Study of Collective Effects in the CERN FCC-ee Top-up Booster

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♦ Abstract

The CERN FCC-ee top-up booster synchrotron will accelerate electrons and positrons from an injection energy of 20 GeV up to an extraction energy between 45.6 GeV and 182.5 GeV depending on the operation mode [1]. These accelerated beams will be used for the initial filling of the high-luminosity FCC-ee collider and for keeping the beam current constant over time using continuous top-up injection. Due to the high-intensities of the circulating beams, collective effects may represent a limitation in the top-up booster [2]. In this work we present a first evaluation of the impedance model and the effects on beam dynamics. Methods to mitigate possible instabilities will be also discussed.

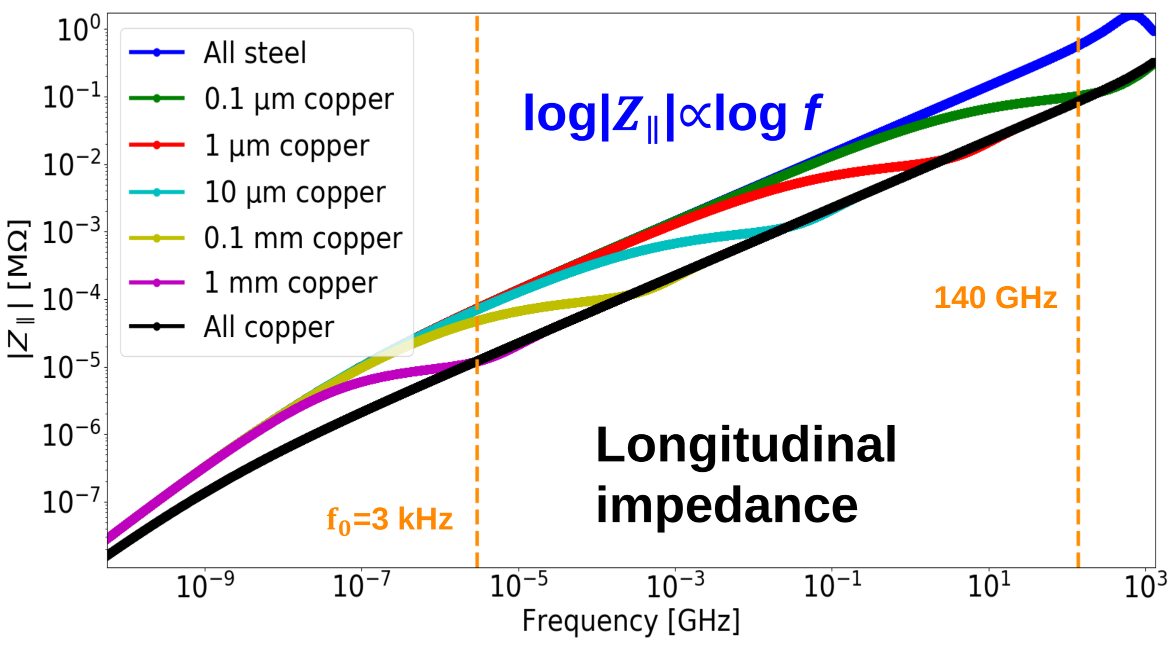
1. Expected machine and beam parameters

- The booster can accelerate electrons and positrons.
- The injection energy is 20 GeV, while the extraction energy depends on the experiment (e.g. 45.6 GeV and 182.5 GeV for the Z and $t\bar{t}$ experiments respectively).
- The injection energy case is considered in this work (most critical for collective effects), but situation can be even worse when φ_a=90°.
- The synchrotron radiation (SR) parameters $\sigma_{dE0,r}$, U_0 and τ_{z0} correspond to a bending radius ρ_b=10.625 km.

