Studies and Mitigation of Collective Effects in FCC-ee

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Acknowledgements: R. Kersevan, S. James Rorison, A. Abramov

Outline

- FCC-ee main parameters
- Wakefields and impedance model
- Single bunch instabilities
- Transverse instabilities and feedback system
- Interplay between longitudinal wakefield and beam-beam

FCC-ee main parameters

Layout	PA31-1.0			
	Z	WW	ZH	$t\hat{t}$
Circumference (km)	91.174117 km			
Beam energy (GeV)	45.6	80	120	182.5
Bunch population (10^{11})	2.53	2.91	2.04	2.64
Bunches per beam	9600	880	248	36
RF frequency (MHz)	400			400/800
RF Voltage (GV)	0.12	1.0	2.08	4.0/7.25
Energy loss per turn (GeV)	0.0391	.37	1.869	10.0
Longitudinal damping time (turns)	1167	217	64.5	18.5
Momentum compaction factor 10^{-6}	28.5		7.33	
Horizontal tune/IP	55.563		100.565	
Vertical tune/IP	55.600		98.595	
Synchrotron tune	0.0370	0.0801	0.0328	0.0826
Horizontal emittance (nm)	0.71	2.17	0.64	1.49
Verical emittance (pm)	1.42	4.34	1.29	2.98
IP number	4			
Nominal bunch length (mm) (SR/BS)*	4.37/14.5	3.55/8.01	3.34/6.0	2.02/2.95
Nominal energy spread (%) (SR/BS)*	0.039/0.130	0.069/0.154	0.103/0.185	0.157/0.229
Piwinski angle (SR/BS)*	6.35/21.1	2.56/5.78	3.62/6.50	0.79/1.15
ξ_x/ξ_y	0.004/0.152	0.011/0.125	0.014/0.131	0.096/0.151
Horizontal β^* (m)	0.15	0.2	0.3	1.0
Vertical β^* (mm)	0.8	1.0	1.0	1.6
Luminosity/IP ($10^{34}/cm^2s$)	181	17.4	7.8	1.25

*SR: syncrotron radiation, BS: beamstrahlung

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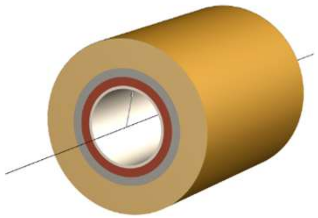
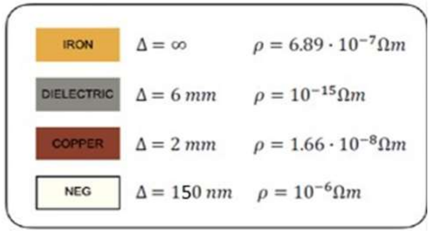
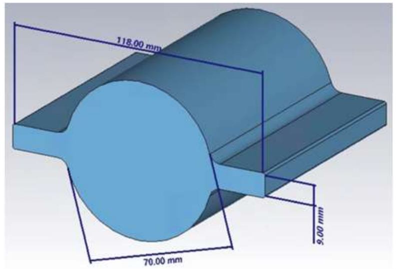
Resistive wall

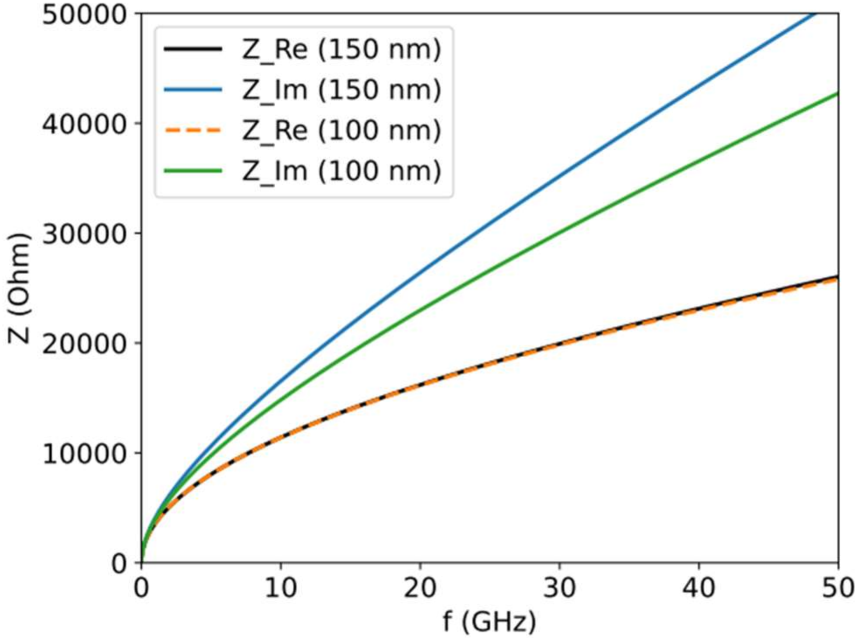


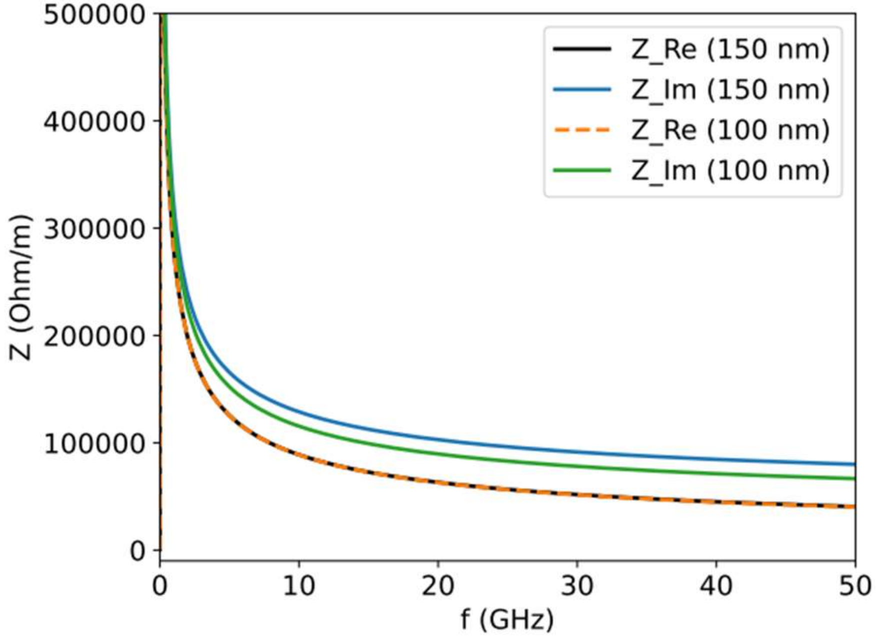


It is the largest impedance source for FCC-ee evaluated so far. NEG coating is needed to mitigate the electron cloud build-up in the positron machine and for pumping reasons in both rings.

