry.

Baseline

Evolution of the booster parameters table

Now with a versioning on CERN gitlab

Modes		z	w	h	$t\bar{t}$	
Ψ	[deg]	(60) → 90		90		phase advance
$I5$	$[10^{-11}]$	(5.21) → 1.70		(1.79) → 1.70		5th synchrotron integral
α_c	$[10^{-6}]$	(14.9) → 7.12		(7.34) → 7.12		Momentum compaction
$\delta_{p_{inj}}$	[%]	(1.63) → 3		(3.63) → 3		Momentum acceptance @ injection
$\delta_{p_{ext}}$	[%]	(old) → 1		(old) → 2		Momentum acceptance @ extraction
$Q_{x/y}$	[.225/.29]	(278/277) → 414/410		(415/416) → 414/410		Horizontal tune
C	[km]	(91.174) → 90.658				Circumference
ν	[MHz]	800				RF frequency
R_p	[mm]	(25/SS) → 30/Cu				Beam pipe radius

Notes. (old) → new/unchanged

https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb

Baseline

Evolution of the booster parameters table

Important for collective instabilities mitigation

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Baseline

Evolution of the injection parameters

Modes		z	w	h	$t\bar{t}$	
E	[GeV]	20				Injection energy
$\varepsilon_{nx,y}$	$[\mu\mathrm{m}]$	10x10				Normnalised transverse emittance
$\sigma_z(1)$	$[\mathrm{mm}]$	1				Bunch length without energy compressor
$\sigma_z(2)$	$[\mathrm{mm}]$	4				Bunch length with an energy compressor
$\sigma_e(1)$	[%]	0.75				Energy disperion without energy compressor
$\sigma_e(2)$	[%]	0.05				Energy disperion with an energy compressor
$N_{p,max/bunch}$	$[10^{10}]$	2.5		(2.5) $\rightarrow$ 1		Maximum number of particules per bunch
N_b	$[10^{10}]$	(11200) $\rightarrow$ 1120	(1780) $\rightarrow$ 890	380	56	Number of bunches/booster

Notes. (old) $\rightarrow$ new/unchanged

https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb

Baseline

Evolution of the injection parameters

To be validated

Modes		z	w	h	$t\bar{t}$	
E	[GeV]	20				Injection energy
$\varepsilon_{nx,y}$	[μm]	10x10				Normnalised transverse emittance
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Coupled bunch instabilities

TCBI

Assumptions

- Transverse resistive-wall wake-field acts in long distances
  - $\rightarrow$ Could lead to transverse coupled bunch instabilities ;
  - $\rightarrow$ Can be destructive for the beam.

Assumptions

- Equally spaced gaussian bunches in the ring ;
- Only coherent bunch modes ;
- Parameters considered at injection energy ($E = 20\,\mathrm{GeV}$) and worst case scenario consideration : 2023$\rightarrow z$ | 2024$\rightarrow t\bar{t}$;
- Analytical growth rate calculation ;
- Only the most prominent radial mode in the longitudinal azimuthal mode.

TCBI

Critical parameters

Number of bunches
Bunch population
Transverse impedance
Momentum compaction

$$\frac{1}{\tau_\perp} \sim \frac{N_p \cdot N_b}{4\pi \cdot Q \cdot E} \cdot \Re(Z_\perp) \cdot \mathcal{G}(Q, \sigma_z, \alpha_c)$$

Bunch length
Energy
Transverse growth
Tune

Transverse growth rate depends on several critical parameters that are different in the 2023 baseline and the 2024 baseline.

Chao et al. (2023)

TCBI

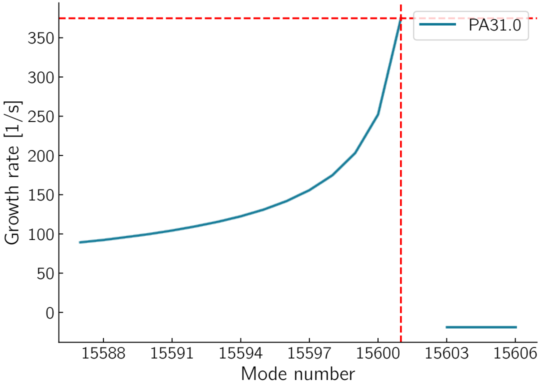
Previous baseline (2023)

- Most unstable mode : 15601 ;
- Rise time : 0.00266 s ;
- growth rate : 374.84 1/s ;

→ 8.77 turns ;

⚠ Faster than SR damping time (30 000 turns) ;

⇒ We need a feedback system.



