Transverse beam instabilities in the SOLEIL II booster

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Outline

Introduction

- Design of the SOLEIL II booster → Previous talk of P. Schreiber
- Why study collective effects in the new booster

Booster model

- Ramp model
- Case study from the present booster
- SOLEIL II booster model
- SOLEIL II impedance model

Energy-dependent collective effects study

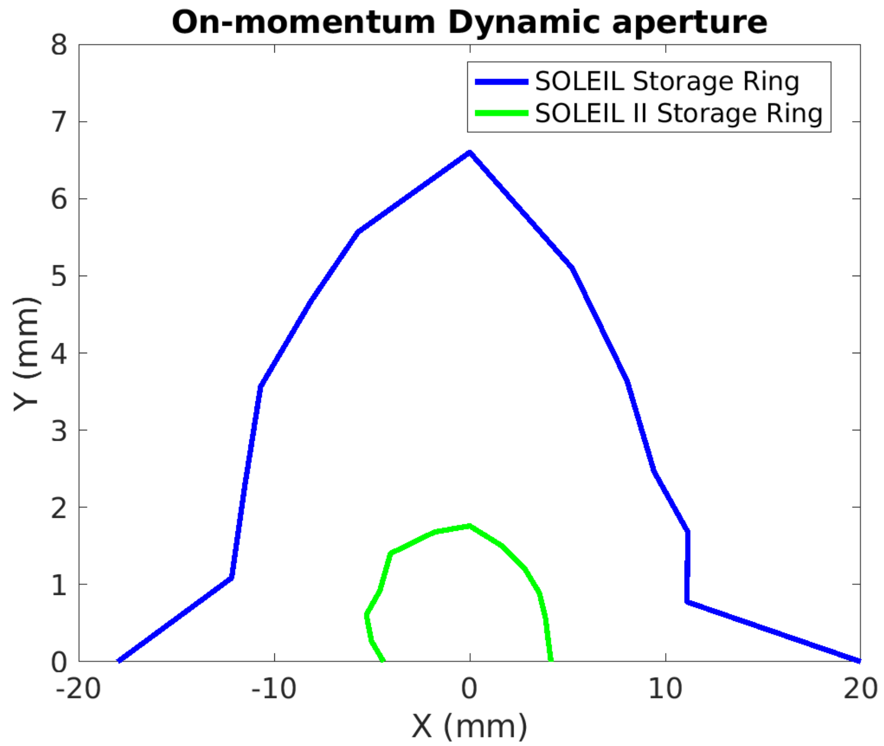
- Transverse Single-Bunch Instabilities (TSBI)
- Transverse Coupled-Bunch Instability (TCBI)

Conclusion and outlook

Introduction

Why study collective effects in the new booster

- The new **7BA-4BA lattice** of the SOLEIL II storage ring results in a much smaller **dynamic aperture (DA)** compared to the present ring.
- The **booster which serves as an injector** to the SR also needs an upgrade to produce low emittance beam to be injected into the new DA.
- The lattice design has evolved from simple **FODO** cells to **16BA** lattice with **stronger dipole** field, **quadrupole** and **sextupole** gradients.


On-momentum Dynamic aperture

Present booster

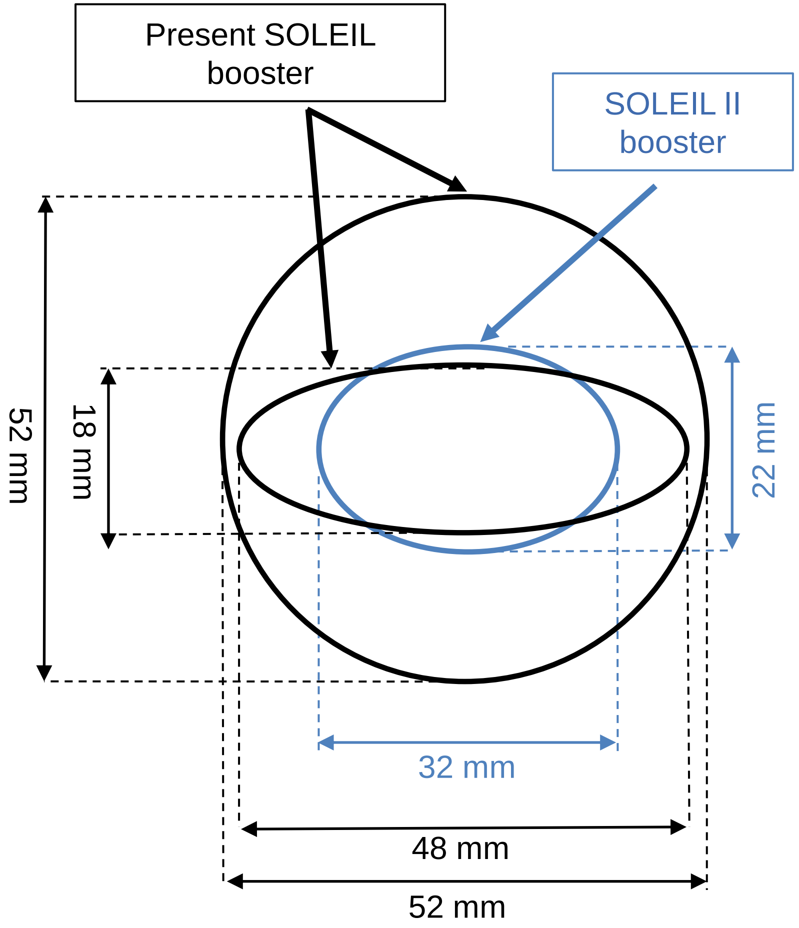
SOLEIL II booster

Emittance at extraction

140 nm rad → 5.2 nm rad → 27 times smaller

Close to the natural emittance of the present storage ring (3.9 nm rad)

Why study collective effects in the new booster



Standard vacuum chamber sizes (to scale)

- To allow for the stronger magnets, the average **vaccum chamber dimension** will be **reduced**.
- This immediately raised concern over the impedance, especially the **resistive-wall (RW)** type since

$$\boxed{\boldsymbol{\tau_{RW} \propto b^3}}$$

RW instability (RWI) growth time

Vaccum chamber radius

Why study collective effects in the new booster

- To asses the importance of the resistive-wall instability (RWI), we calculated its growth time at the injection enegy and compared it to the synchrotron radiation damping time.

RWI growth time [1] :

$$\tau_{\mathrm{RW}}^{\xi=0} = \frac{4\pi E_0/e}{\beta_0\omega_0 I}\frac{b^3}{R}\left[\frac{\left(1-\Delta Q_\beta\right)\omega_0}{2cZ_0\rho_r}\right]^{1/2} \quad (1)$$

$$\boxed{\tau_{\mathrm{RW}} \propto E_0 b^3}$$

Synchrotron radiation damping time :

$$\tau_{\mathrm{rad}} = \frac{2}{j}\frac{E_0}{U_0}T_0 \quad (2)$$

$$\boxed{\tau_{\mathrm{rad}} \propto E_0^{-3}}$$

Stable beam when $\tau_{\mathrm{RW}} > \tau_{\mathrm{rad}}$

Where E_0 is beam energy

Parameter	Estimated value	Stability condition	Condition satisfied
τ_{RW}	1.4 ms	> 142 ms (beam passage time)	✗
τ_{rad}	31 s	< 1.4 ms (τ_{RW})	✗
Threshold current	0.6 μA	> 6 mA (nominal current)	✗

Obtained by substituting $\tau_{\mathrm{RW}} = \tau_{\mathrm{rad}}$ in Eq. (1) → Threshold current

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[1] R. Nagaoka and K. L. F. Bane, J Synchrotron Rad **21**, 937–960 (2014), https://doi.org/10.1107/S1600577514015215

Why study collective effects in the new booster

Then, a simple exponential model was used to calculate the oscillation amplitude of a particle with energy ramp to take into account the energy dependence of τ_{RW} and τ_{rad}

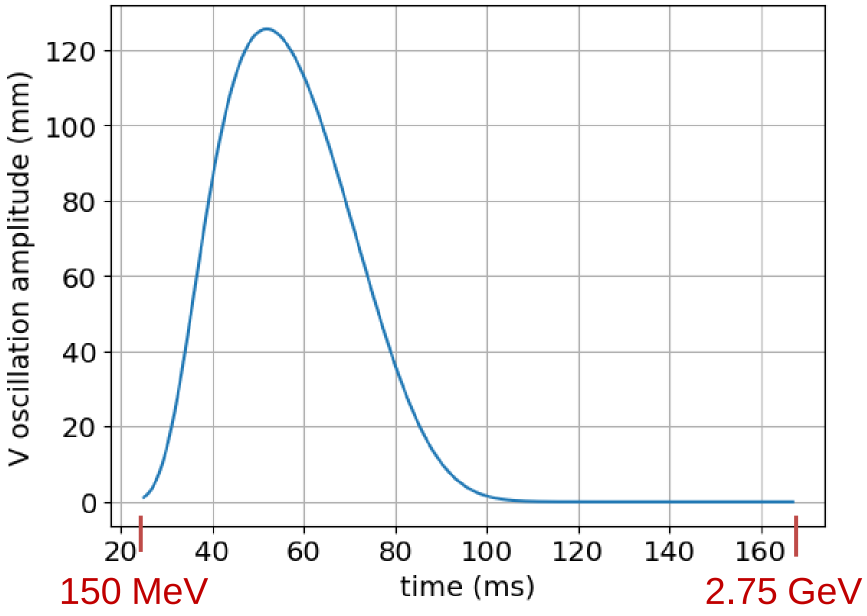
$$y(t) = y_0 e^{t/\tau(t)}$$

where $$\tau(t) = \frac{\tau_{\mathrm{rad}}\tau_{\mathrm{RW}}}{\tau_{\mathrm{rad}}-\tau_{\mathrm{RW}}} \begin{cases} < 0\ ; \mathrm{damping} \\ > 0\ ; \mathrm{exciting} \end{cases}$$

