



SAPIENZA
UNIVERSITÀ DI ROMA

DIPARTIMENTO DI SCIENZE DI BASE
E APPLICATE PER L'INGEGNERIA



Istituto Nazionale di Fisica Nucleare

Sezione di Roma

FCC-ee: Single-beam collective effects

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**Acknowledgements: R. Calaga, G. Castorina, A. Drago, R. Kersevan, B. Spataro,
F. Zimmermann, ...**



The Future Circular Collider Innovation Study (FCCIS) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754

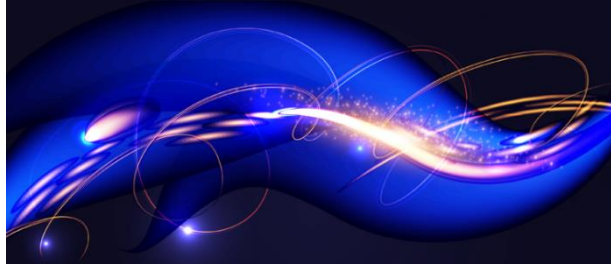
Outline

- FCC-ee main parameters
- Overview of wakefields and impedances evaluated so far
- Study of single beam instabilities
- Other studies on collective effects (e. g. in the Booster, e-cloud, ...)
- Challenges and plan for the Innovation Study

FCC-ee: The Lepton Collider

Future Circular Collider Conceptual Design Report Volume 2

Michael Benedikt et al. (Eds.)



<https://www.shutterstock.com/image-vector/abstract-motion-light-effect-futuristic-wave-56876030>
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Lowest beam energy: highest beam current, highest number of bunches, lowest emittance, and longest damping times

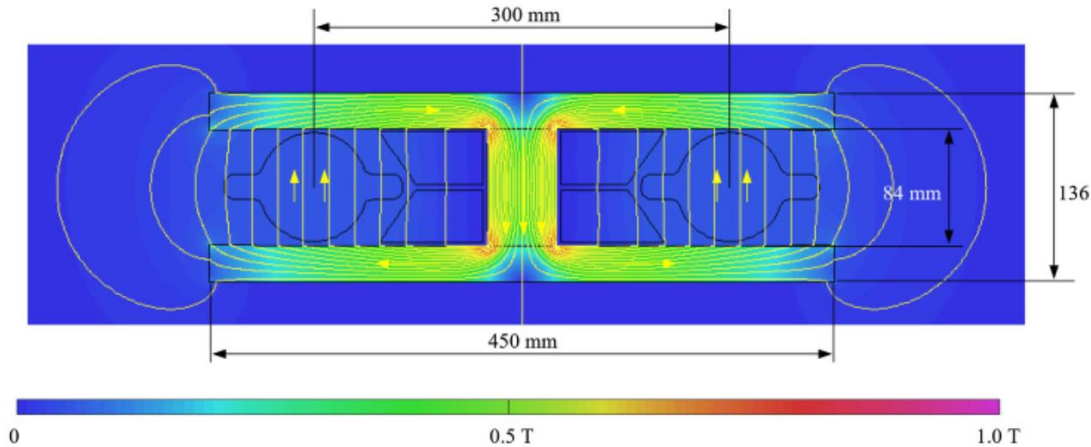
FCC-ee main parameters

Table 2.1. Machine parameters of the FCC-ee for different beam energies.