Growth rate as a function of the mode number for the PA31.0 baseline (2023), z operation, E =20 GeV, σ_z =4 mm, N_b = 15880, Cu beam pipe (R =25 mm).

TCBI

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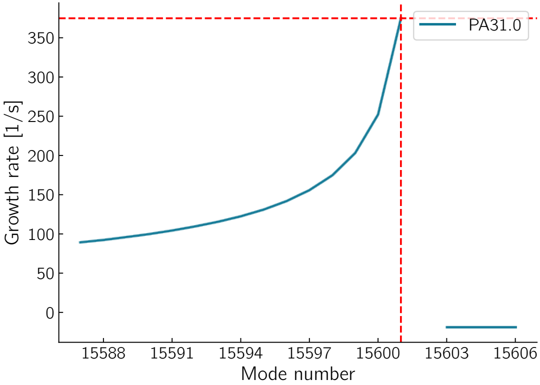


Growth rate as a function of the mode number for the PA31.0 baseline (2023), z operation, $E = 20\,\mathrm{GeV}$, $\sigma_z = 4\,\mathrm{mm}$, $N_b = 15880$, Cu beam pipe ($R = 25\,\mathrm{mm}$).

TCBI

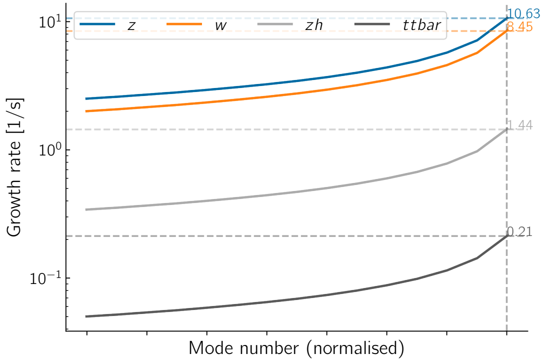
New baseline (2024)

- Rise times : from 0.09 to 4.7 s ;
- growth rates : from 0.21 to 10 1/s ;

→ from 310 to 15547 turns ;

⚠ Still faster than SR damping time.

⇒ We still need a feedback system but it is now less challenging.



Growth rate as a function of the mode number (normalised) for the PA31.3 baseline (2024), $N_p = 1 \rightarrow 2.5 \times 10^{10}$, $N_b = 56 \rightarrow 1120$, Cu beam pipe ($R = 30\,\mathrm{mm}$).

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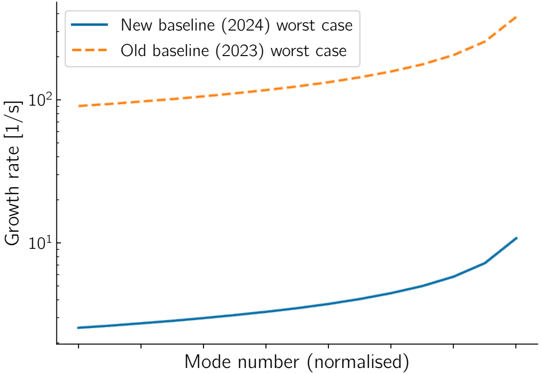

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TCBI

Takeaway on coupled bunch instabilities

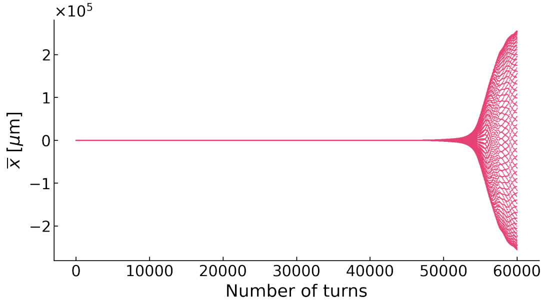
- Coupled bunch instabilities are present ;
  - → We need a feedback system to suppress them ;
  - → The new booster baseline design relaxes the constraints on the needed feedback system ;
  - → However, such feedback system has an effect on single bunch motion and would need a specific investigation.