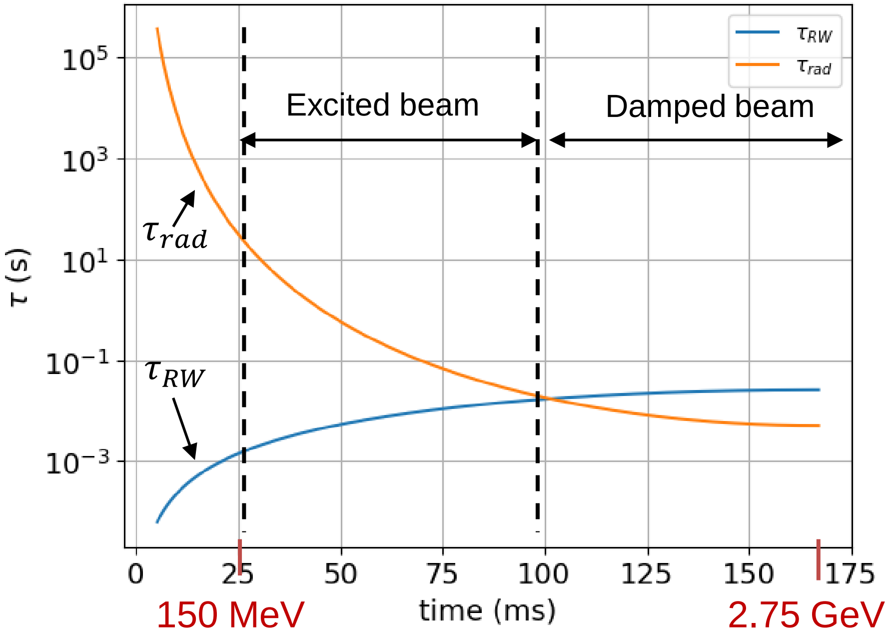
It was found that the particle oscillation amplitude exhibited a large inflation along the ramp due to a competition between τ_{RW} and τ_{rad}.

This worrying result had brought us to a more sophisticated model by doing particle tracking simulation with energy ramp.

Particle vertical oscillation amplitude along the SOLEIL II booster ramp



Analytical RWI growth time and SR damping time along the ramp



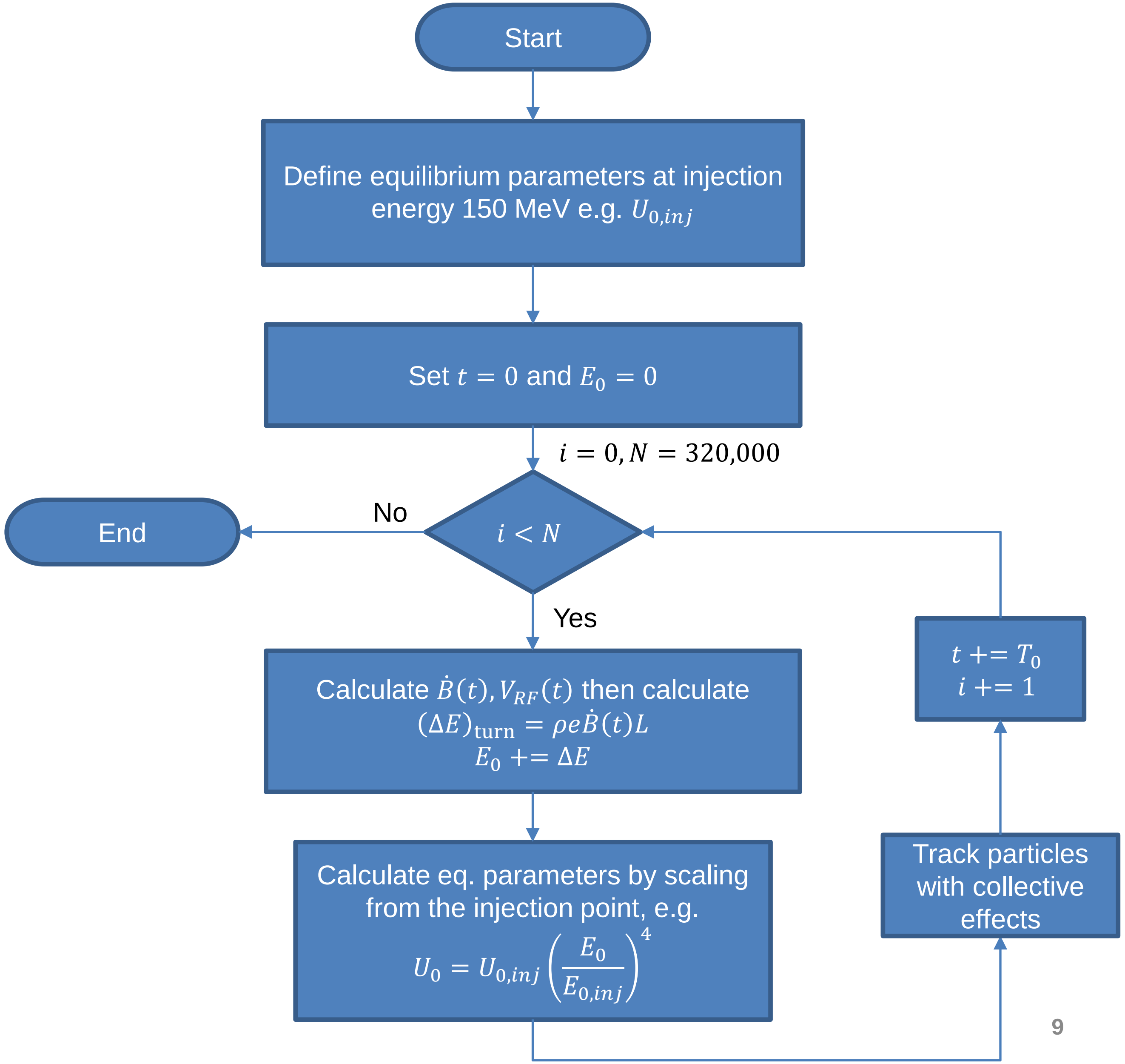
Booster model

Ramp model

Equilibrium parameters variation along the ramp

As shown previously that beam energy plays a significant role in estimating the beam instability since $\boldsymbol{\tau_{\mathrm{RW}}} \propto \boldsymbol{E_0}$ and $\boldsymbol{\tau_{\mathrm{rad}}} \propto \boldsymbol{E_0^{-3}}$, it is important to vary beam energy while doing particle tracking

– Energy gain per turn	$(\Delta E)_{turn} = \rho e \dot{B} L$
– Energy loss per turn	$U_0 \propto E_0^4$
– Synchronous phase	$\phi_s = \arccos\left(\frac{(\Delta E)_{turn} + U_0}{V_{RF}}\right)$
– Radiation damping time	$\tau_{\mathrm{rad}} \propto 1/E_0^3$
– Natural energy spread	$\sigma_\delta \propto E_0$
– Natural emittance	$\varepsilon_0 \propto E_0^2$



Start

Define equilibrium parameters at injection energy 150 MeV e.g. $U_{0,inj}$

Set $t = 0$ and $E_0 = 0$

$i = 0, N = 320{,}000$

$i < N$

No

End

Yes

Calculate $\dot{B}(t), V_{RF}(t)$ then calculate
$(\Delta E)_{\mathrm{turn}} = \rho e \dot{B}(t) L$
$E_0 \mathrel{+}= \Delta E$

Calculate eq. parameters by scaling from the injection point, e.g.

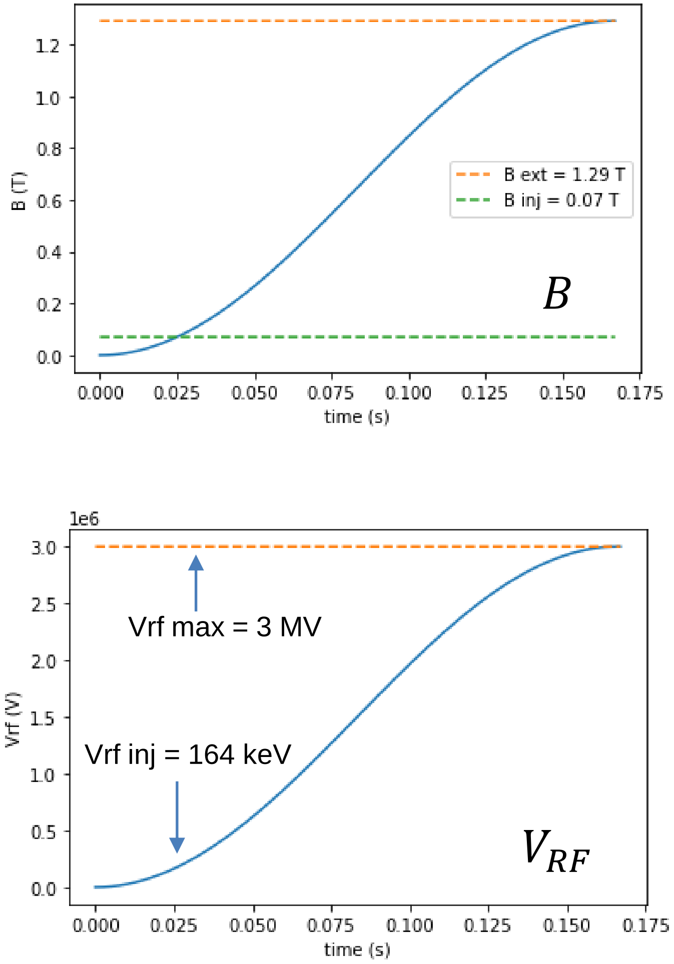
$$U_0 = U_{0,inj}\left(\frac{E_0}{E_{0,inj}}\right)^4$$