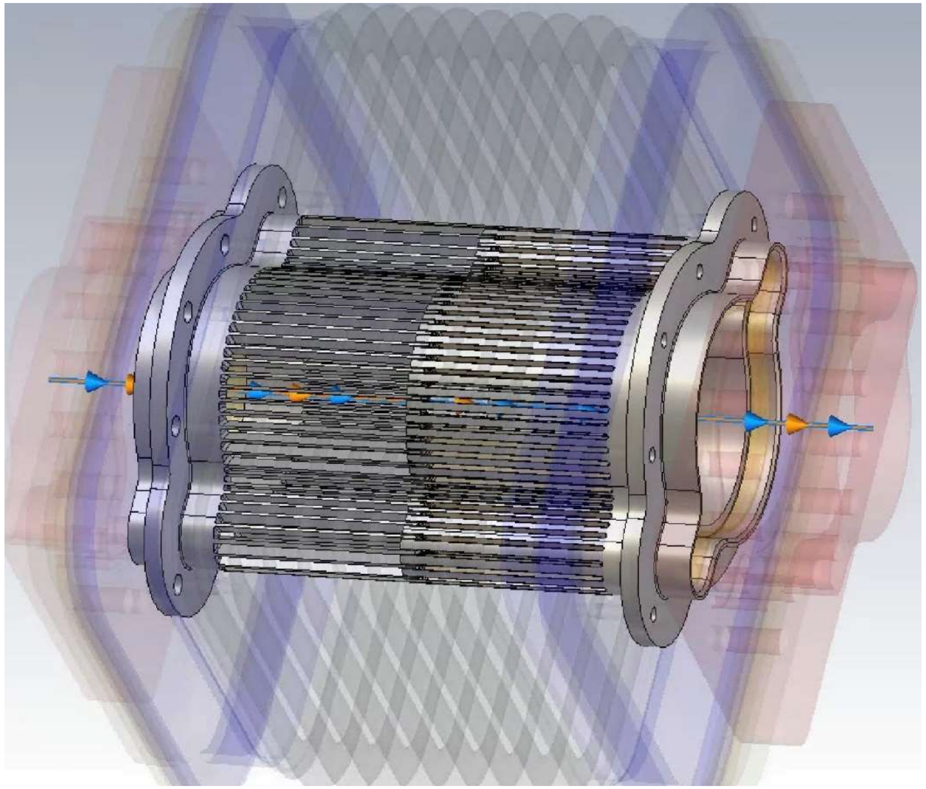


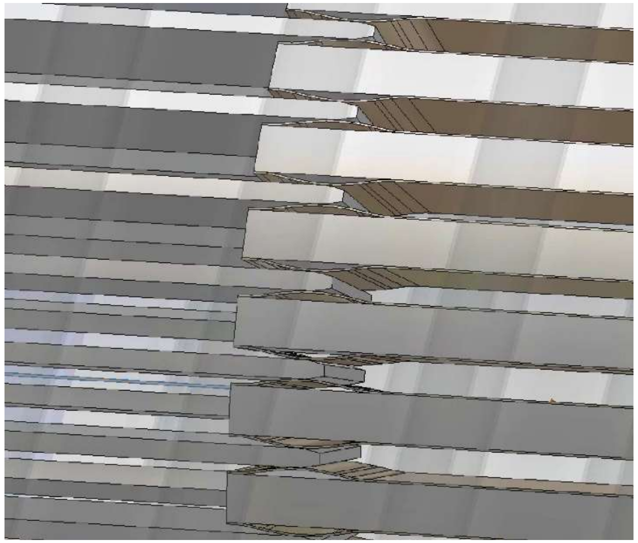
IW2D results for a circular pipe. We estimated a factor 1.1 for winglets contribution





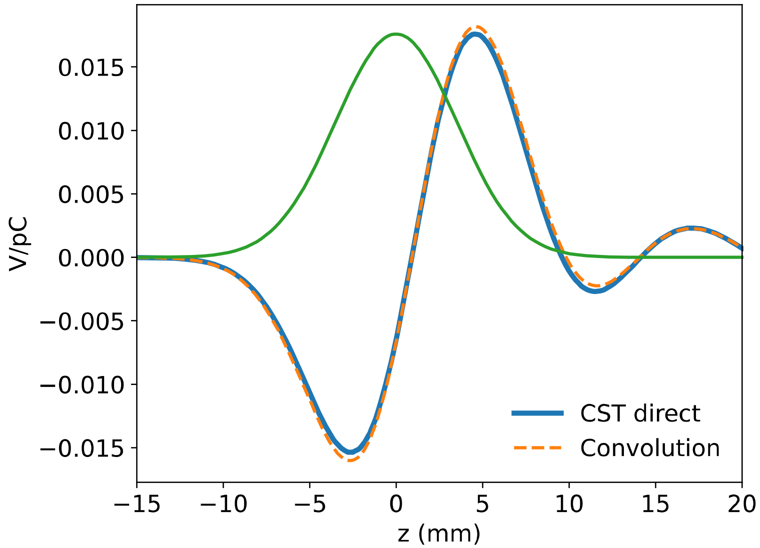
Bellows



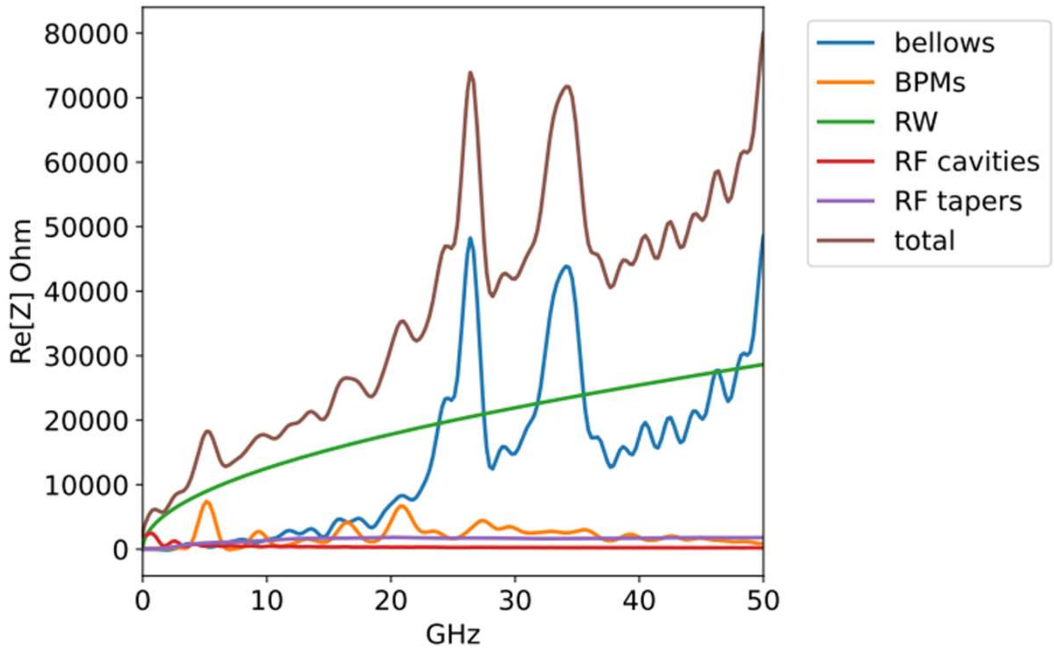


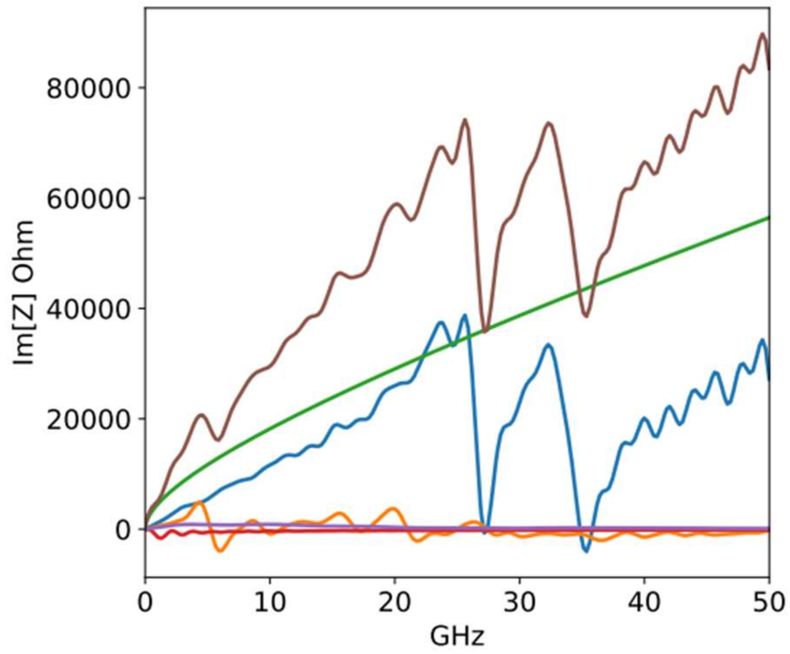
They represent the second highest impedance source. We have used an upper estimate of 20000 bellows