Single bunch instabilities

TMCI and MI

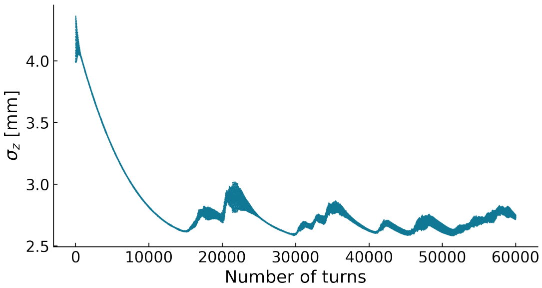
Previous baseline (2023) - $E = 20\,\mathrm{GeV}$; z *operation* ; *Cu pipe* ($R = 25\,\mathrm{mm}$)

Transverse Coupled Mode Instabilities



Transverse blow-up

Microwave Instabilities



Longitudinal instabilities

wiki

TMCI and MI

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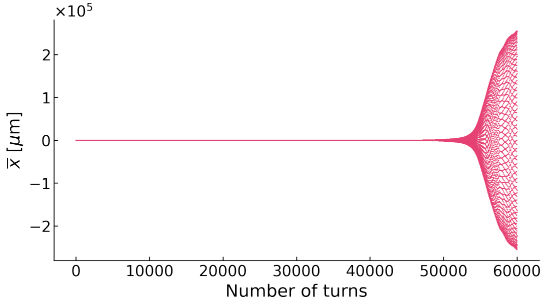

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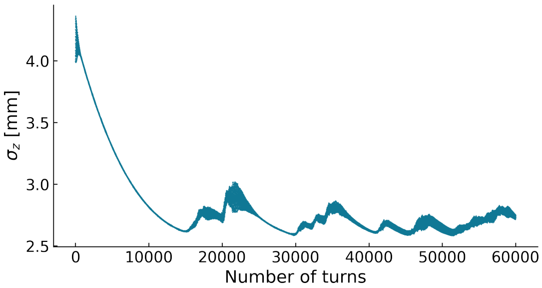

Longitudinal instabilities

wiki

TMCI and MI

Mitigation strategies

Transverse Coupled Mode Instabilities

$$N_{p,th}^{TMCI} = \frac{Q_{x,y} \cdot Q_s \cdot E \cdot \sigma_z}{\Im Z_\perp} \quad (1)$$

Microwave Instabilities

$$N_{p,th}^{MI} \propto \frac{n \cdot \alpha_c \cdot E \cdot \sigma_e \cdot \sigma_z}{\left| Z_\parallel \right|} \quad (2)$$

- Increase energy → injection
- Decrease impedance → geometry, material, ...

- Increase longitudinal emittance (ie. σ_e, σ_z) → wigglers
- Increase momentum compaction → lattice

Chao et al. (2023)

TMCI and MI

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TMCI and MI

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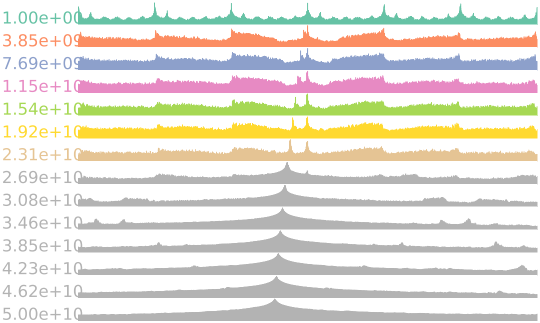
Chao et al. (2023)

TMCI

Parametric investigations - Previous baseline (2023)

1. We represent the momenta in the Fourier space to visualise the coupling mode instabilities
2. ... and we explore different parameters :
   - → Bunch population
   - → Momentum compaction factor
   - → Beam pipe material
   - → Beam pipe radius



Y momenta specta as a function of the bunch population variation at injection energy ($E = 20\,\mathrm{GeV}$) for PA31.0 baseline (2023), z operation and with a Cu beam pipe ($R = 25\,\mathrm{mm}$).

TMCI

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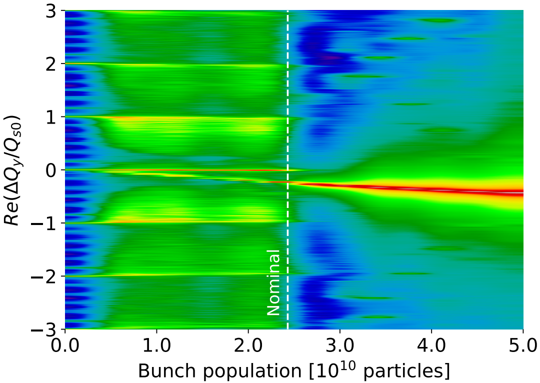

Modes scan as a function of the bunch population at injection energy ($E = 20\,\mathrm{GeV}$) for PA31.0 baseline (2023), z operation and with a Cu beam pipe ($R = 25\,\mathrm{mm}$).