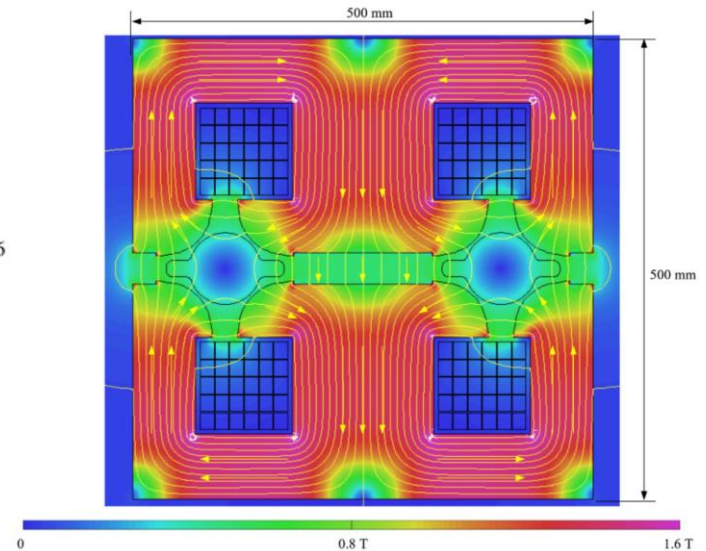
	Z	WW	ZH	tt̄	
Circumference (km)				97.756	
Bending radius (km)				10.760	
Free length to IP ℓ^* (m)				2.2	
Solenoid field at IP (T)				2.0	
Full crossing angle at IP θ (mrad)				30	
SR power / beam (MW)				50	
Beam energy (GeV)	45.6	80	120	175	182.5
Beam current (mA)	1390	147	29	6.4	5.4
Bunches / beam	16640	2000	328	59	48
Average bunch spacing (ns)	19.6	163	994	2763 ^a	3396 ^a
Bunch population (10^{11})	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x (nm)	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y (pm)	1.0	1.7	1.3	2.7	2.9
Horizontal size at IP σ_x^* (μ m)	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ_y^* (nm)	28	41	36	66	68
Energy spread (SR/BS) σ_δ (%)	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z (mm)	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Energy loss / turn (GeV)	0.036	0.34	1.72	7.8	9.2
RF frequency (MHz)	400			400 / 800	
RF voltage (GV)	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Synchrotron tune Q_s	0.0250	0.0506	0.0358	0.0818	0.0872
Longitudinal damping time (turns)	1273	236	70.3	23.1	20.4
RF bucket height (%)	1.9	3.5	2.3	3.36	3.36
Energy acceptance (DA) (%)	± 1.3	± 1.3	± 1.7	$-2.8 +2.4$	

Overview of wakefields and coupling impedances

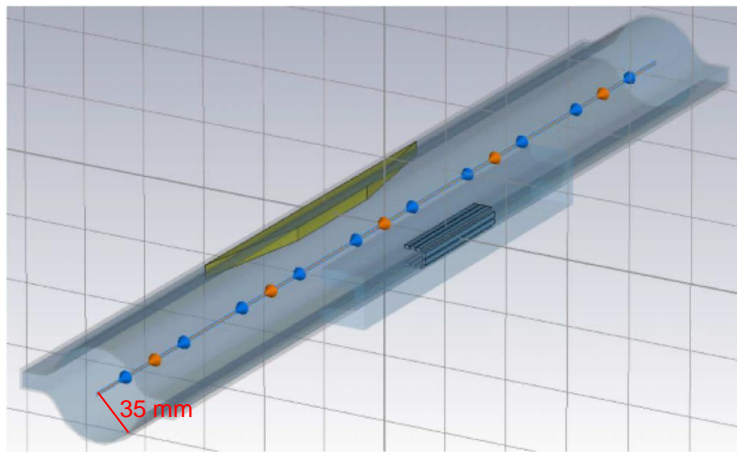
Beam pipe cross section (from CDR)



Main bending magnet; the outline of vacuum chambers with side winglets is also shown.



Cross-section of the main quadrupole, for a 10 T/m gradient.



3D model of the FCC-ee vacuum chamber with a synchrotron radiation absorber and pumping slots used for CST simulations.