Track particles with collective effects

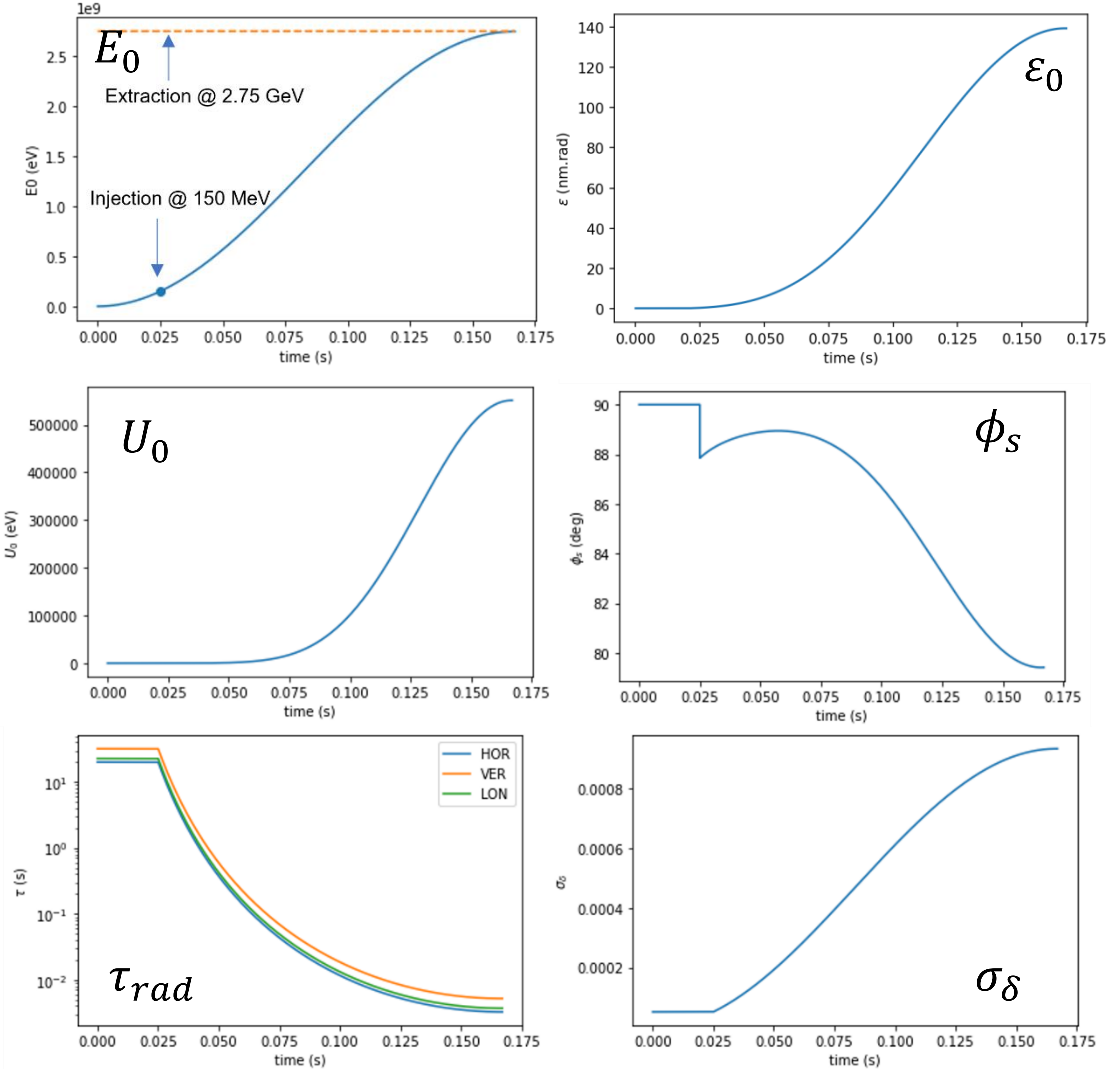
$t \mathrel{+}= T_0$
$i \mathrel{+}= 1$

Ramp model

Dipole field and RF voltage ramp in SOLEIL II booster



Equilibrium parameters along the ramp in SOLEIL II booster



What else do I need to correctly model the booster?

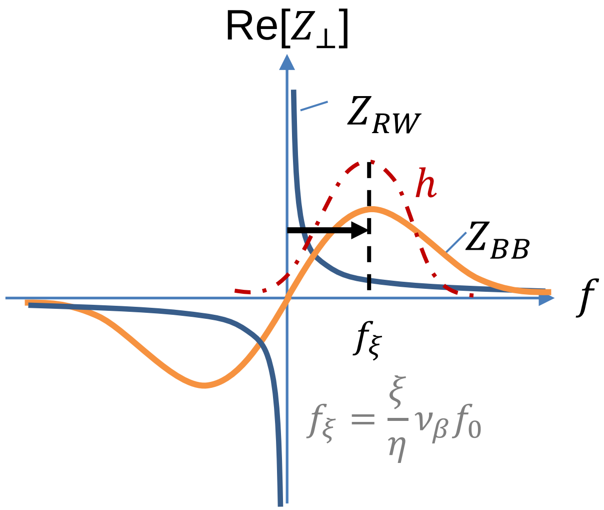
Case of the present booster

Present booster model

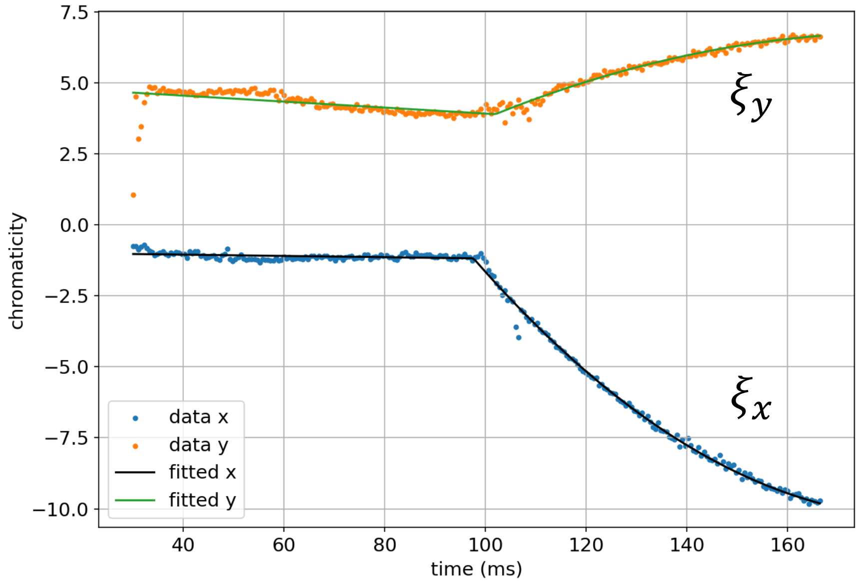
1. Chromaticity

Positive chromaticity can:

- Induce ‘**head-tail damping**’ which is favorable for coupled-bunch instabilities.
- Decrease head-tail instability growth rate



Measured chromaticity along the ramp



2. Amplitude-Dependent Tune Shift (ADTS)

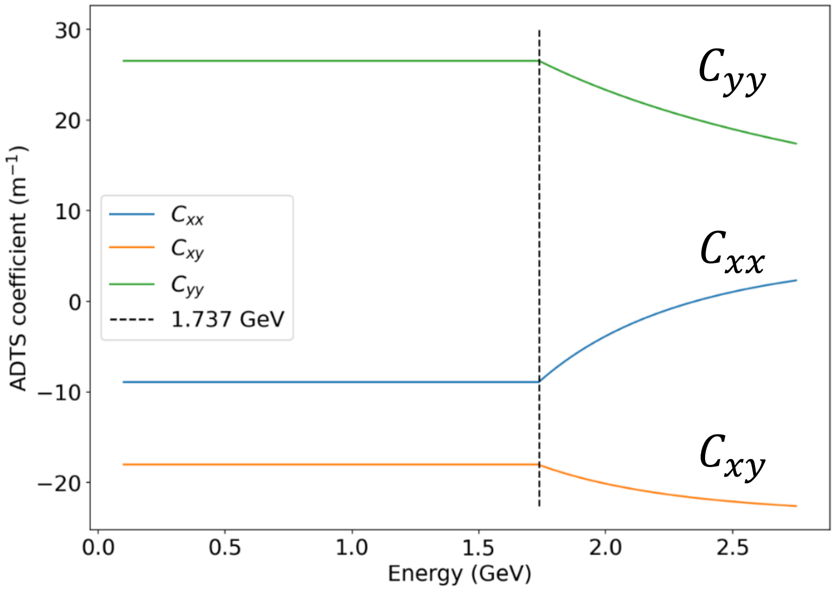
ADTS can prevent instabilities to build up since it induces incoherent tune spread in the beam which breaks the coherent behavior of the particles.