TMCI

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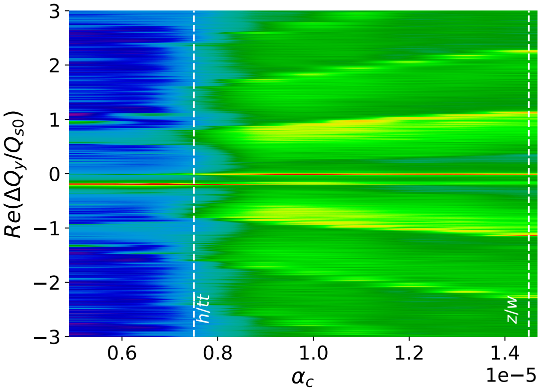

Modes scan as a function of the momentum compaction factor at injection energy ($E = 20\,\mathrm{GeV}$ for PA31.0 baseline (2023), z operation and with a Cu beam pipe ($R = 25\,\mathrm{mm}$).

TMCI

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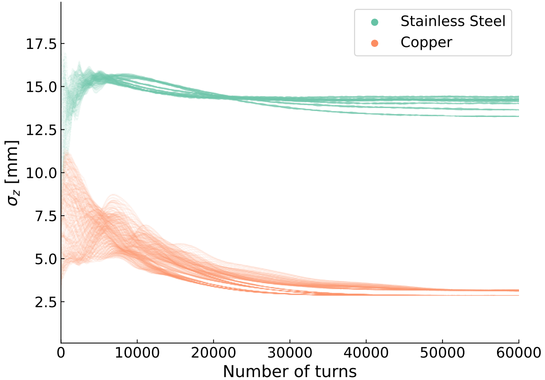

Bunch length evolution for a copper and stainless steel pipe at injection energy ($E = 20\,\mathrm{GeV}$) for PA31.0 baseline (2023), z operation and with a beam pipe of $R = 25\,\mathrm{mm}$.

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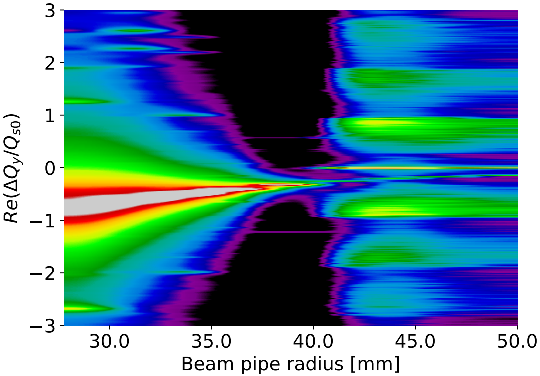

Modes scan as a function of beam pipe radius at injection energy ($E = 20\,\mathrm{GeV}$) for PA31.0 baseline (2023), z operation and with a Stainless steel.

TMCI

Parametric investigations - Previous baseline (2023)

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2. ... and we explore different parameters :
   - → Bunch population
   - → Momentum compaction factor
   - → Beam pipe material
   - → Beam pipe radius

$\Rightarrow$ We need to find a compromise between beam-pipe material, beam-pipe radius, bunch population, momentum compaction, ...

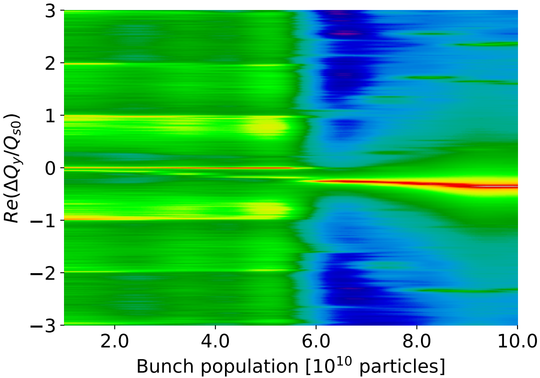
TMCI

New baseline (2024) - No margin - No transverse damper

Now, if we update the booster parameters table with :

- Decreased momentum compaction
- Increased beam pipe diameter
- Beam pipe material set to copper

$\Rightarrow$ TMCI threshold is more than doubled !



Modes scan as a function of bunch population at injection energy ($E = 20\,\mathrm{GeV}$) for the PA31.3 baseline (2024), $t\bar{t}$ operation and a $30\,\mathrm{mm}$ radius copper beam pipe.