wakefield of 3.5 mm Gaussian bunch

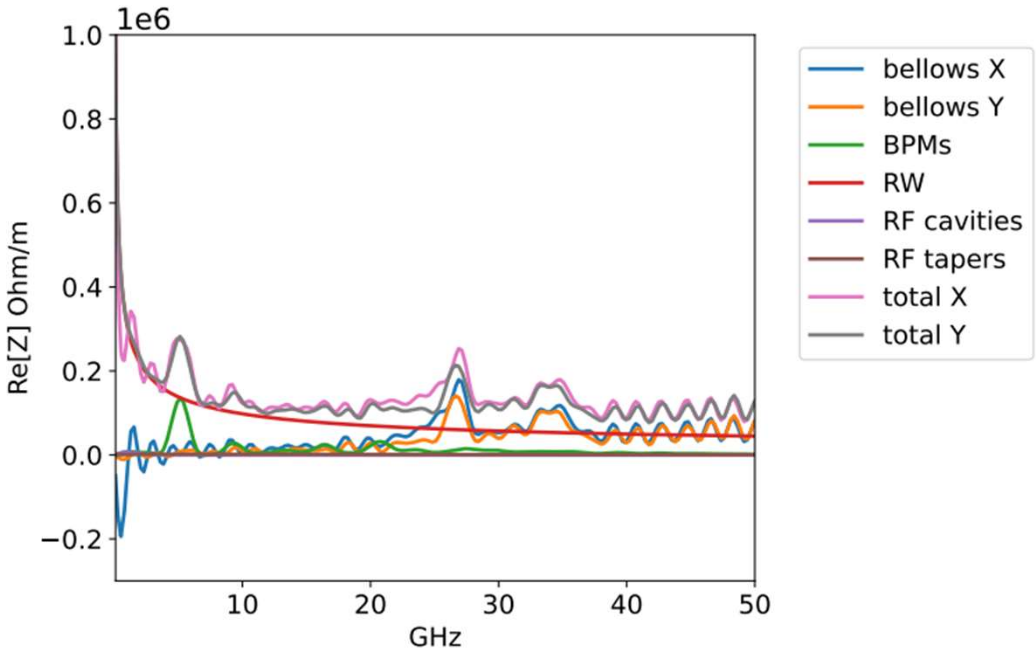


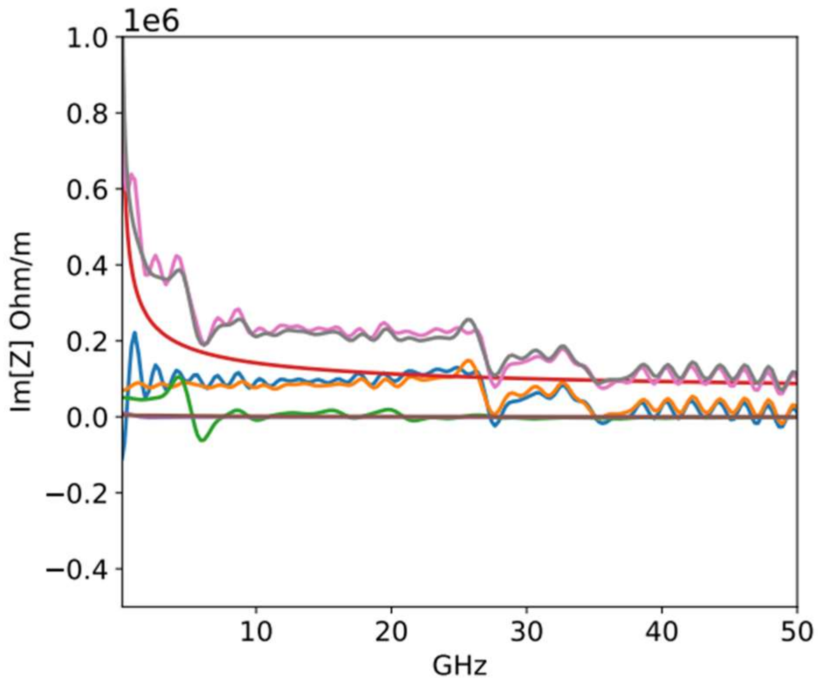
Total impedance: longitudinal



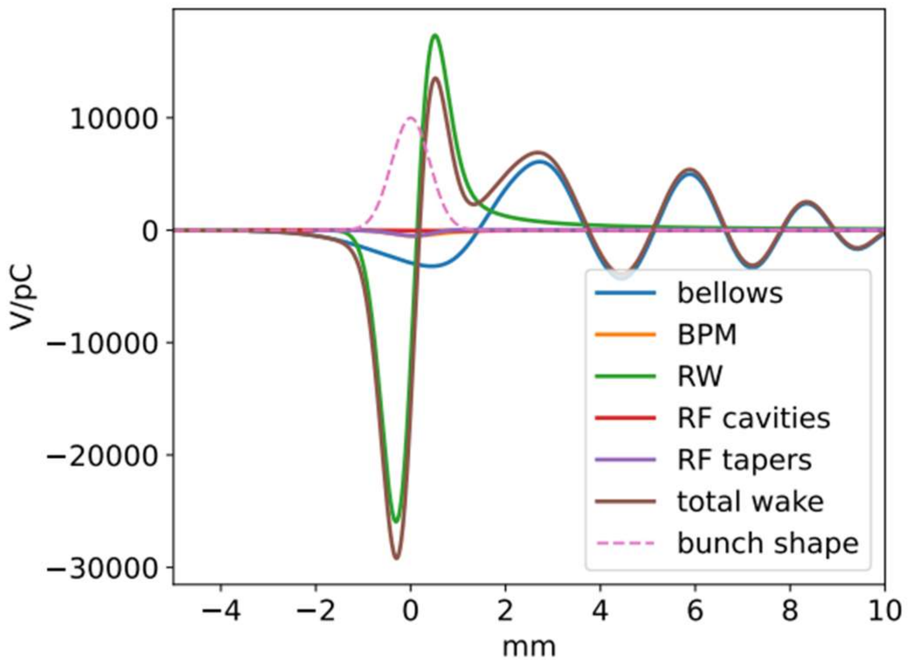


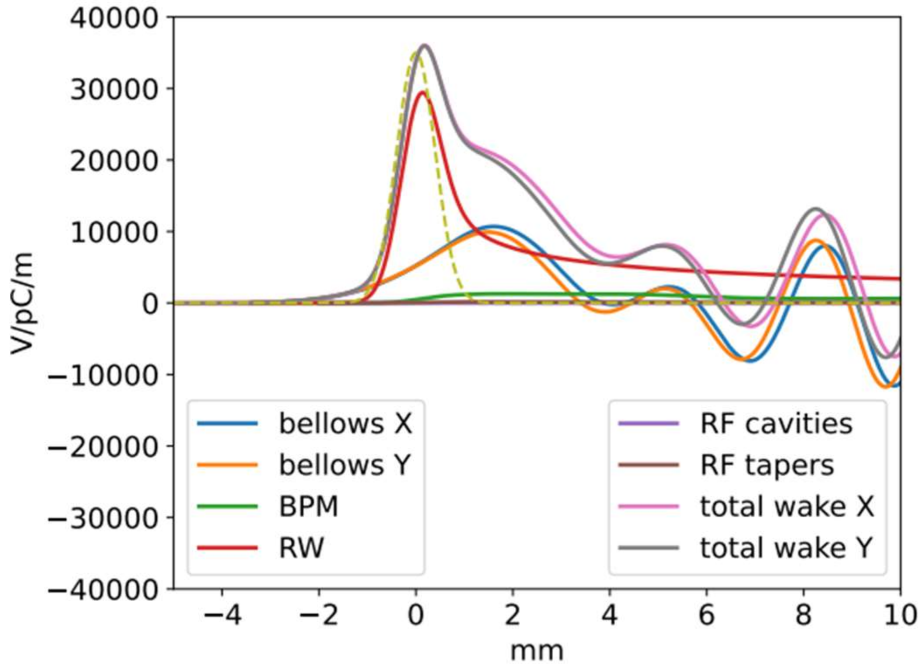
Total impedance: transverse dipolar



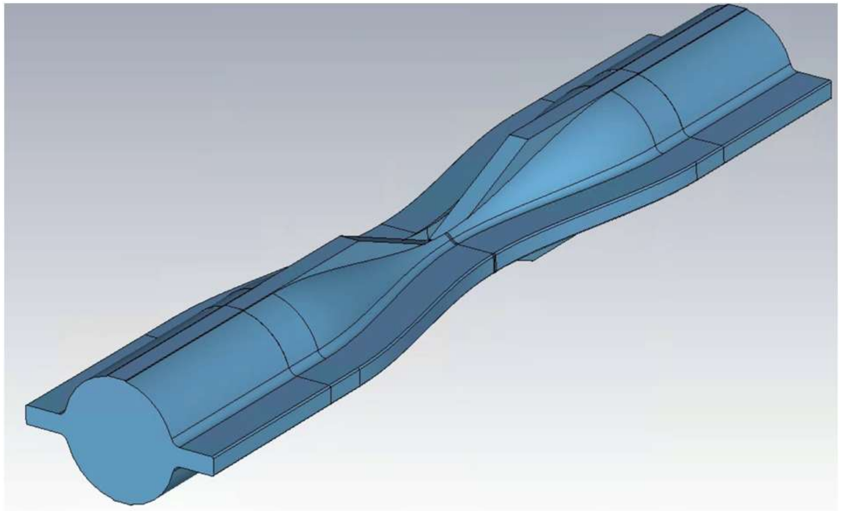


Wake potential of 0.4 mm Gaussian bunch

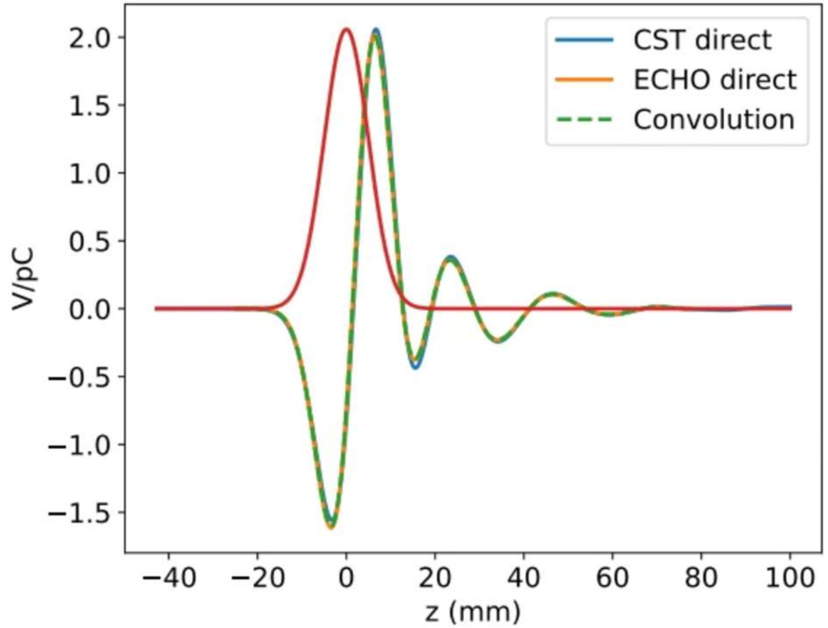




Preliminary work on collimation system



geometric longitudinal wakefield of a 5 mm Gaussian bunch



Summary of the collimator settings for the Z mode. The table doesn't include the SR collimators around the IPs, nor the collimators for a separate off-momentum collimation insertion. The collimator settings and parameters are very preliminary.

#ID	name	S_from_IPA[m]	angle[rad]	betax[m]	betay[m]	halfgap[m]	Material	Length[m]	nsig
1	TCP.H.B1	42515.0	0.0000000000E+00	2.3409490076E+03	5.2815752133E+01	1.5900392552E-02	C	6.00000E-01	2.00000E+01
2	TCP.V.B1	42520.0	1.5707963268E+00	2.2052869730E+03	5.3330774325E+01	1.0223908927E-03	C	6.00000E-01	1.40000E+02
3	TCS.V1.B1	42544.43	1.5707963268E+00	1.6009831201E+03	6.9460296781E+01	1.2834797764E-03	C	1.00000E+00	1.54000E+02