Parameter	Value
Machine circumference (C_r)	97.756 km
Beam energy at injection (E_0)	20 GeV
Bunch population (N_b)	3.4×10^{10} ppb
SR 1 σ rel. energy spread ($\sigma_{dE0,r}$)	0.166×10^{-3}
SR energy loss per turn (U_0)	1.33 MeV
SR damping time (τ_z)	15013 turns
RF frequency (f_{rf})	400 MHz
Harmonic number (h)	130432
RF voltage (V_{rf})	60 MV
Arc phase advance (φ_a)	60°
Mom. compaction factor (α_c)	1.48×10^{-5}
Synchrotron tune (Q_s)	0.030
SR 1 σ bunch length (σ_{z0})	1.26 mm

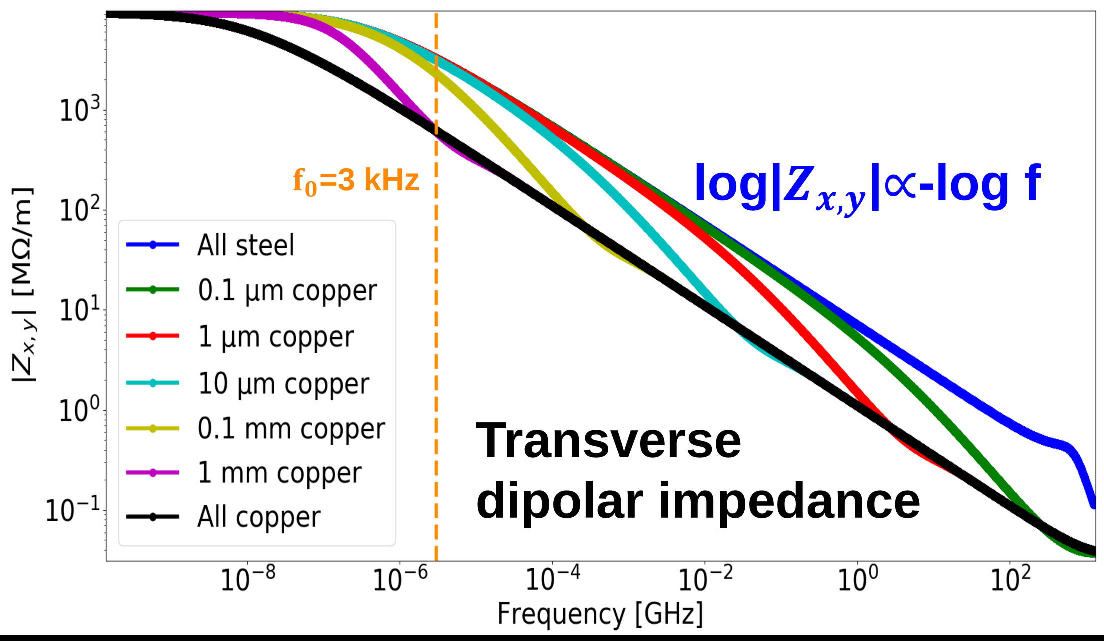
2. Resistive wall (RW) impedance

- The RW impedance is the dominant component of the impedance model.
- The baseline for costs minimization is to have a circular chamber in stainless steel (ρ_r=7 × 10^{-7} Ωm) with radius r_c=25 mm, but the related impedance is relatively large.
- To reduce this impedance, the CERN IW2D code [3] was used to compute the RW impedance of a two-layer beam-pipe, being the external layer in stainless steel and the internal layer in copper (ρ_r= 1.7 × 10^{-8} Ωm) with variable thickness δ_l.
- Being the Booster a fast-cycling machine, eddy currents in presence of a copper layer could be an issue during acceleration and their effects should be investigated.



- The spectrum of a Gaussian bunch with σ_z=1.26 mm reduces by 1000 at 140 GHz.
- The beam revolution frequency is f_0=3 kHz.
- δ_l=0.1 μm reduces significantly $|Z_\parallel^{steel}|$ only at relatively high frequencies (~140 GHz).
- δ_l ≥1 μm affects also the frequencies close to f_0.

- $|Z_{x,y}^{steel}|$ is affected at frequencies close to f_0 only when δ_l ≥1 μm.
- For single-layer beam-pipes and certain frequencies, $|Z_{x,y}|\propto 1/\sqrt{f}$ linearly decreases in logarithmic scales.
- $|Z_{x,y}|$ for double-layer beam-pipes is close to $|Z_{x,y}^{steel}|$ and $|Z_{x,y}^{copper}|$ respectively for relatively low and high frequencies (true also for $|Z_\parallel|$).