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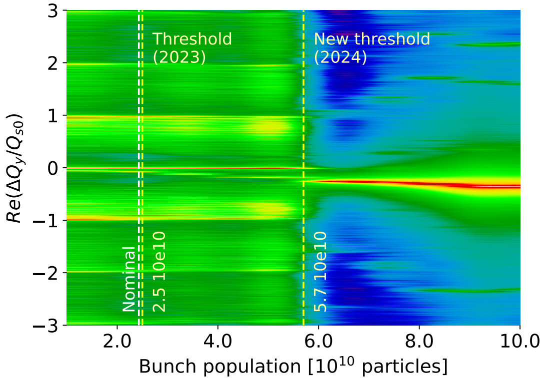


Modes scan as a function of bunch population at injection energy ($E = 20\,\mathrm{GeV}$) for the PA31.3 baseline (2024), $t\bar{t}$ operation and a $30\,\mathrm{mm}$ radius copper beam pipe.

TMCI

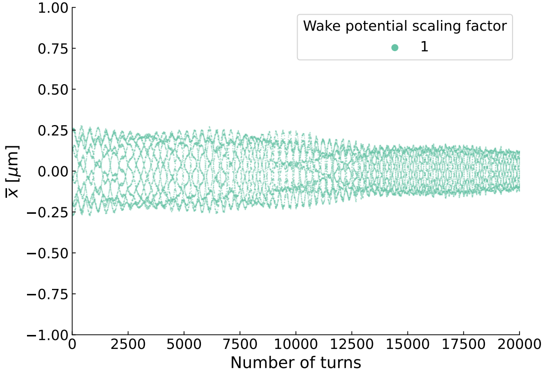
New baseline (2024) - Impedance margin - No transverse damper

Only resistive wall is taken into account here ;

If we double the wake potential contribution ;

→ We are back to critical threshold.

⇒ We need a complete impedance budget.



Mean transverse motion with and without scaling the wake potential at injection energy ($E = 20\,\mathrm{GeV}$) for the PA31.3 baseline (2024), $t\bar{t}$ operation and a $30\,\mathrm{mm}$ radius copper beam pipe.

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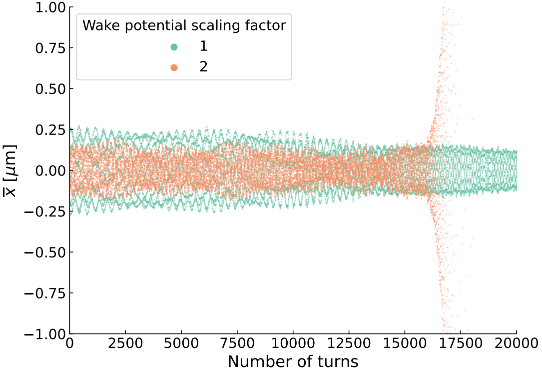

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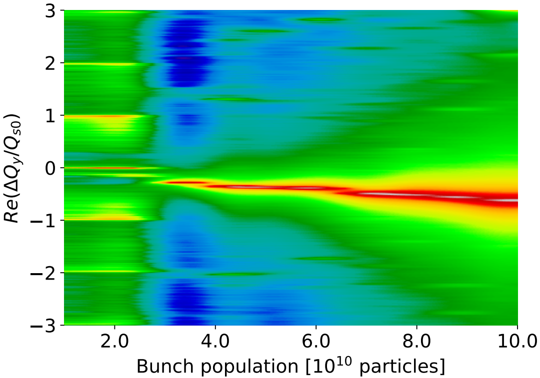

Modes scan as a function of bunch population for the PA31.3 baseline (2024), $t\bar{t}$ operation and with a doubled wake-field contribution.

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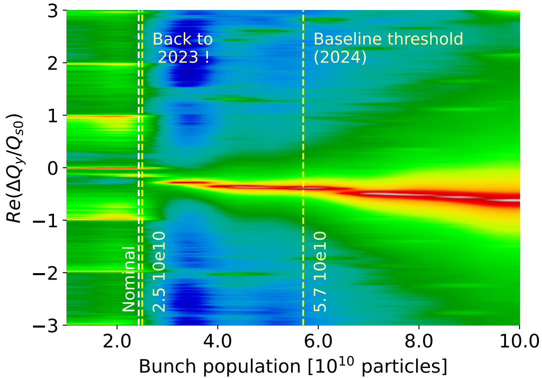