4	TCS.H1.B1	42661.16	0.0000000000E+00	5.5183272400E+01	4.5851766751E+02	2.6243639250E-03	C	1.00000E+00	2.15000E+01
5	TCS.H2.B1	42781.26	0.0000000000E+00	4.9268611828E+02	1.3375254057E+02	7.8416146547E-03	C	1.00000E+00	2.15000E+01
6	TCS.V2.B1	43103.49	1.5707963268E+00	3.7084032928E+02	1.4986857019E+03	5.9617806710E-03	C	1.00000E+00	1.54000E+02

Some comments on the impedance budget and collective effects

- FCC-ee is still an ongoing project, and, as we evaluate and add new devices, the total machine impedance increases more and more
- We are still missing several important devices, such as the collimation system, vacuum flanges, …
- On the other hand, the impedance evaluated so far already demonstrates how this machine can become critical due to collective effects
- The instabilities shown in the following will change based on the new impedance contributions that will gradually be added, but they suggest that we need to look for diversified mitigation solutions.

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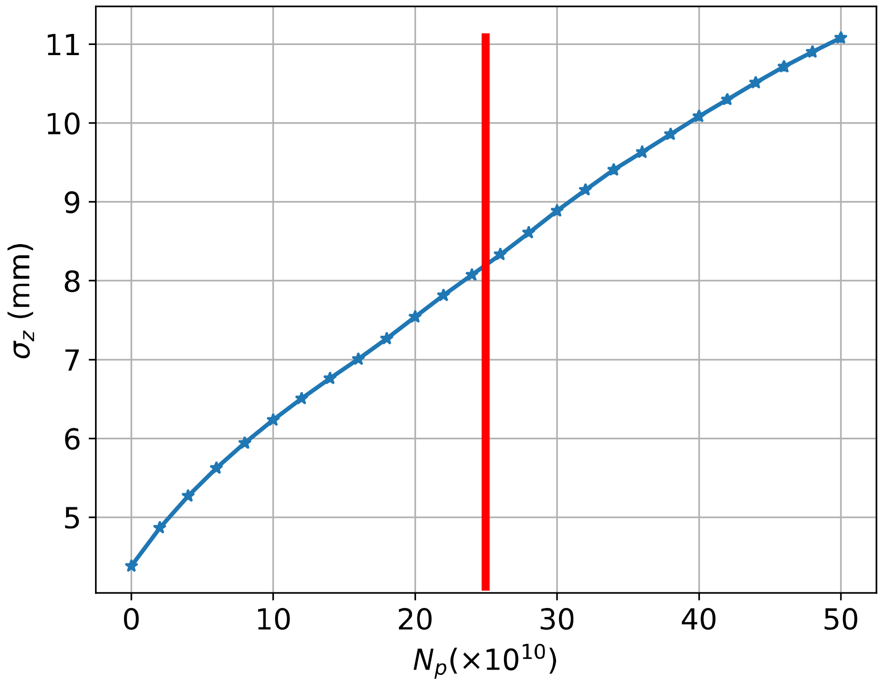
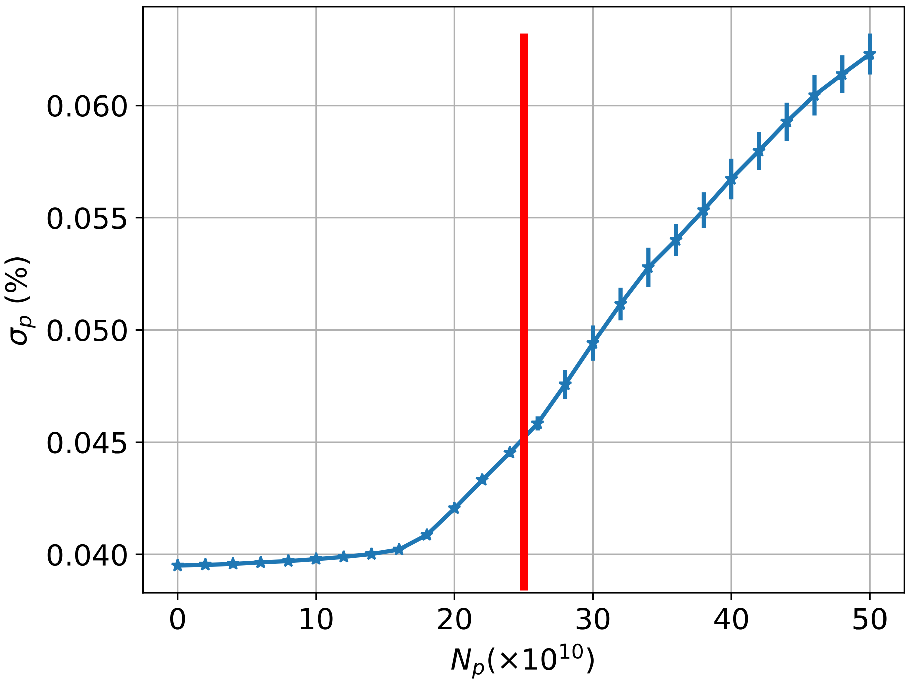
Longitudinal microwave instability