♦ References

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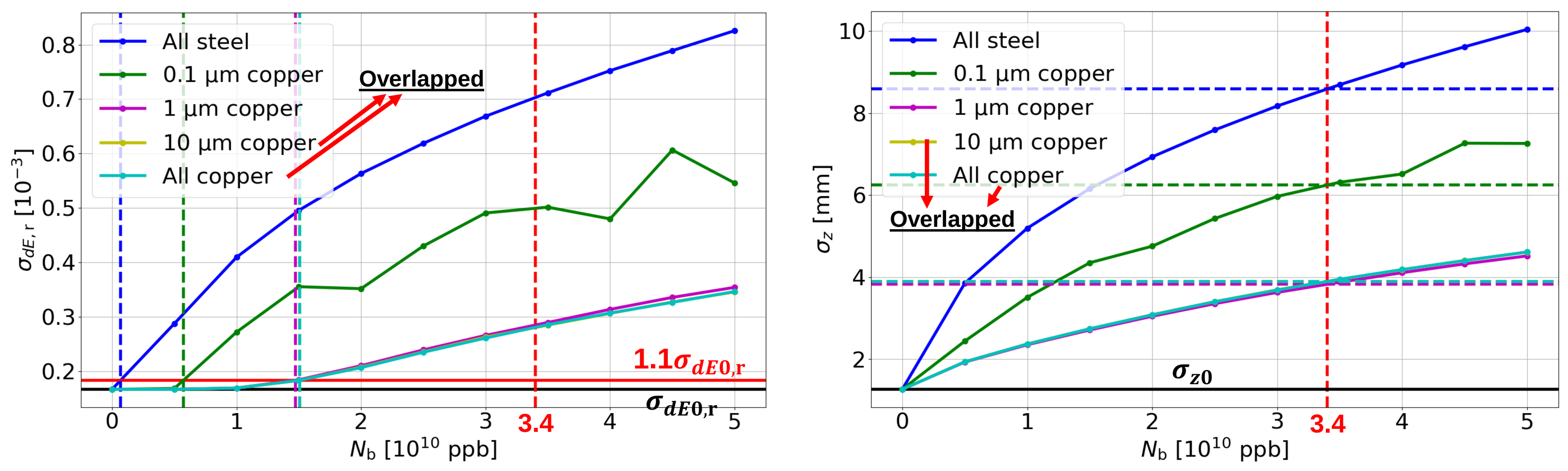
♦ Acknowledgements

Special thanks go to E. Belli, R. Kersevan, K. Oide and F. Zimmermann for their precious support.

3. Microwave instability (MI)

- Macroparticle longitudinal beam dynamics simulations were performed with the CERN BLonD code [4]. The RW impedance considering different chamber layers was included.
- Microwave instability was observed, leading to relatively large values of $\sigma_{dE,r}$ and σ_z.
- Setting the intensity threshold at 1.1 × $\sigma_{dE0,r}$, only a maximum of N_b~1.5 × 10^{10} ppb can be accelerated using a copper layer of 10 μm (best case scenario).



- For the Boussard criterion [5], the intensity threshold for MI scales as

$$N_b^{th} \propto \frac{\alpha_c E_0 \boxed{\sigma_{dE0,r}^2 \sigma_{z0}}}{\boxed{|Z_\parallel/n|}}$$

They can be increased for example with wigglers which lead to higher U_0.