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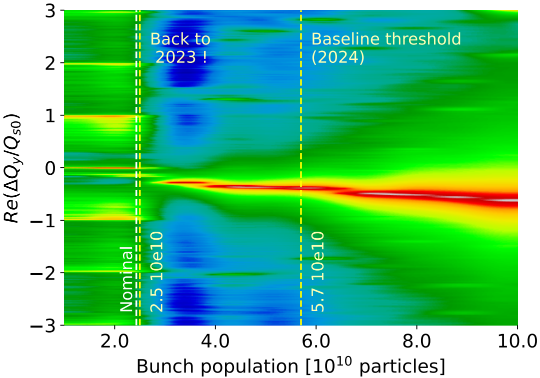


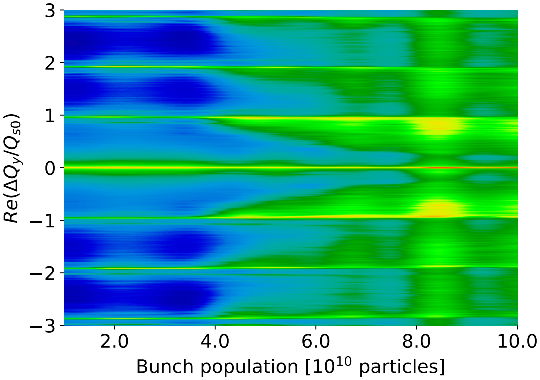
Modes scan as a function of bunch population for the PA31.3 baseline (2024), $t\bar{t}$ operation and with a doubled wake-field contribution.

TMCI

New baseline (2024) - Transverse damper

- Including a 310 turns transverse damper
  - → No ITSR instabilities[a] visible ;
  - → Threshold pushed to 15×10^{10} particles per bunch ;
  - → Does help to reduce the required impedance margin.

[a] Imaginary tune split and repulsion - Métral (2021)



Modes scan as a function of the bunch population at injection for the PA31.3 baseline (2024) including a 310

TMCI

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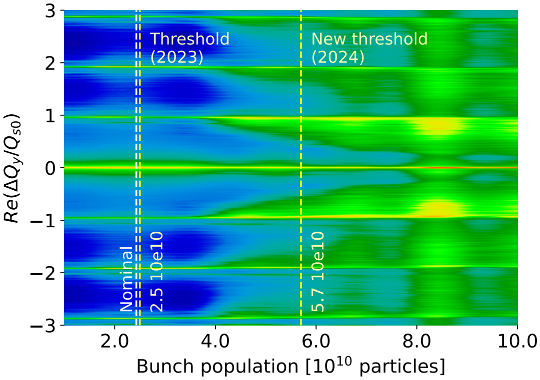

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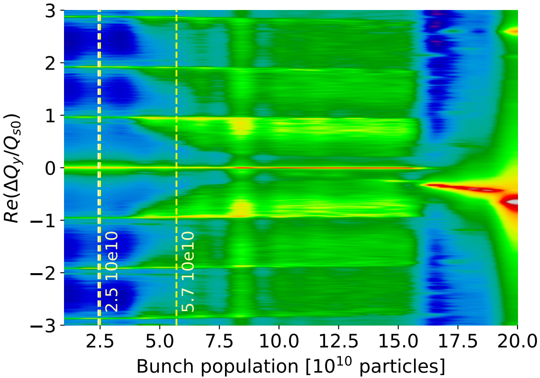


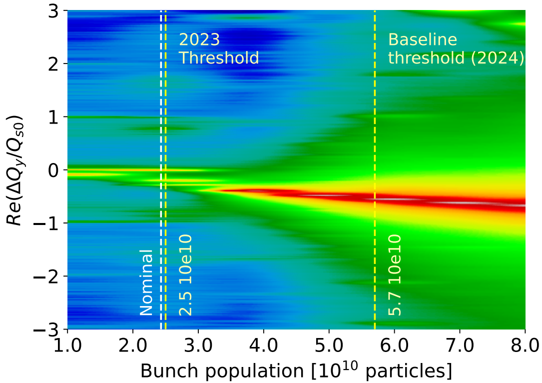
Modes scan as a function of the bunch population at injection for the PA31.3 baseline (2024) including a 310 turns transverse damper.

[a] Imaginary tune split and repulsion - Métral (2021)

TMCI

New baseline (2024) - Transverse damper

- Including a 310 turns transverse damper
  - → No ITSR instabilities[a] visible ;
  - → Threshold pushed to 15×10^{10} particles per bunch ;
  - → Does help to reduce the required impedance margin.