2

2^{nd} order ADTS equation :

$$\begin{pmatrix}\Delta\nu_x\\ \Delta\nu_y\end{pmatrix} = \underbrace{\begin{pmatrix}C_{xx} & C_{xy}\\ C_{yx} & C_{yy}\end{pmatrix}}_{\text{ADTS coefficients}} \underset{\substack{\downarrow\\ \text{Particle amplitude or Courant-Snyder (CS) invariant}}}{\begin{pmatrix}J_x\\ J_y\end{pmatrix}}$$

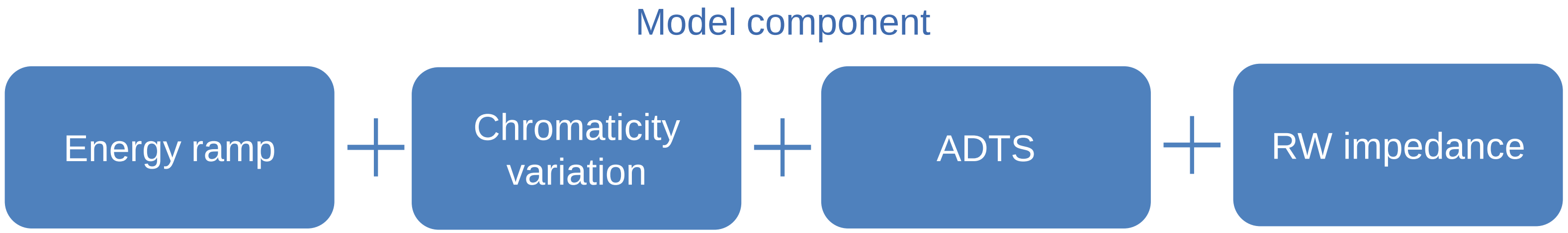
ADTS coefficients along the ramp obtained from AT code



Present booster model

TCBI simulation results

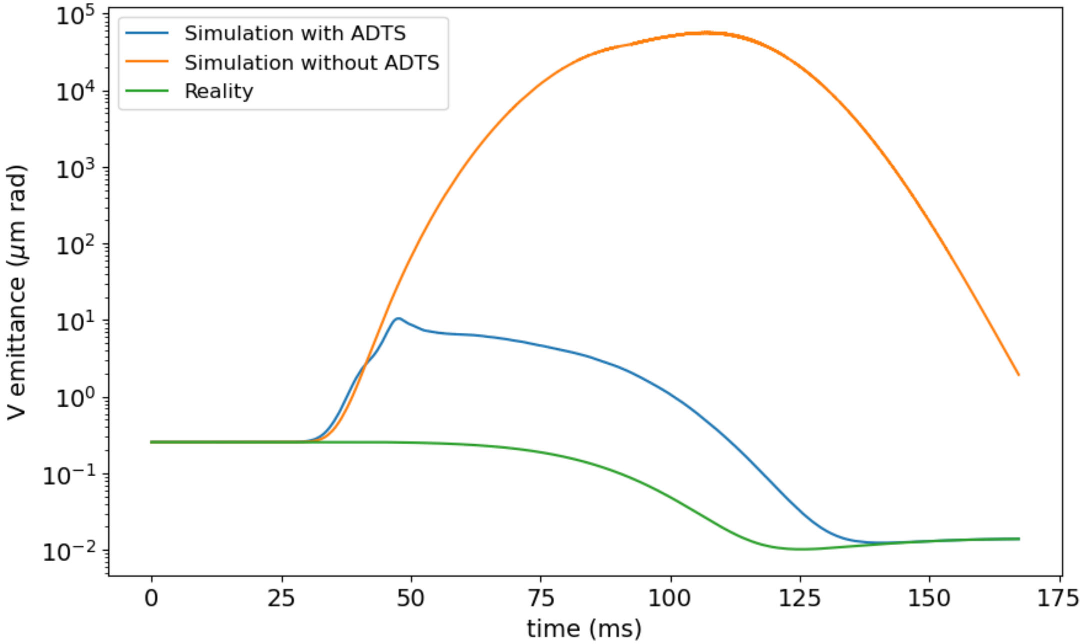
* All tracking simulations in this talk were by *mbtrack2* [1,2]



Model component

Energy ramp + Chromaticity variation + ADTS + RW impedance

Vertical emittance along the ramp



Total charge = 3 nC (nominal multibunch charge)

- It was found that the beam can indeed exhibit a large emittance blow-up along the ramp (blue line), but this behavior does not match the reality (green line)
- Without ADTS, the blow-up gets even worse (orange line). So, the ADTS is necessary for the model.
- This shows that the model was incomplete.

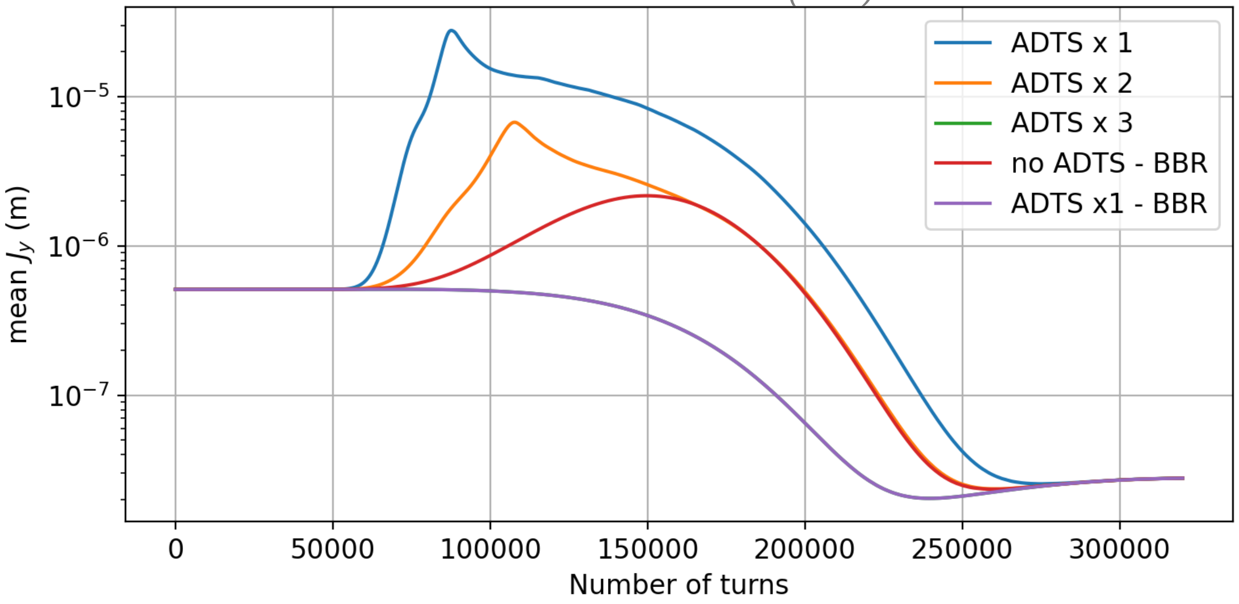
[1] A. Gamelin, W. Foosang, and R. Nagaoka, Proc. IPAC'21 (2021), pp. 282–285, https://doi.org/10.18429/JACoW-IPAC2021-MOPAB070

[2] mbtrack2, https://gitlab.synchrotron-soleil.fr/PA/collective-effects/mbtrack2

Present booster model

TCBI simulation results

Vertical amplitude along the ramp with different combinations of ADTS and broadband resonator (BBR)



Broadband resonator parameters: $R_s = 5\ \mathrm{M\Omega/m},\ f_r = 2\ \mathrm{GHz},\ Q = 2$

- To **investigate** this results, **the ADTS was increased** by a factor of 2 and 3 since it is possible that the ADTS in the model is underestimated.
- A **mock-up BBR** was also added as an **approximate impedance of all the special chambers** whose model does not exist, so they were not taken into account in the model.
- Only at **ADTSx3** or when the **nominal ADTS is present simultaneously with the BBR,** the instability can be suppressed completely.

Case study conclusion: essential elements for collective effect modeling

Energy ramp + Chromaticity variation + ADTS + RW impedance + Broadband impedance

Moving back to the SOLEIL II booster

SOLEIL II booster model

Chromaticity → **Constant throughout the ramp** due to constant sextupole strength.

ADTS → **Also constant ADTS** (for a given chromaticity*).

* In reality, ADTS coefficients are different for each chromaticity since the sextupole strength is not equal. However, in this work, every chromaticity was estimated to have identical ADTS coefficients.

Comparison of the ADTS coefficients in the two boosters computed from the AT code

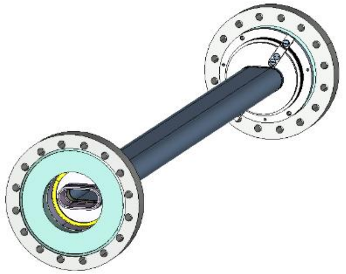
Coefficient	Value (m^{-1})		
	SOLEIL (varied ξ)		SOLEIL II $(\xi = 1)$
	$<$ 1.73 GeV	At 2.75 GeV	
C_{xx}	-8.9	4.08	-688
C_{xy}	-18.0	-23.25	-491
C_{yx}	-18.0	-23.25	-491
C_{yy}	26.54	14.05	-604

→ ADTS is much stronger in the new booster due to the stronger chromaticity correction.

SOLEIL II booster model

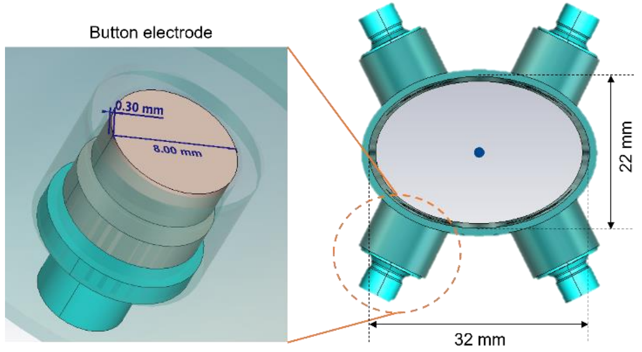
Preliminary impedance model

Kicker chamber (3)



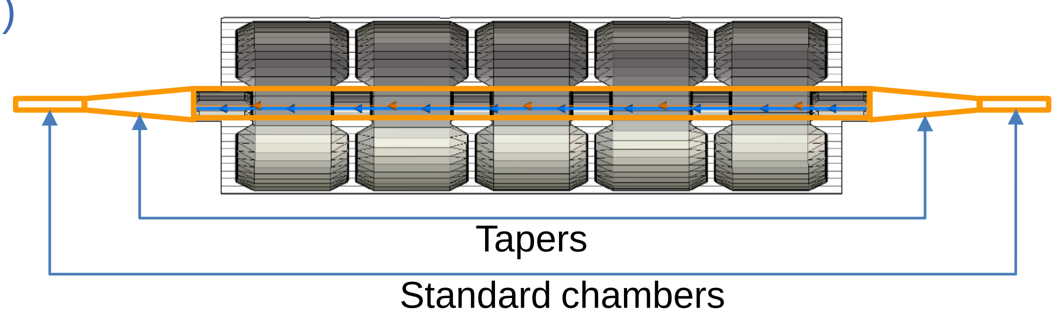
- Existing elliptical chambers reused, 40 x 16 mm^2
- Ceramic chamber with 200 nm Ti coating, $3 \times 10^{-6}\ \Omega\text{m}$ (amorphous structure from sputtering technique used for the deposition)