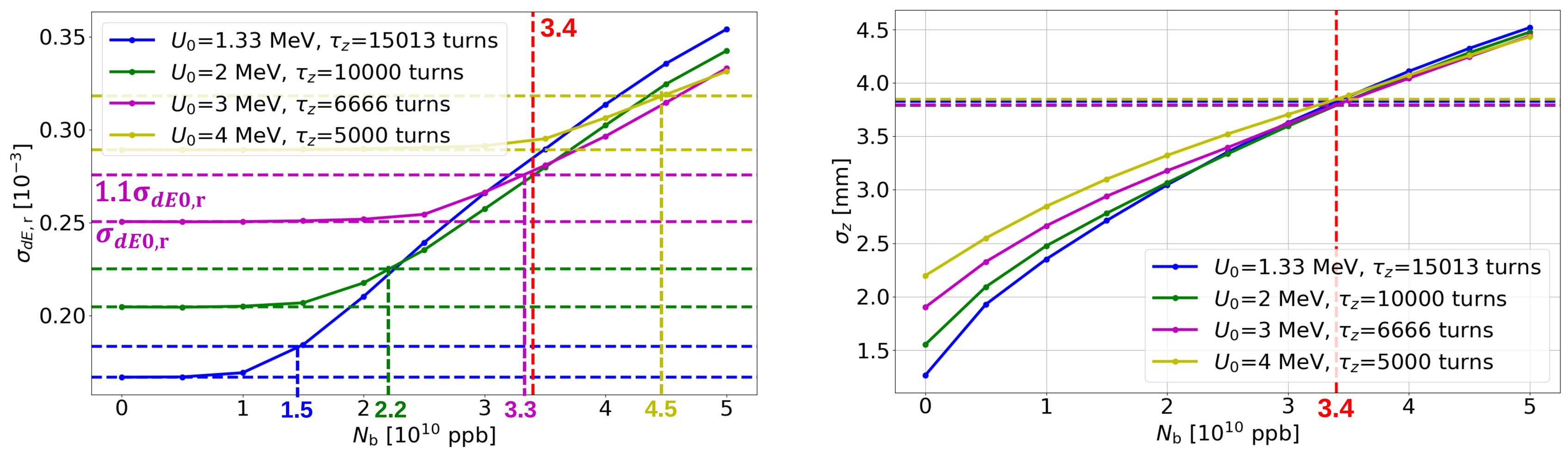
It was decreased adding a copper layer to the beam pipe.

$$\rho_b \propto \frac{1}{U_0} \quad \tau_z \propto \frac{1}{(1+AU_0)U_0}$$

$$\sigma_{dE0,r} \propto \sqrt{\frac{U_0}{1+BU_0}}$$

positive constants

- Using the 1 μm RW impedance, simulations show that U_0 should be larger than 3 MeV.



- Using the 10 μm RW impedance, the $\sigma_{dE,r}$ thresholds are at 1.5, 2.3, 3.4, 4.7 × 10^{10} ppb.

4. RW transverse mode coupling instability (TMCI)

- The CERN DELPHI code [6] was used to evaluate the TMCI intensity threshold due to the 1 μm copper-layer RW impedance.
- The values for σ_z were derived from the BLonD simulations with U_0=4 MeV (see Box 3).
- The threshold for TMCI scales as [7]

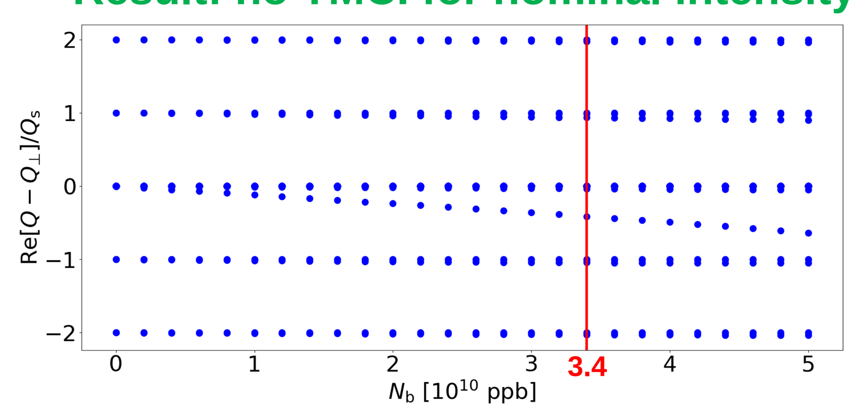
Result: no TMCI for nominal intensity

betatron tune $[Q_\perp]$=269

$$N_b^{th} \propto \frac{Q_\perp Q_s E_0 \boxed{\sigma_z}}{\boxed{\mathrm{Im}\, Z_\perp}}$$

It increases with intensity due to SR and MI. It increases also with U_0 for not too high intensities (see Box 3).