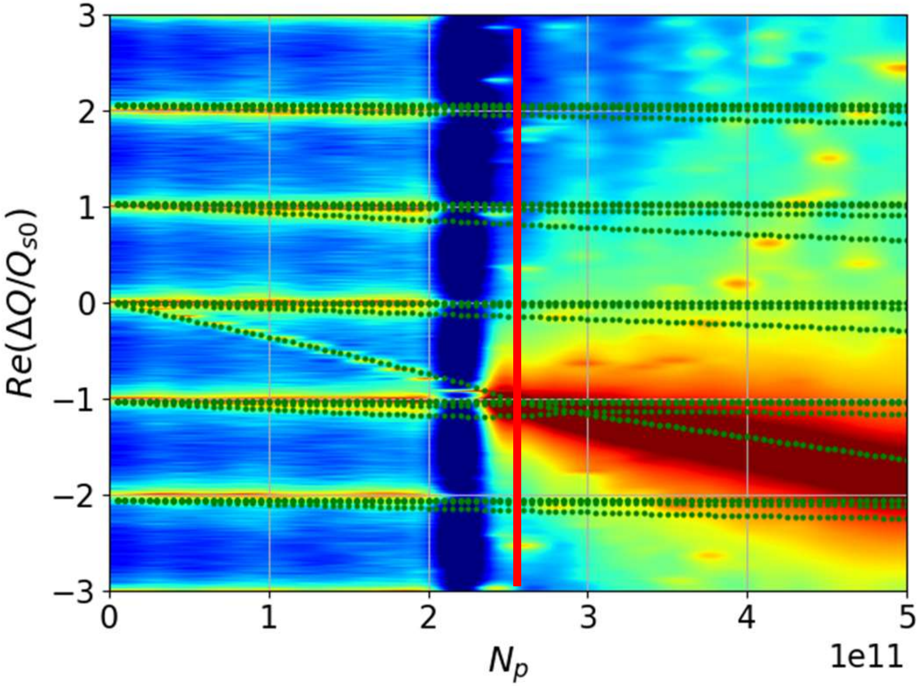




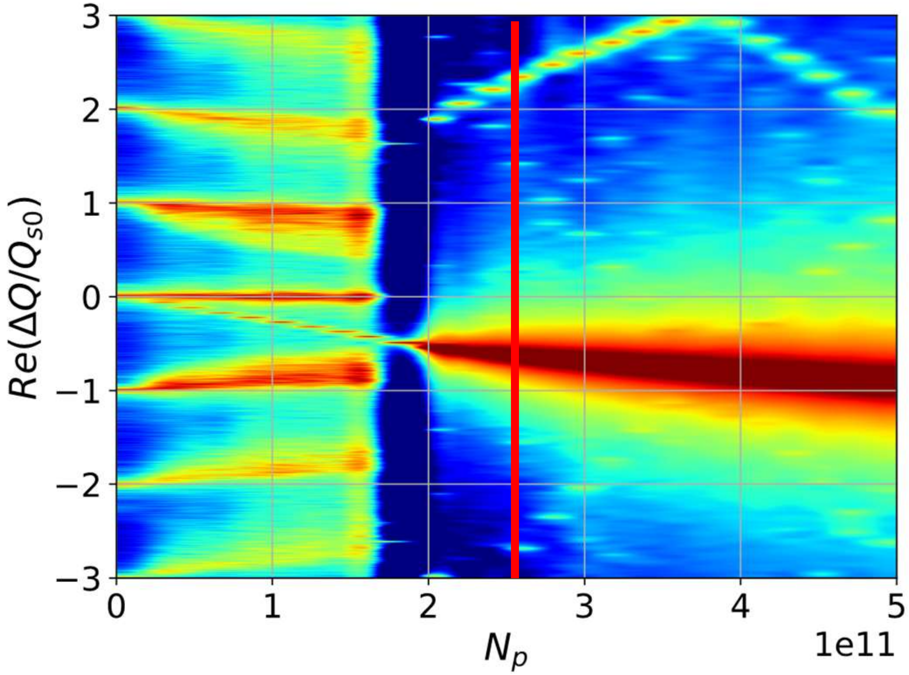
no collision → no beamstrahlung effect
The inclusion of beamstrahlung effect changes the bunch behaviour

Transverse Mode Coupling Instability

only transverse wakefield
(green dots → DELPHI)



longitudinal + transverse wakefield



no collision → no beamstrahlung effect
no chromaticity. When $Q' = 5$ the threshold remains essentially unchanged

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TCBI and feedback system

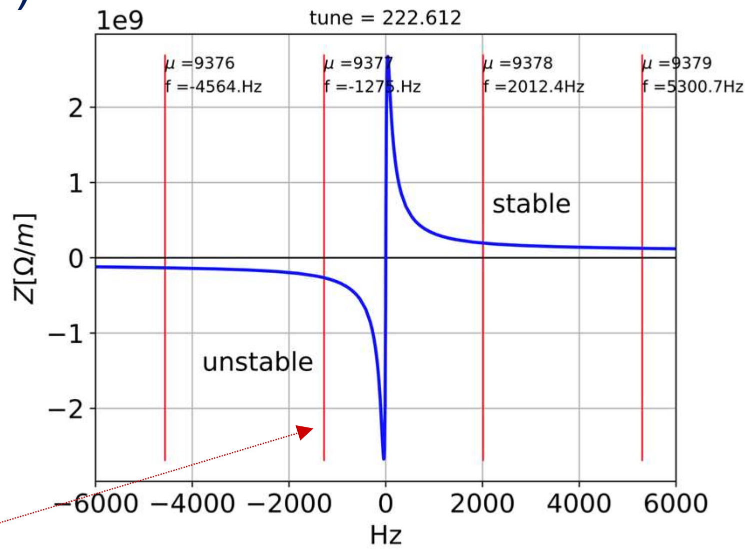
Transverse Coupled Bunch Instability (TCBI)

$$\frac{1}{\tau_{\mu,\perp}} = -\frac{ecI}{4\pi E Q_\beta}\sum_q Re[Z_\perp(\omega_q)]G_\perp\left(\frac{\sigma_z}{c}\omega'_q\right)$$

where $Re[Z_\perp(\omega_q)] = \mathrm{sgn}(\omega)\frac{C}{2\pi b^3}\sqrt{\frac{2Z_0 c}{\sigma_c|\omega|}}$

$$\omega_q = (qM + \mu + Q_\beta)\omega_0$$

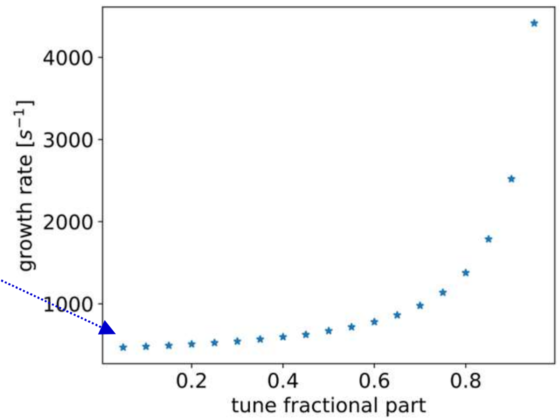
$$\omega'_q = \omega_q + \xi\frac{\omega_\beta}{\eta}$$



The most dangerous mode is that closest to the origin (with negative frequency)

Rise time of about 6 revolution turns

A robust feedback is required for the instability suppression!