BPM (42)



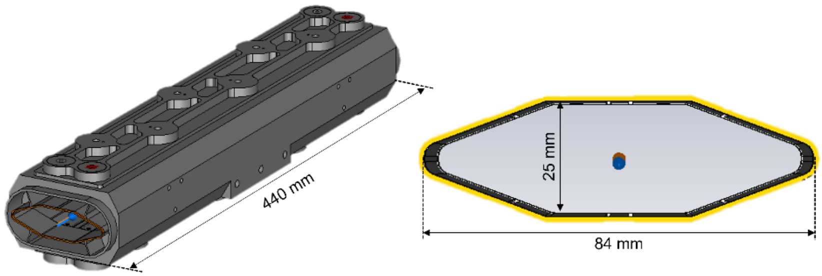
- New design Molybdenum ($\rho = 5.49 \times 10^{-8}\ \Omega\text{m}$)
- 0.3 mm gap between the electrode and the BPM body.

RF cavity (2)



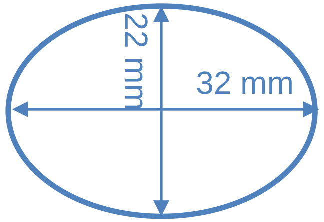
- Present RF cavity reused.
- Taper modeled as a frustum of a right cone, 300 mm long with an angle of 7.41°

Stripline (2)



- Present storage ring striplines reused

Standard chamber

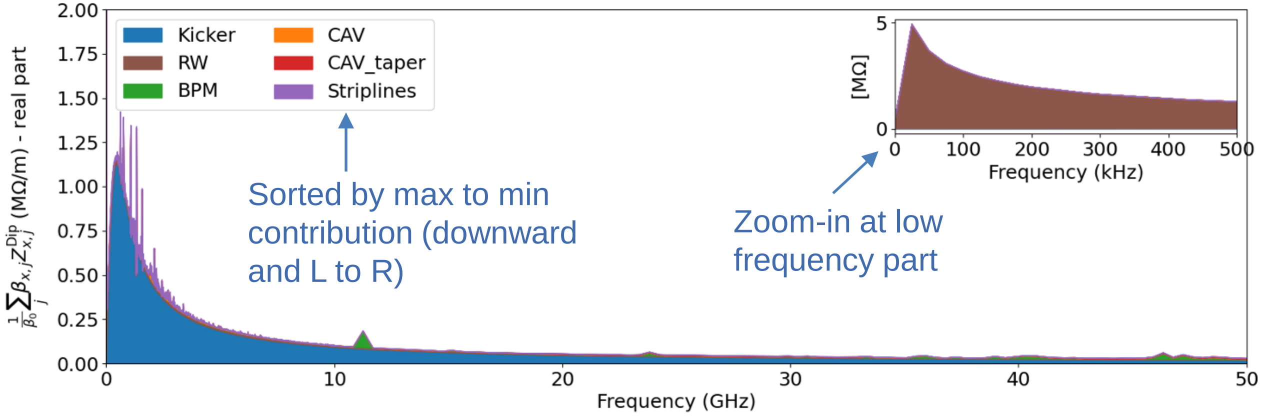


- Elliptical chamber 32 x 22 mm^2 ***(conservative H dim.)***
- Stainless steel 316LN ($\rho = 7.6 \times 10^{-7}\ \Omega\text{m}$)

SOLEIL II booster model

Total transverse impedance

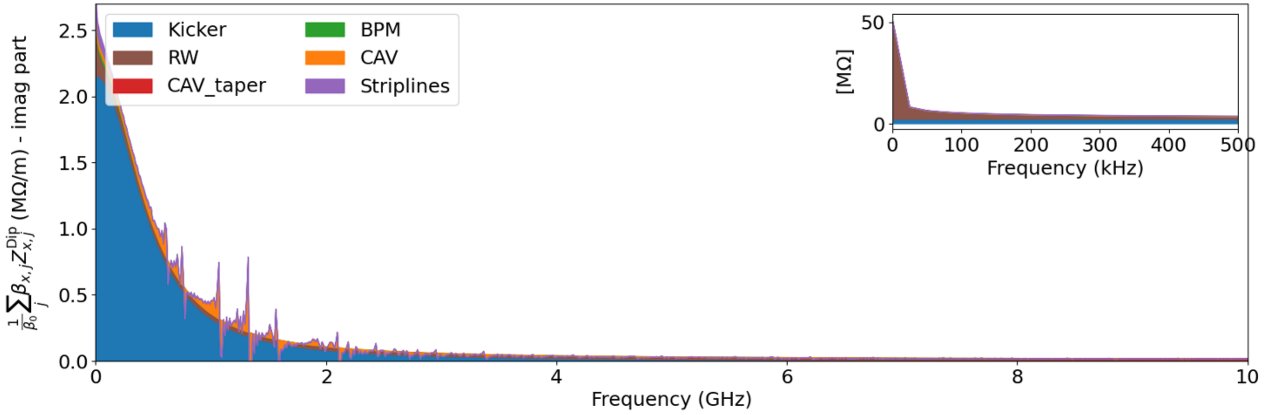
Horizontal dipolar impedance (real part)



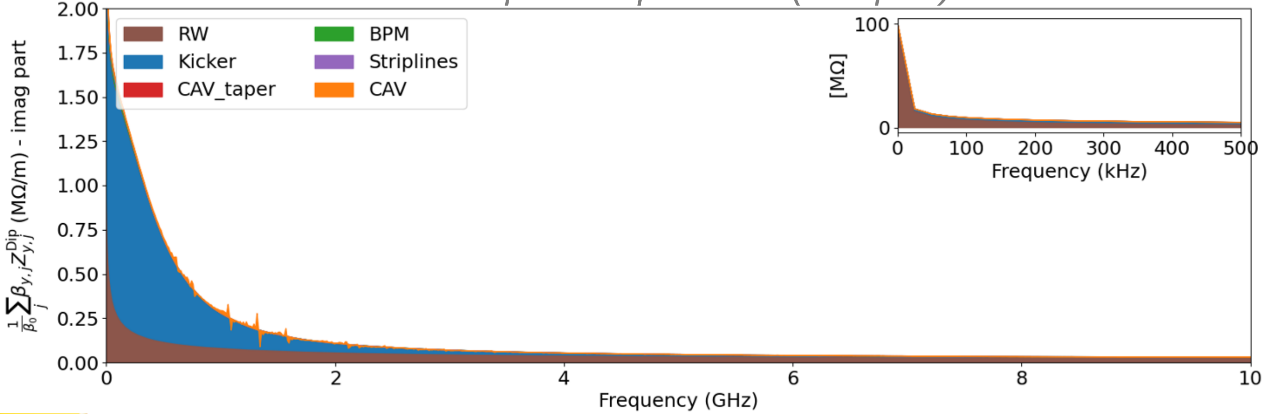
Sorted by max to min contribution (downward and L to R)

Zoom-in at low frequency part

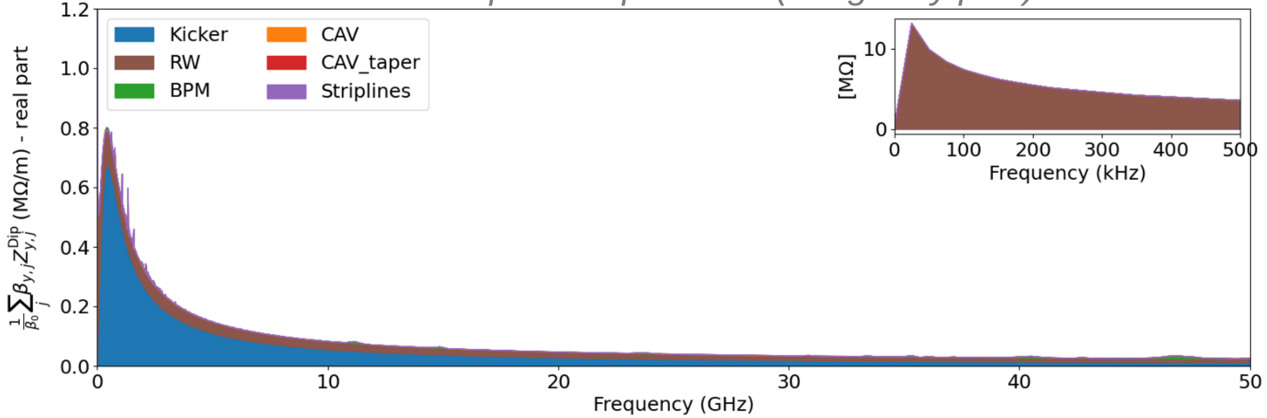
Horizontal dipolar impedance (imaginary part)



Vertical dipolar impedance (real part)



Vertical dipolar impedance (imaginary part)



Conclusion:

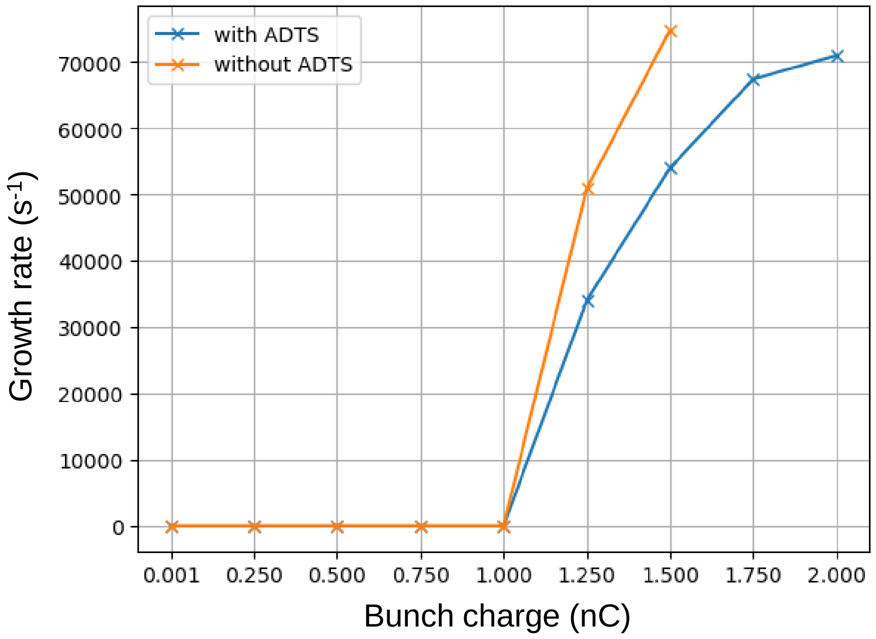
- Overall, the kicker chambers contribute the most to the budget, but the resistive wall dominates the low frequency part which is important for multibunch instability.
- The kicker chambers add a significant broadband impedance at around 450 MHz.

Energy-dependent collective effect study

Single-bunch regime (without energy ramp)

Transverse mode-coupling instability (TMCI)

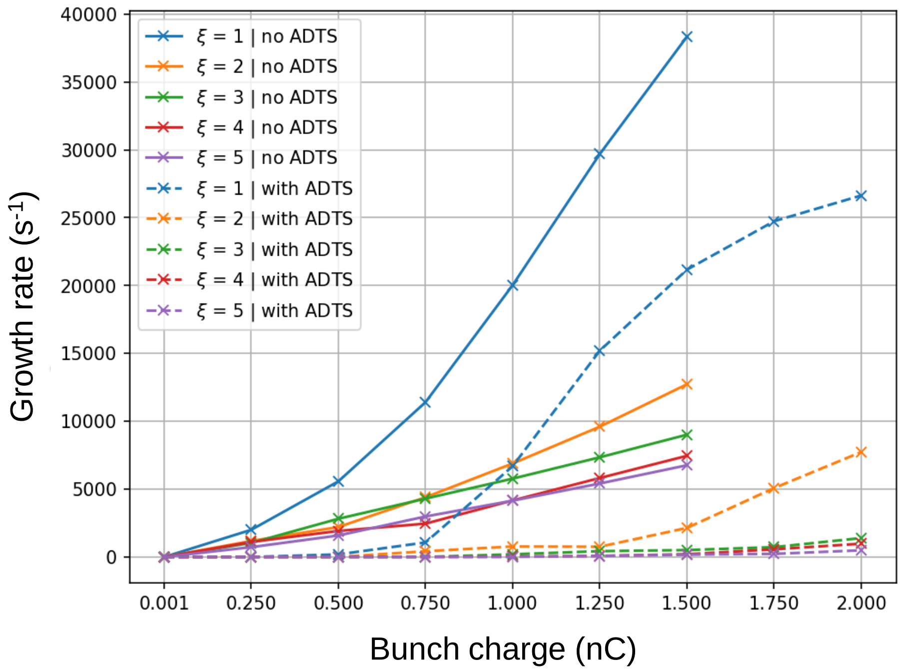
TMCI Growth rate at 150 MeV at $\xi = 0$



- ADTS does not have an impact on the threshold but does significatly reduce the growth rate

Head-tail Instability (HTI)

HTI Growth rate at 150 MeV at $\xi > 0$



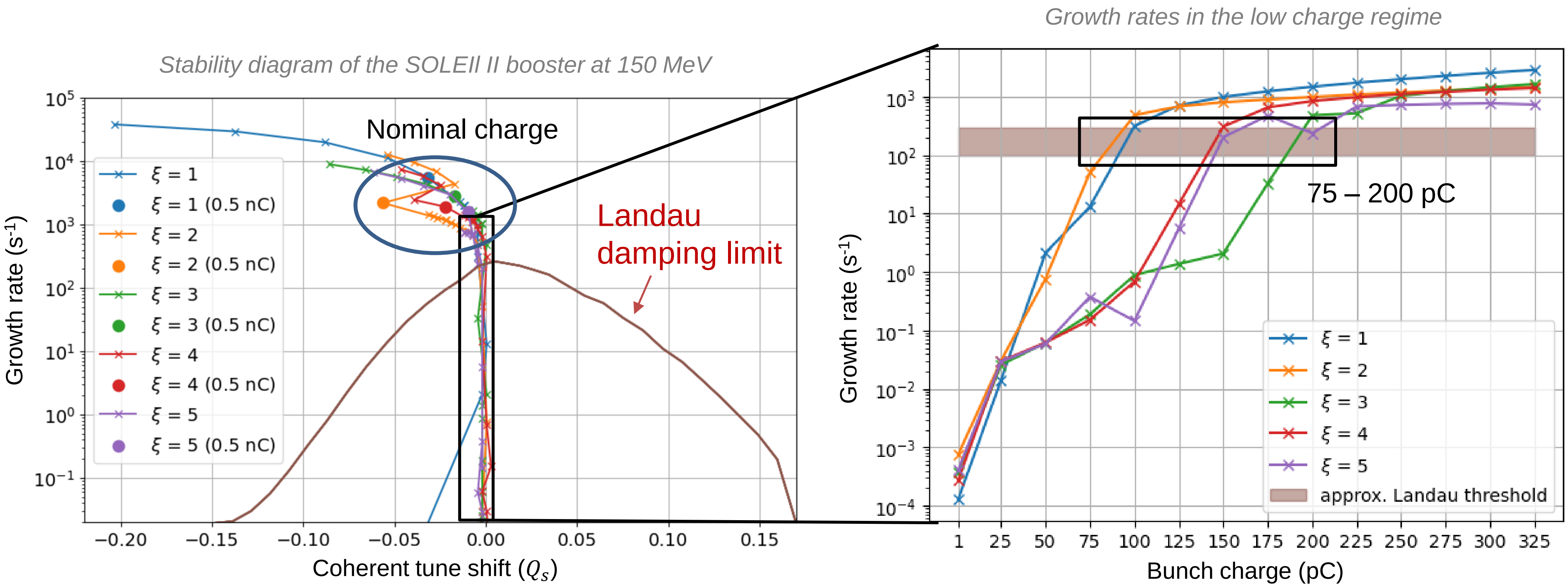
- Growth rate reduces at higher chromaticity
- ADTS also greatly reduce the growth rate.

This shows Landau damping effect in the booster

Single-bunch regime (without energy ramp)

Stability diagram

Emittance at injection : $\epsilon_x = \epsilon_y = 0.17\ \mu\mathrm{m\ rad}$


Stability diagram of the SOLEIl II booster at 150 MeV

Growth rates in the low charge regime

Nominal charge

Landau damping limit

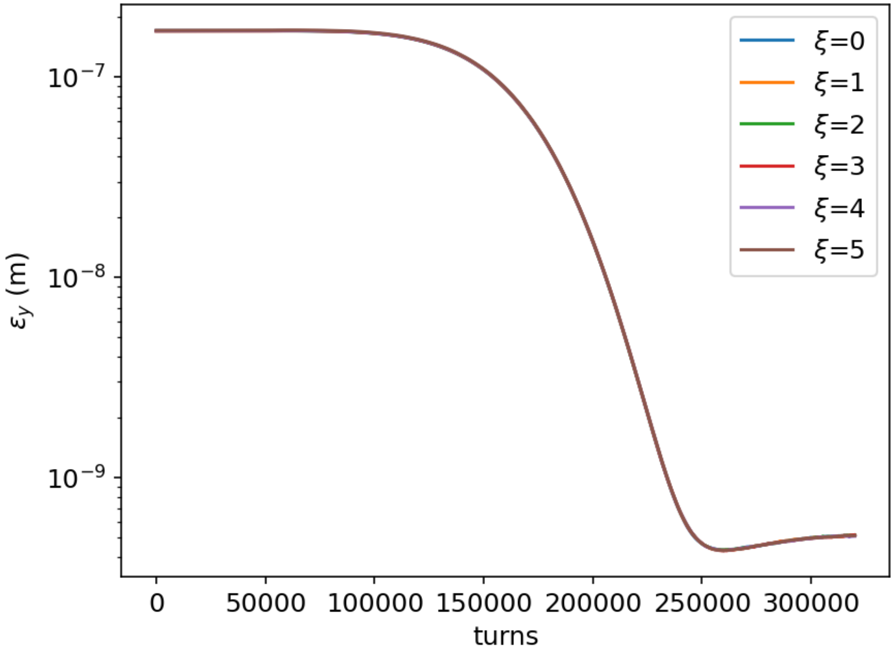
75 – 200 pC

- **The stability limit** is approximately 75 – 200 pC which is **lower than 500 pC** (nominal charge) at every chromaticity.
- Landau damping cannot stabilize the beam with the nominal charge at the injection.
- However, it **cannot** be concluded immediately if the beam will be stable **throughout** the ramp. Simulations with an energy ramp then needs to be pursued.