Modes scan as a function of the bunch population at injection for the PA31.3 baseline (2024) including a 310 turns transverse damper.

[a] Imaginary tune split and repulsion - Métral (2021)

TMCI

Takeaway on single bunch instabilities

- [x] A compromise has been found to mitigate TMCI with one optics configuration for all operation modes ;
- [x] A 300 turns damper improves the bunch population (or impedance margin) further ;
- [ ] However, a complete impedance budget is needed to estimate our real margin.

Beam parameters at injection

Beam parameters at injection

Purpose and assumptions

- Previous studies have shown a robust design with respect to various injection parameters $(\sigma_e, \sigma_z, \varepsilon_{x,y})$;
- Now, with an updated design :
  - → Do we need an energy compressor ?
  - → What can we accept as longitudinal injection parameters ?
  - → What is our tolerance to a transverse jitter ?

Assumptions

- Injection from the LINAC at $E = 20\,\mathrm{GeV}$;
- A round beam with $\varepsilon_{n,xy} = 10\,\mu\mathrm{m}$;
- 2.5×10^{10} particles per bunch ;
- Updated booster design and $t\bar{t}$ configuation.

Longitudinal mismatch

New baseline (2024)

- Without an energy compressor

  → Parameters @injection

  $\sigma_z = 1\,\mathrm{mm}$; $\sigma_e = 0.75\,\%$

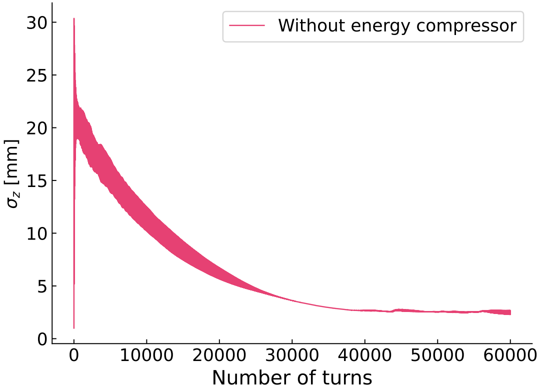
  ⚠ Important longitudinal mismatch

- With an energy compressor

  → Parameters @injecton

  $\sigma_z = 4\,\mathrm{mm}$; $\sigma_e = 0.05\,\%$

  ✓ Longitudinal motion restored to acceptable levels.



Evolution of the bunch length as a function of the number of turns for the PA31.3 (2024) baseline configuration with $\varepsilon_{nxy} = 10\,\mu\mathrm{m}$ and at $t\bar{t}$ operation.

Longitudinal mismatch

New baseline (2024)

- Without an energy compressor
  - → Parameters @injection
    $\sigma_z = 1\,\mathrm{mm}$; $\sigma_e = 0.75\,\%$
  - ⚠ Important longitudinal mismatch
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  - → Parameters @injecton
    $\sigma_z = 4\,\mathrm{mm}$; $\sigma_e = 0.05\,\%$
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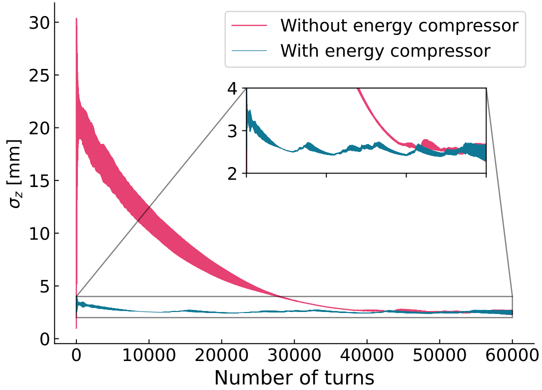


Evolution of the bunch length as a function of the number of turns for the PA31.3 (2024) baseline configuration with $\varepsilon_{nxy} = 10\,\mu\mathrm{m}$ and at $t\bar{t}$ operation.