TMCI and feedback system

- In SuperKEKB the transverse feedback was one important source of the '-1' mode instability which limited the machine to reach the nominal intensity. Its damping time is around 100 turns, that is about 1000 1/s.

- What is the effect of feedback in FCC-ee that needs about the same damping time, but this corresponds to only few turns?

- Is the TMCI perturbed by the feedback? And what about the longitudinal effect of the wake?

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Imaginary tune split and repulsion single-bunch instability mechanism in the presence of a resistive transverse damper and its mitigation

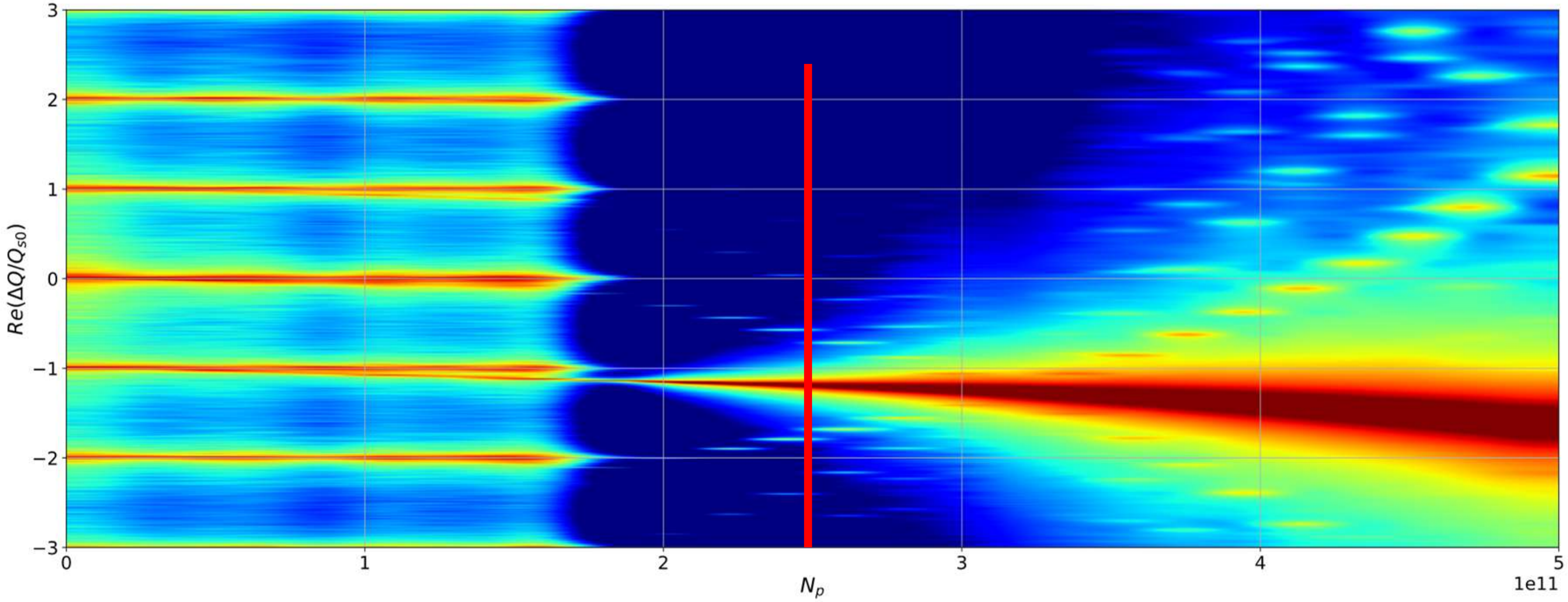
E. Métral*

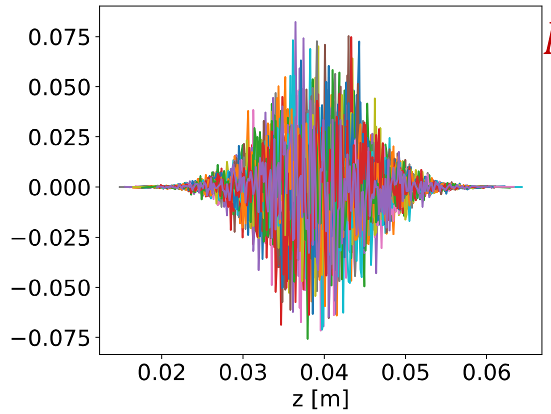
Introduction

[…] However, a resistive transverse damper also destabilizes the single-bunch motion below the transverse mode coupling instability intensity threshold (for zero chromaticity), introducing a new kind of instability, which has been called ITSR instability (for imaginary tune split and repulsion). […]

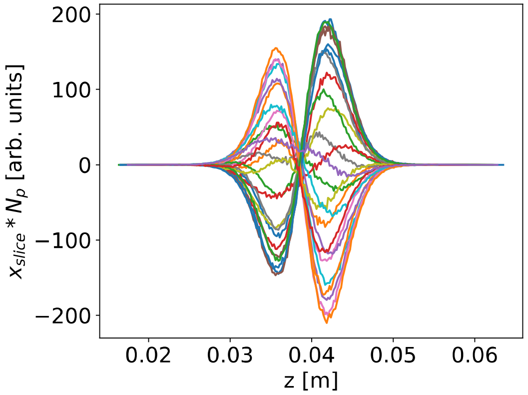
TMCI and feedback system: ITSR instability