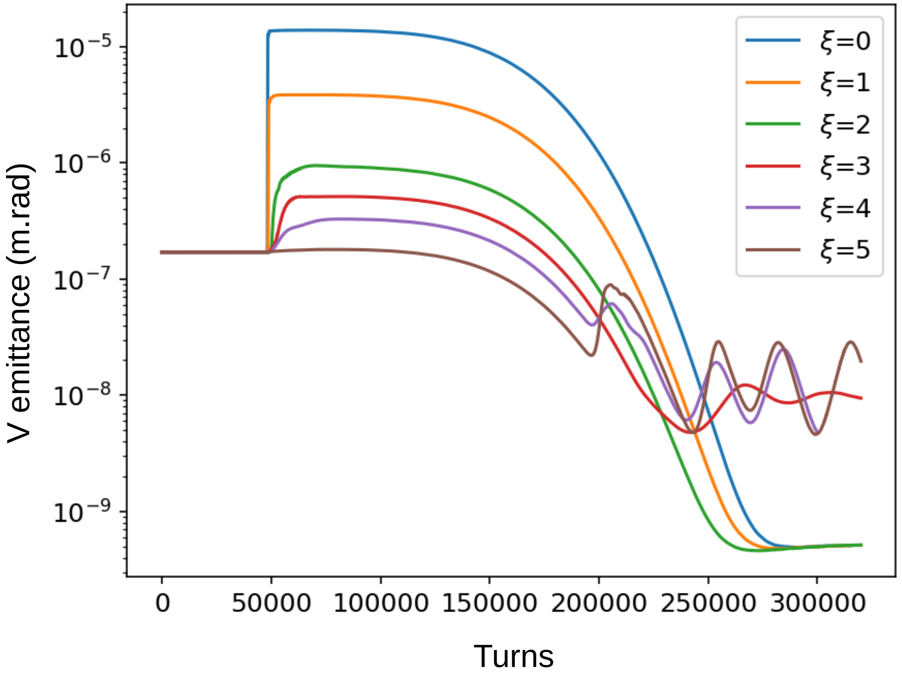
Single-bunch regime (with energy ramp)

Transverse single-bunch instabilities (TSBI) along the ramp

0.5 nC (nominal single-bunch charge) with ADTS



1.5 nC (maximum single-bunch charge) with ADTS



Conclusion:

- A beam with the **nominal charge** is in fact stable throughout the ramp.
- For the **maximum charge**, only chromaticity 5 can suppress the instability at low energy.
- An unexpected sawtooth feature at high energy was discovered for chromaticities 3-5.

Could be the loss of Landau damping due to the beam size reduction (reducing the tune spread for the same ADTS coefficients) ➡ To be investigated

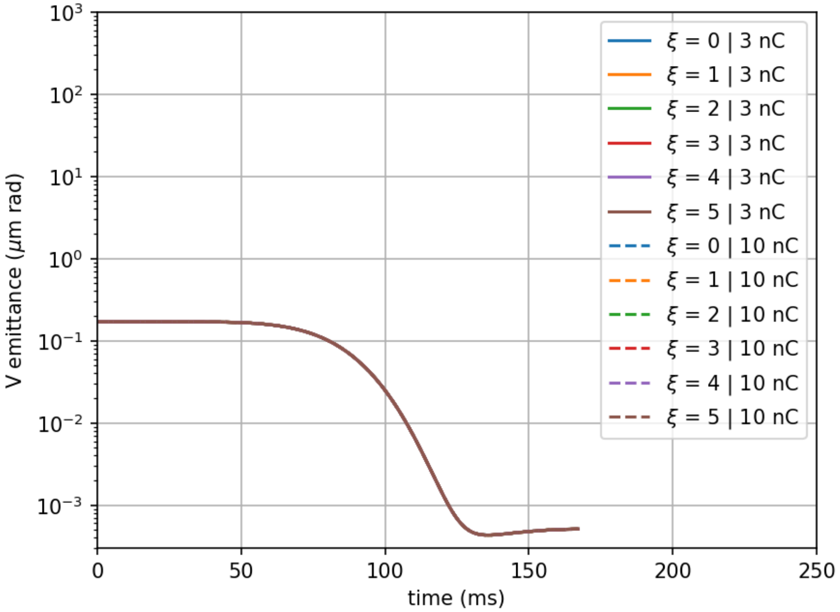
Multibunch regime (with energy ramp)

Transverse coupled-bunch instability (TCBI) driven by RW impedance [1]

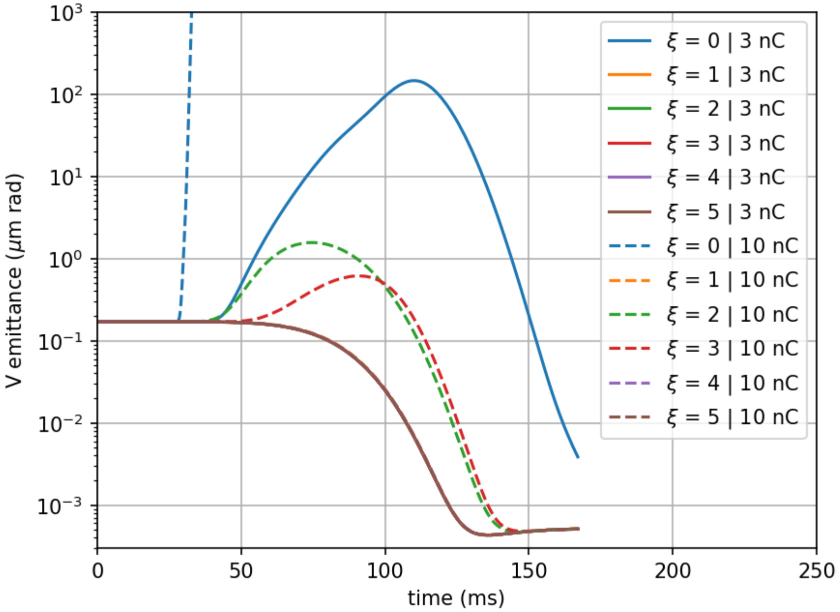
Simulations with energy ramp were also performed for TCBI to confirm the stability throughout the ramp at

- **3 nC** (nominal multibunch charge)
- **10 nC** (maximum achievable charge)

Vertical emittance with ADTS



Vertical emittance without ADTS



Conclusion:

- The beam at **both charges** are indeed **stable** all along the ramp when **ADTS is present**.
- On the contrary, the beam **withtout ADTS** would **not** be **stable** at low chromaticity: $\boldsymbol{\xi \geq 1}$ for **3 nC** and either $\boldsymbol{\xi = 1}$ or $\boldsymbol{\xi \geq 4}$ for **10 nC** to be stable.

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[1] More about this topic: W. Foosang et al, J. Phys.: Conf. Ser. **2687** 062017 (2024), https://doi.org/10.1088/1742-6596/2687/6/062017

Conclusion

Conclusion

It has been shown that

- **ADTS** and **broadband impedance** are key elements for accurate modeling of collective effects in boosters.

- **Tracking with energy ramp is important** to determine beam's stability throughout the ramp.

Conclusion from the SOLEIL II project's aspect

- **Single-bunch regime**
  - The beam is stable throughout the ramp at nominal charge (0.5 nC) for positive chromaticity.
  - Possible stability issue for maximum charge (1.5 nC), to be investigated.

- **Multibunch regime**
  - The beam is stable up to 10 nC (maximum charge) for positive chromaticity.

Bottom line:
SOLEIL II booster is safe from TMCI, HTI, and RW instability at the nominal charge.

- **Cost optimization**: collective effect study can help optimize the construction cost of the machine by neglecting unneccessary impedance optimization (tapers, RF fingers, pumping grid etc.).

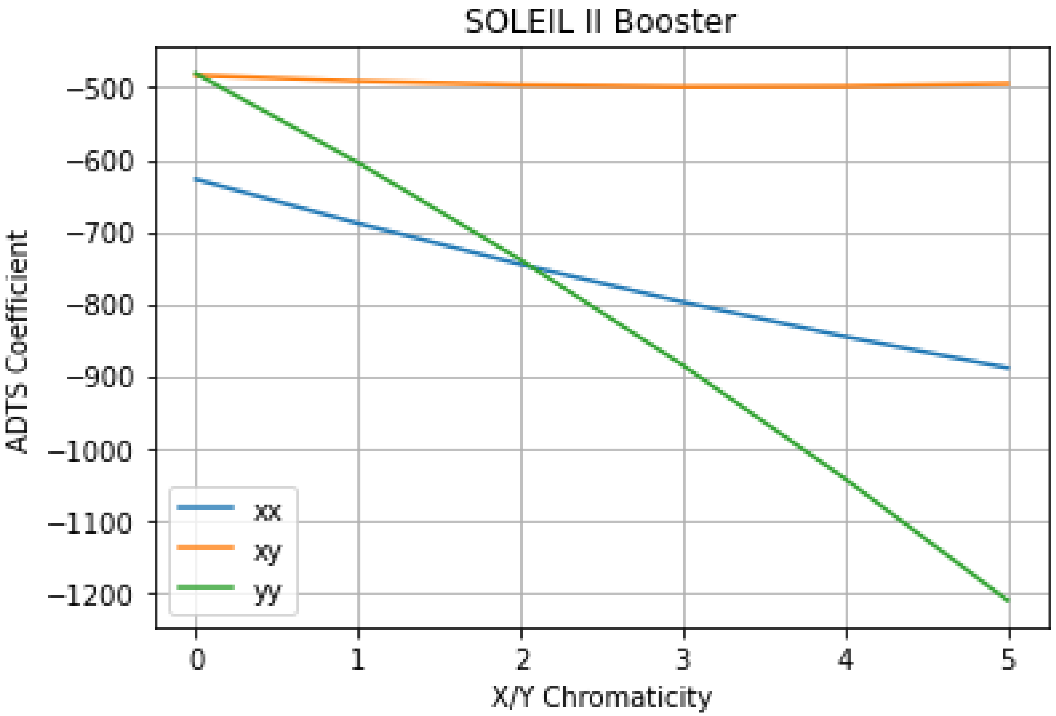
Thank you for your attention

Back-up slides

Outlook

Next steps

- New impedance model following the advance of mechanical design.
- Use of different ADTS coefficients according to the chromaticity.
- Investigate the sawtooth feature at the end of the ramp of the single-bunch simulation.
- Add physical aperture in tracking.