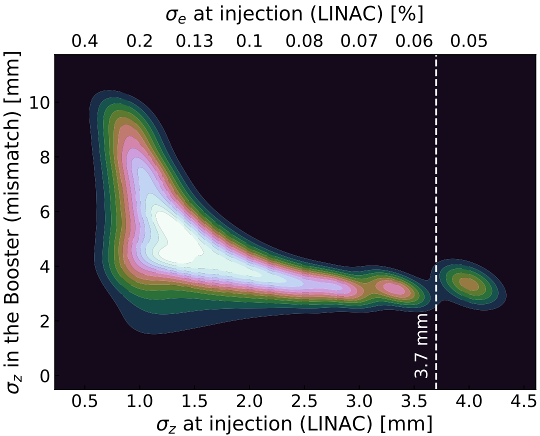
Longitudinal mismatch

New baseline (2024)

- If we keep the longitudinal emittance constant and we vary σ_z | σ_e

  $\rightarrow$ optimal values

  $\sigma_z = 3.7\,\mathrm{mm}$; $\sigma_e = 0.054\,\%$

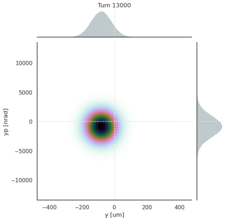


Longitudinal mismatch during the first 300 turns as a function of the injection bunch length and energy dispersion

Transverse jitter at injection

New baseline (2024)

- We introduce a transverse jitter of up to 1 σ at injection ;
- No significant effect after 30,000 turns ;
- However, amplitude detuning has not been considered here.



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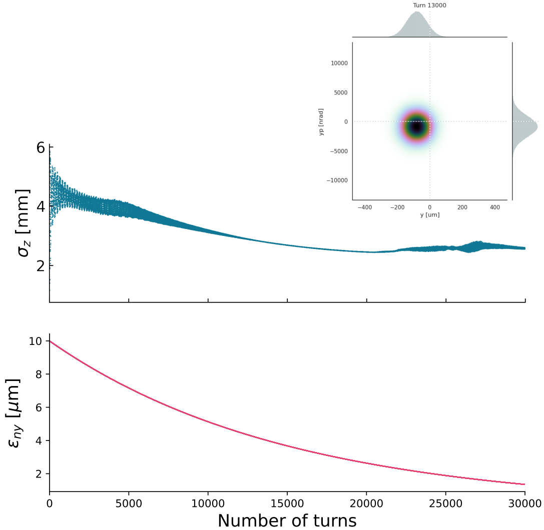

Evolution of the bunch length and vertical normalized emittance with a 1 σ transverse jitter at injection.

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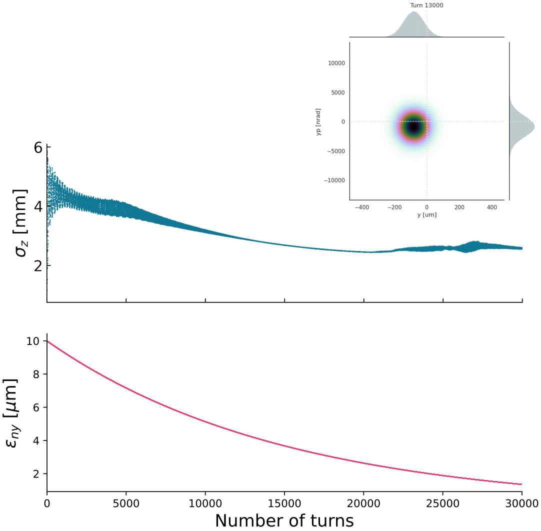

Evolution of the bunch length and vertical normalized emittance with a 1 σ transverse jitter at injection.

Takeaway on injection parameters from the LINAC

- [x] Booster design is still robust to different injection parameters ;
- [x] An energy compressor is needed ;
- [ ] Transverse jitter needs further investigations with amplitude detuning taken into account.

Summary

Summary

We have a new realistic baseline design that :

- ☑ mitigates single bunch instabilities ;
- ☑ is compatible with a 310 turns transverse damper ;
- ☑ is robust to various injection parameters.

But there is still a lot to do :

- A complete and realistic impedance budget ;
- A more realistic transverse jitter study ;
- IBS, synchrotron radiation and wake-field interplay with respect to the chosen cycling strategy.

Miscellaneous

- All data available on CERN project eos storage space `/eos/project-f/fcc-ee-ce`;
- Simulations made on PyHEADTAIL (mostly) and XSuite (coming) ;
- Codes available on CERN gitlab ;
- Impedance budget space (common to booster and collider) on CERN gitlab ;
- Other information available on the collective effects studies wiki ;
- Calculations made on several computing clusters : LXPLUS (CERN), FEYNMAN (CEA), now with dedicated computing resources on Jean-Zay (IDRIS) and CC IN2P3 ;
- Dedicated chat spaces for the high energy booster and the collective effects studies on mattermost.

Thank you !

Questions

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