only transverse wakefield, resistive feedback, 10 turns damping time





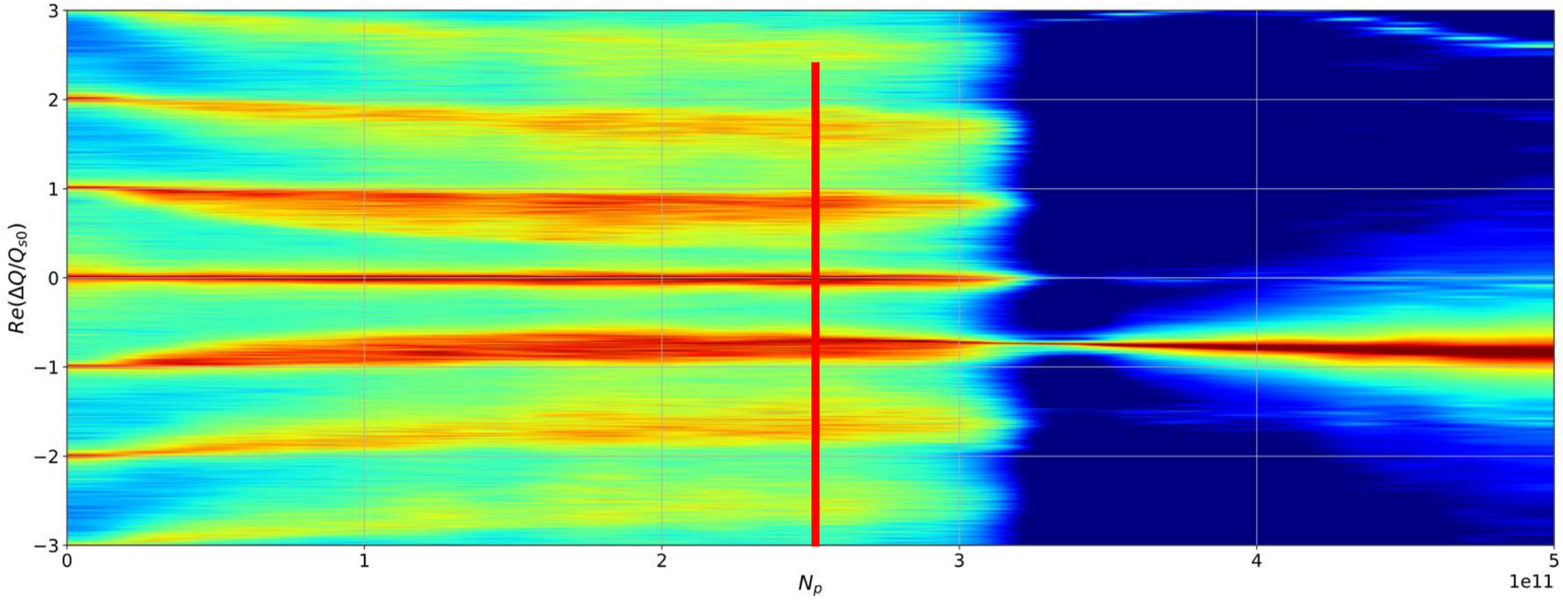
$N_p = 16 \times 10^{10}$

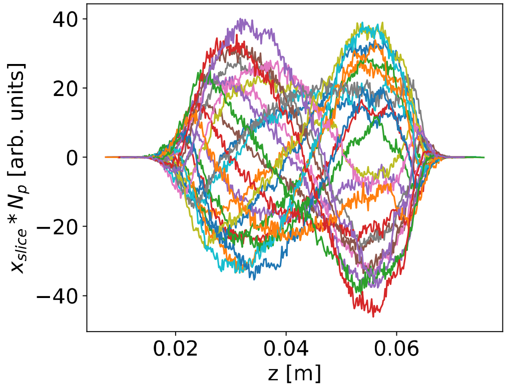


$N_p = 18 \times 10^{10}$

TMCI and feedback system: ITSR instability

long. + transverse wakefield, resistive feedback, 10 turns damping time



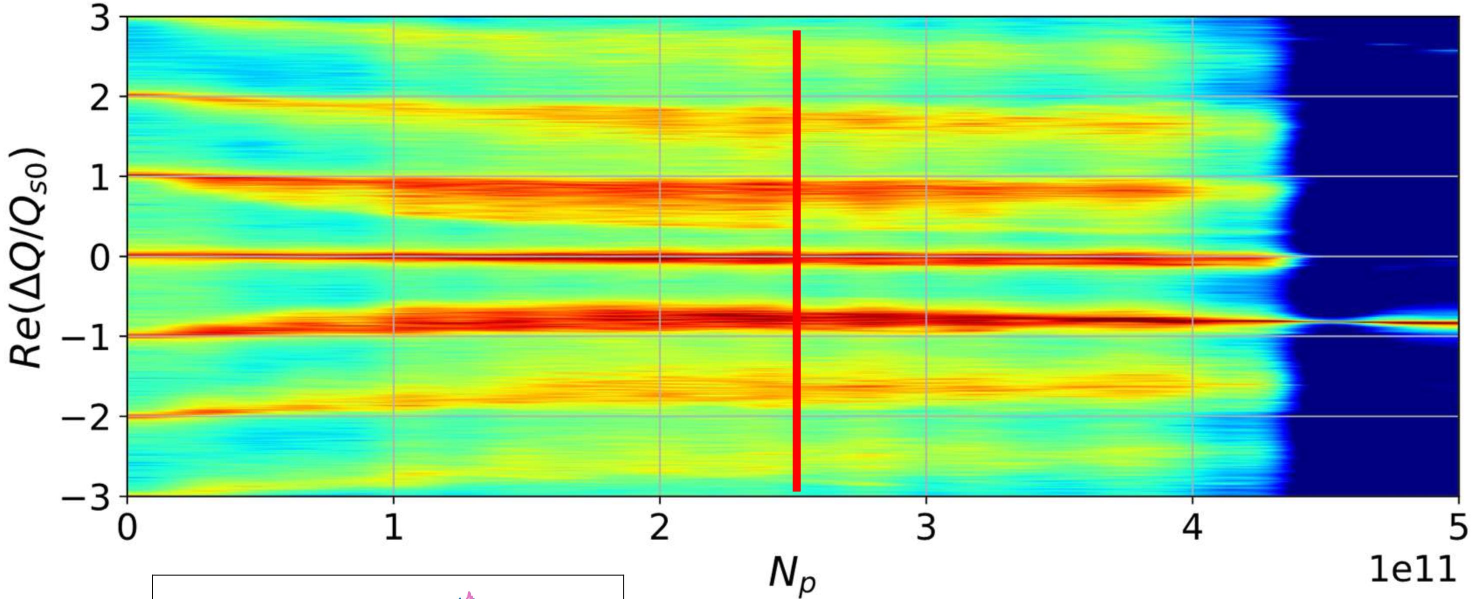


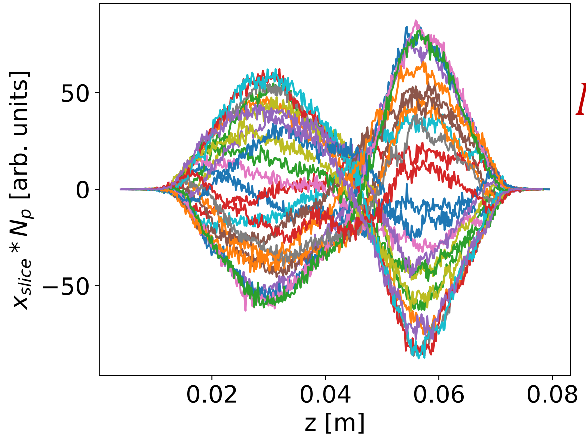
$N_p = 34 \times 10^{10}$

The spread in the synchrotron tune due to the longitudinal wakefield helps to mitigate the ITSR instability

TMCI and feedback system: ITSR instability

long. + transverse wakefield, resistive feedback, 4 turns damping time





$N_p = 46 \times 10^{10}$

Beamstrahlung reduces the effect of the longitudinal wakefield which, on its turn, has a beneficial effect on the TMCI with a resistive transverse damper. What happens if both effects are present?