It was decreased adding a copper layer to the beam pipe.



5. RW transverse coupled bunch instability (TCBI)

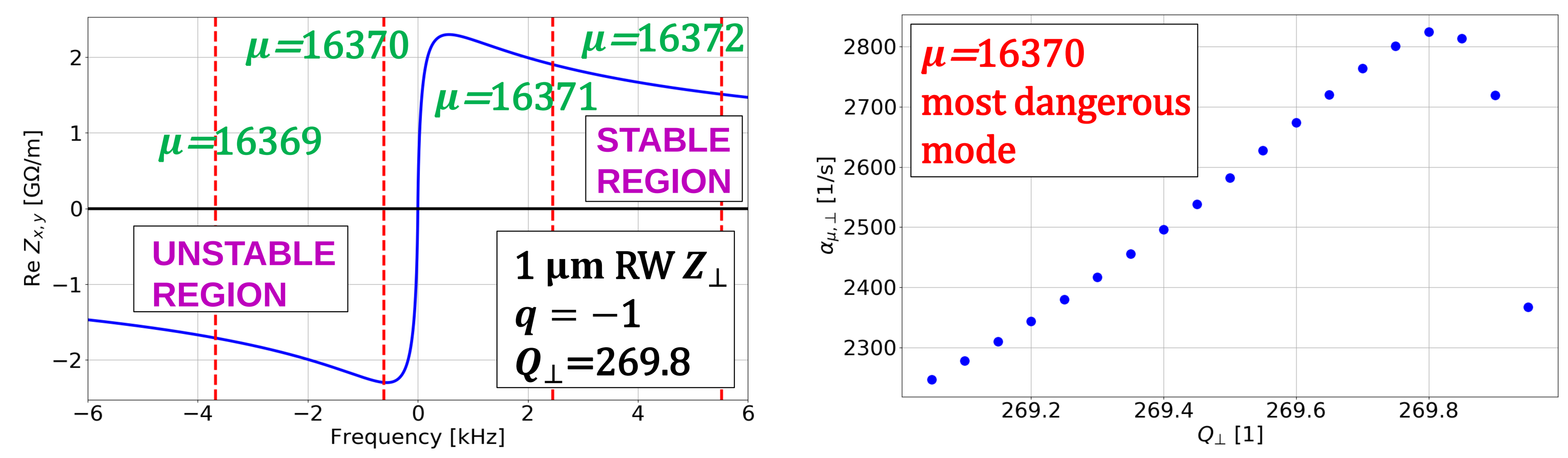
- The RW long-range transverse wakefield is responsible for the TCBI.
- If the motion of the beam is seen as a sum of coherent coupled-bunch modes, then the growth rate of the lowest azimuthal mode m=0 for a Gaussian bunch is [8]

$$\alpha_{\mu,\perp} = -\frac{ceM_b N_b f_0}{4\pi(E_0/e)Q_\perp} \sum_{q=-\infty}^{q=\infty} \mathrm{Re}\left[Z_\perp(f_q)\right]$$

coupled-bunch mode

$$f_q = f_0(qM_b + \mu + Q_\perp)$$

 # bunches=16640



- Depending on the fractional part of $Q_\perp$, the TCBI rise-time varies from 0.35 ms (1.07 turns) with $Q_\perp$=269.8 to 0.45 ms (1.38 turns) with $Q_\perp$=269.05.
- New challenging feedback systems are under study [9].

♦ Conclusions

This work showed that the baseline parameters for the FCC-ee Booster cannot provide stable beams to the main ring. This is due to the resistive wall impedance which leads to MI for nominal-intensity beams even if a copper layer is added to the stainless-steel beam pipe. Therefore, a second mitigation technique, namely the increase of the power lost by the beam for synchrotron radiation, was also considered. Using a proper combination of parameters neither MI nor TMCI was observed for nominal-intensity beams. However the TCBI rise-time is only about one revolution turn and new feedback systems are necessary.