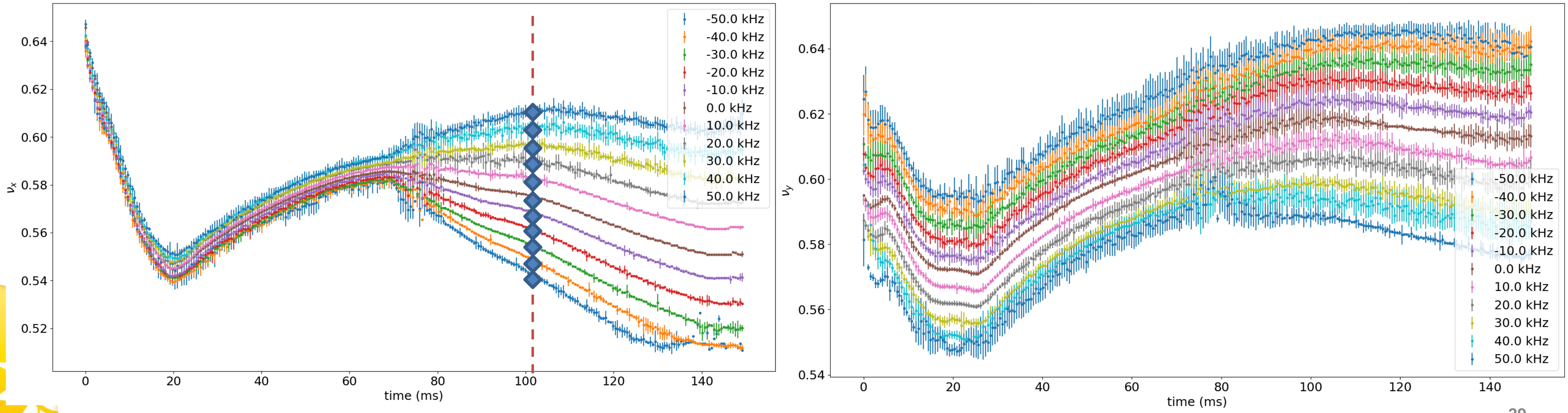


In the present booster

Chromaticity

- To obtain the **chromaticity along the ramp** in the present booster, a measurement of the **betatron tune along the ramp** at **various energy deviation δ** was conducted.
- Energy deviation is adjusted via RF frequency f_{RF}: $\Delta\delta = \frac{\Delta f_{RF}}{\alpha f_{RF}}$

Betatron tunes along the present booster’s ramp at various energy deviation

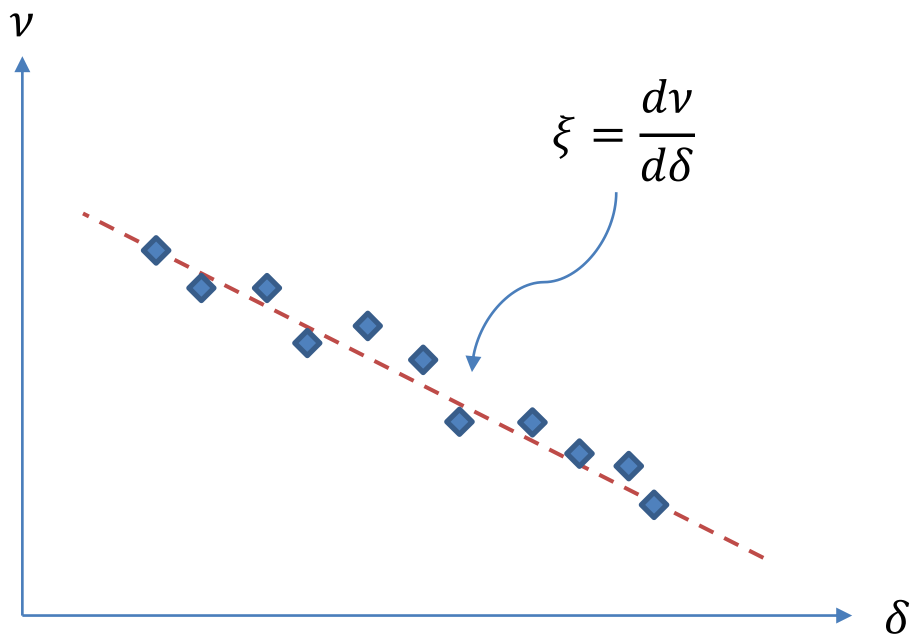


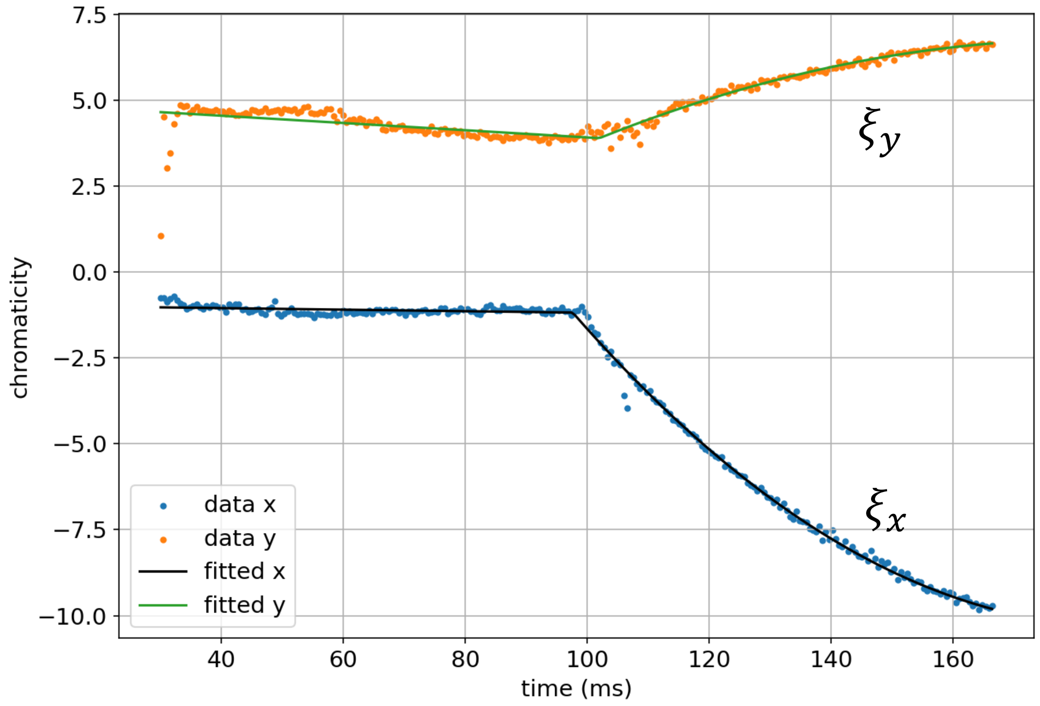
Horizontal tune

Vertical tune

In the present booster

Chromaticity & ADTS



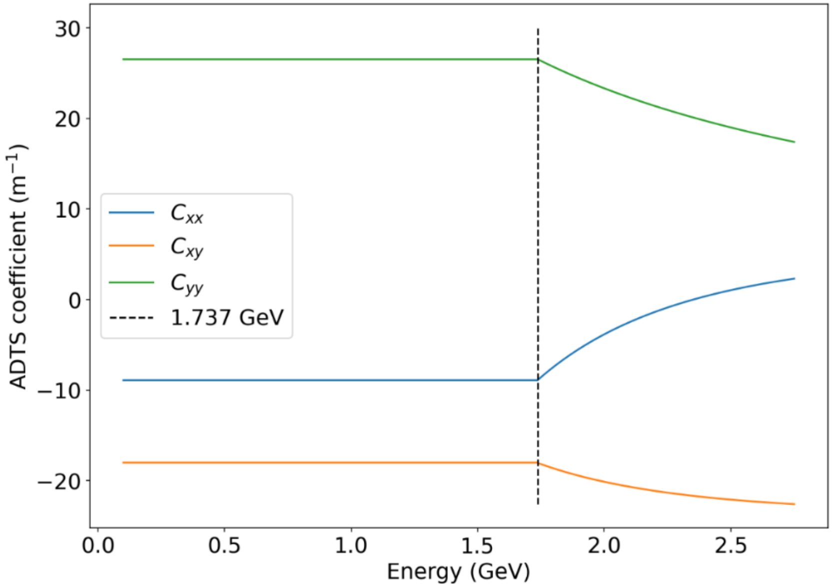


- **Between 0-100 ms**, the sextupole strength in both planes ramps up accordingly to the beam energy resulting in a constant normalized sextupole force K_f and thus fairely constant chromaticities.
- However, due to the inconstant K_f in the horizontal plane **after 100 ms**, the chromaticities vary by a large amount from this point until extraction.

In the present booster

ADTS

Present booster's ADTS coefficients along the ramp calculated using the real chromaticity variation



Coefficient	value (m^{-1})	
	< 1.73 GeV	At 2.75 GeV
C_{xx}	-8.9	4.08
C_{xy}	-18.0	-23.25
C_{yx}	-18.0	-23.25
C_{yy}	26.54	14.05

$$\begin{pmatrix}\Delta\nu_x\\ \Delta\nu_y\end{pmatrix} = \begin{pmatrix}C_{xx} & C_{xy}\\ C_{yx} & C_{yy}\end{pmatrix}\begin{pmatrix}J_x\\ J_y\end{pmatrix}$$

- The **ADTS coefficients** were then determined from element-by-element tracking in Accelerator Toolbox (AT) code.
- As a consequence of the **inconstant K_f**, the ADTS coefficients vary after 100 ms (1.73 GeV) in the present booster.