Overview of wakefields and coupling impedances

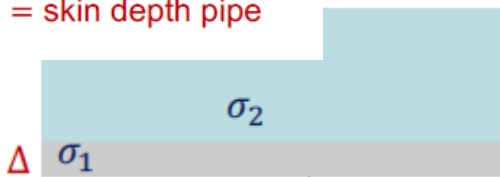
- One main difference of FCC-ee with respect to other colliders is the large circumference of $C = 97.75$ km.
- Since the resistive wall impedance is proportional to C , its contribution to the total machine impedance increases linearly with the machine length.
- This scaling law is not true for other machine devices, i.e. bellows, BPMs, rf cavities, etc.
- Example: the number of bellows. In KEKB, having a circumference of about 3 km, there are about 1000 bellows, while in FCC-ee we need about 8000 of them (8 times), despite a circumference about 30 times larger.
- **By increasing the machine length the contribution of the RW impedance assumes more and more importance with respect to other elements.**

Overview of wakefields and coupling impedances

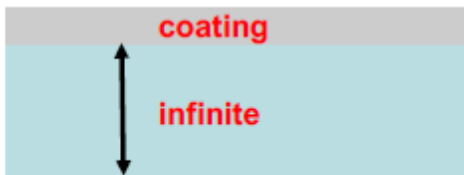
RW is a dominant source of wakefield and coupling impedance. For its evaluation we considered a circular beam pipe (ignoring the winglets).

A coating is required to suppress the e-cloud in the positron ring and/or for suppression needs in both rings.

- Δ = coating thickness
- δ_1 = skin depth coating
- δ_2 = skin depth pipe



$$Z_L(\omega) = \frac{Z_0 \omega}{4\pi c b} \left(\text{sgn}(\omega) - i \right) \delta_1 \frac{\alpha \tanh \left[\frac{1 - i \text{sgn}(\omega)}{\delta_1} \Delta \right] + 1}{\alpha + \tanh \left[\frac{1 - i \text{sgn}(\omega)}{\delta_1} \Delta \right]}$$



$$Z_T(\omega) = \frac{Z_0}{2\pi b^3} [1 - i \text{sgn}(\omega)] \delta_1 \frac{\alpha \tanh \left[\frac{1 - i \text{sgn}(\omega)}{\delta_1} \Delta \right] + 1}{\alpha + \tanh \left[\frac{1 - i \text{sgn}(\omega)}{\delta_1} \Delta \right]}$$

$$\varepsilon' = \varepsilon_r \varepsilon_0 + i \sigma / \omega; \quad \lambda = \frac{1 - i \text{sgn}(\omega)}{\delta}; \quad \alpha = \frac{\lambda_1 \varepsilon'_2}{\lambda_2 \varepsilon'_1}$$

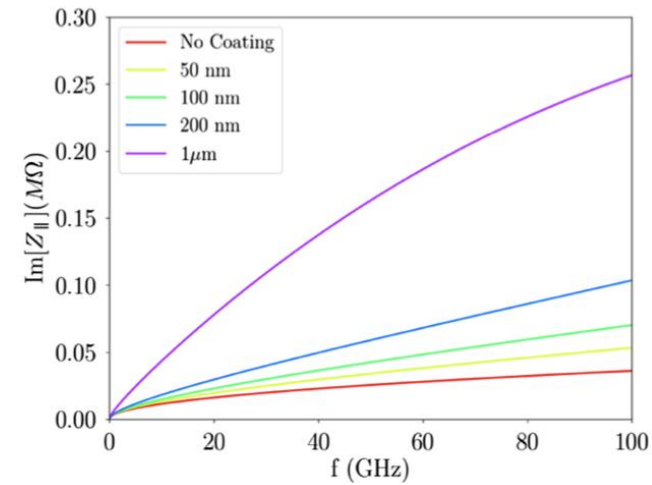
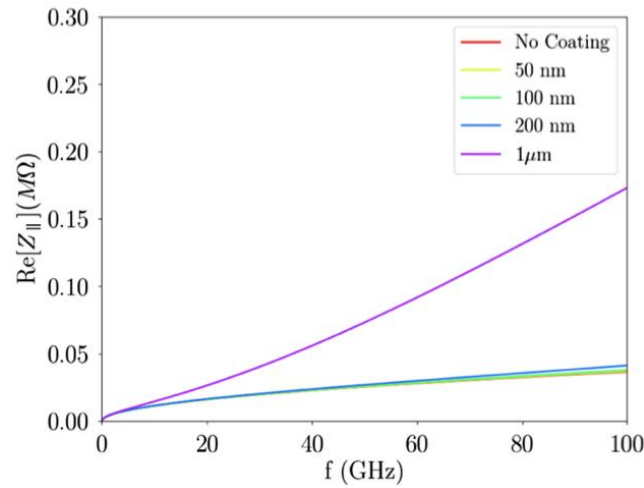
if $\Delta \ll \delta_1$