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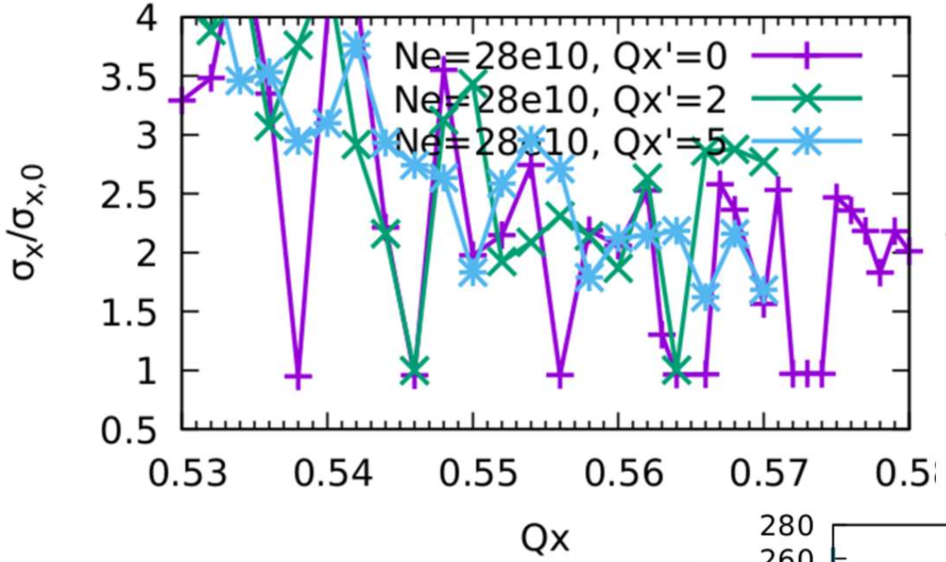
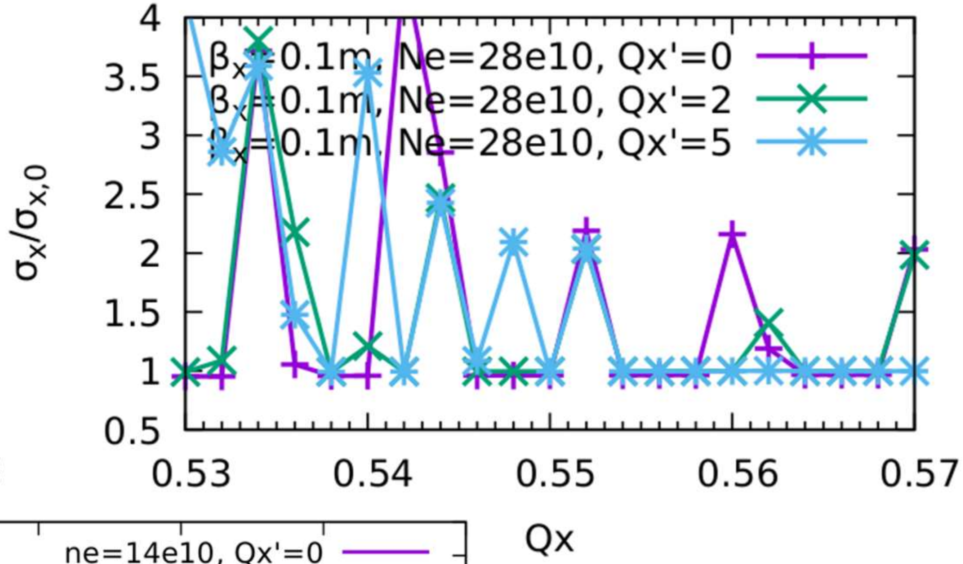
Beam beam with 4 IPs and longitudinal wakefield

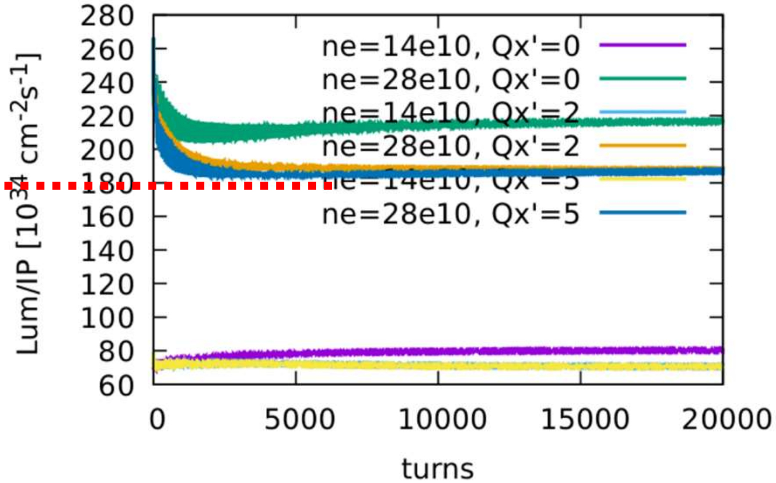
$\beta_x^* = 15$ cm



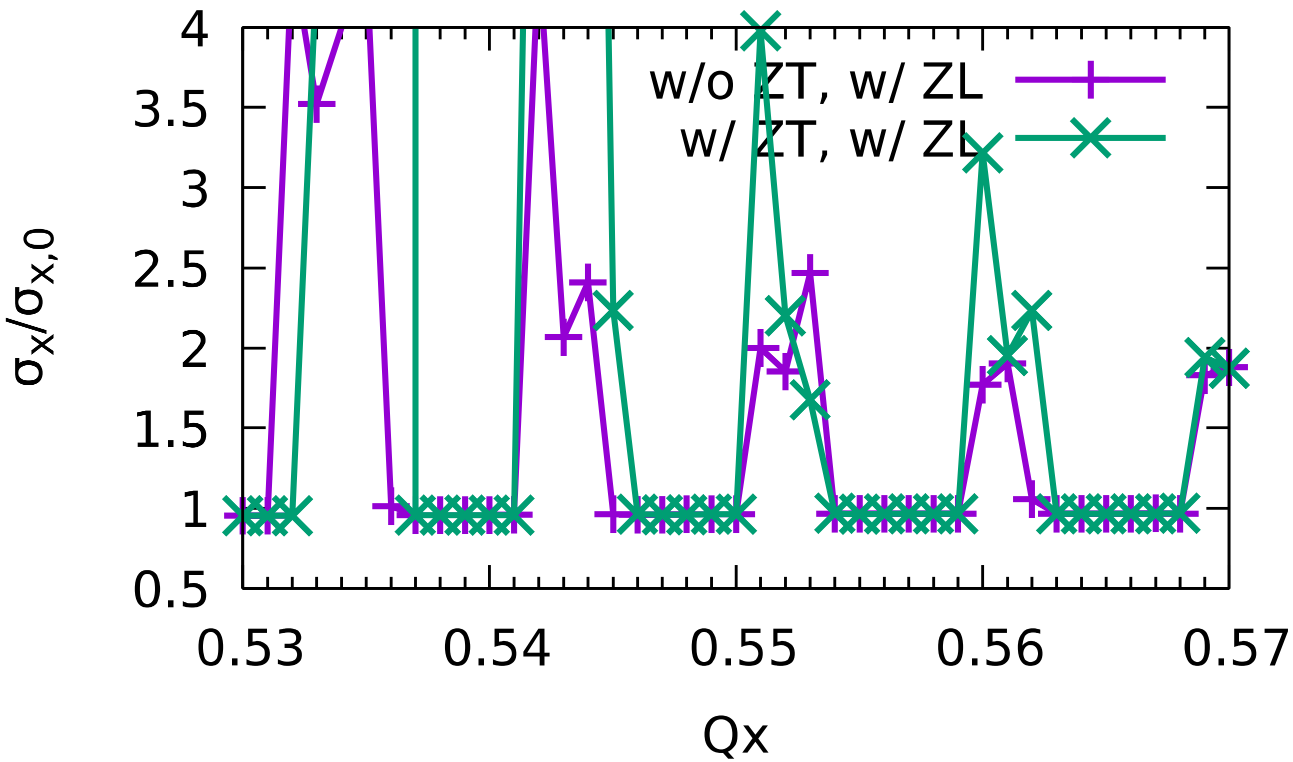
$\beta_x^* = 10$ cm



Nominal luminosity per IP



Effect of transverse wake (preliminary results)



$\beta_x^* = 10$ cm, $N_p = 24 \times 10^{10}$

Challenges and future plan

- Continue the evaluation of impedance and wakefield of other machine devices (collimation sytem, …)
- Evaluate the detuning (quadrupolar) impedance and its effect
- Continue to update the impedance repository
- Continue to investigate the interplay between beamstrahlung, longitudinal and transverse coupling impedance
- Continue to investigate diversified mitigation techniques (feedback system, chromaticity, …)
- Split the machine into segments, each one having its own longitudinal wake, transverse wake weighted by the local beta function, RF system (which is not evenly distributed along the machine), …
- Study the effects of possible transverse localized impedances (in particular for the collimation system)
- Use a more realistic transverse lattice
- Other effects: electron could, (also multi-bunch), ion instabilities …

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Thank you for your attention