Overview of wakefields and coupling impedances

$$\frac{Z_{\parallel}(\omega)}{C} \simeq \frac{Z_0 \omega}{4\pi c b} \left\{ [\text{sgn}(\omega) - i]\delta_2 - 2i\Delta \left(1 - \frac{\sigma_1}{\sigma_2} \right) \right\} \quad \frac{Z_{\perp}(\omega)}{C} = \frac{Z_0}{2\pi b^3} \left\{ [\text{sgn}(\omega) - i]\delta_2 - 2i\Delta \left(1 - \frac{\sigma_1}{\sigma_2} \right) \right\}$$

1. The real part of the impedances depends neither on the coating thickness nor on its conductivity (no power losses due to the coating).
2. The imaginary part has an additional term linear with the coating thickness.

These results have been confirmed by the code IW2D, developed at CERN, which evaluates the wakes and impedances of a generic multilayer circular (or flat) vacuum chamber.

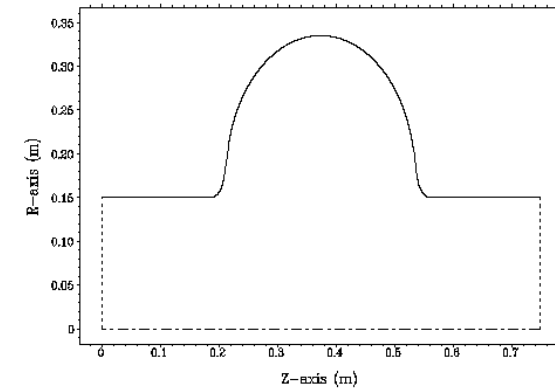
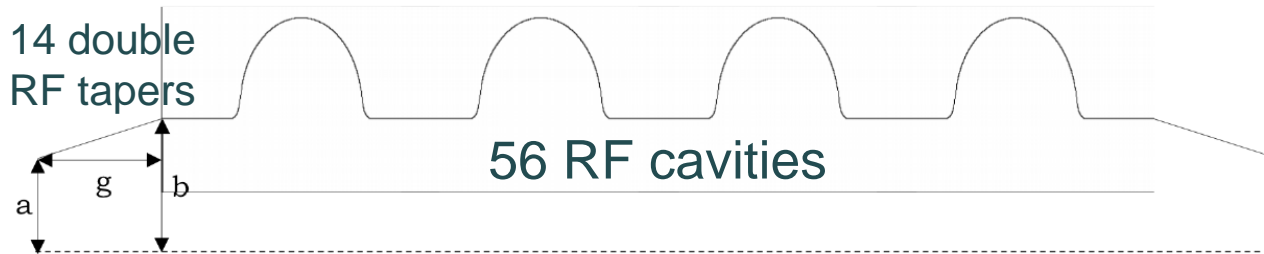


Overview of wakefields and coupling impedances

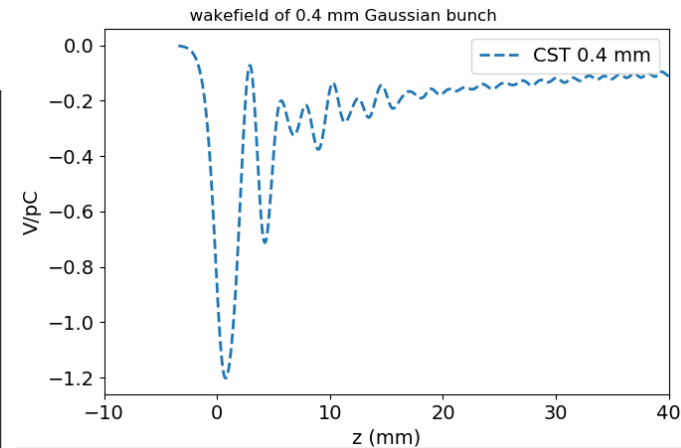
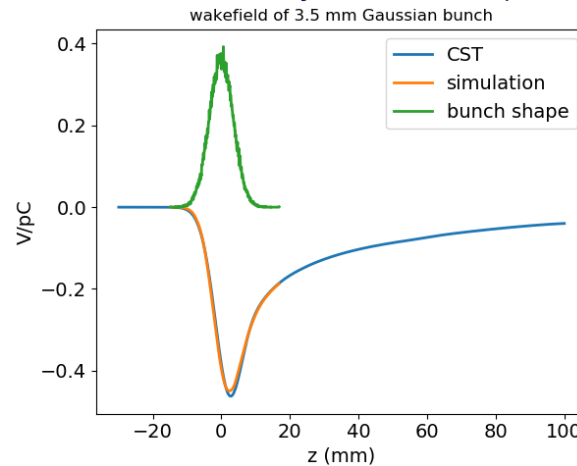
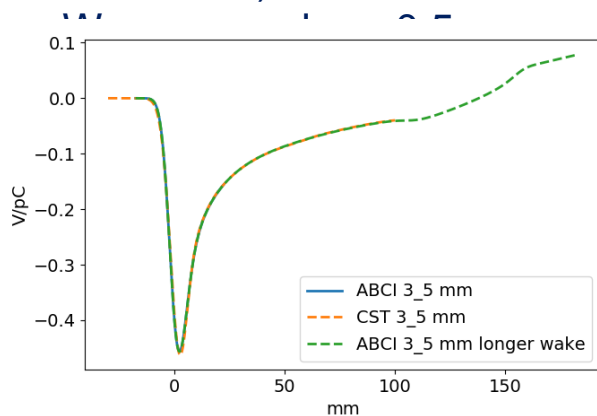
- The lower is the thickness of the coating, the lower is its contribution to the (imaginary) longitudinal impedance with respect to pure copper.
- Since a coating is needed, some measurements were performed at CERN to characterize NEG thin films, with the purpose of finding the minimum effective thickness satisfying vacuum and electron cloud requirements.
- A NEG film thickness between 100 and 200 nm, is a good candidate for coating thickness. For the beam collective effects we use, as reference, 100 nm.

Overview of wakefields and coupling impedances

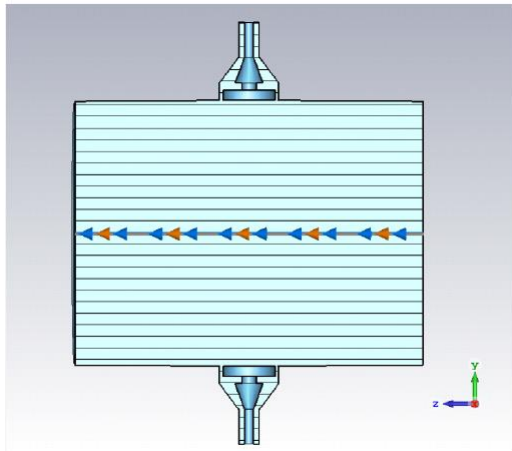
The wake fields and impedance have been evaluated for some important vacuum chamber components



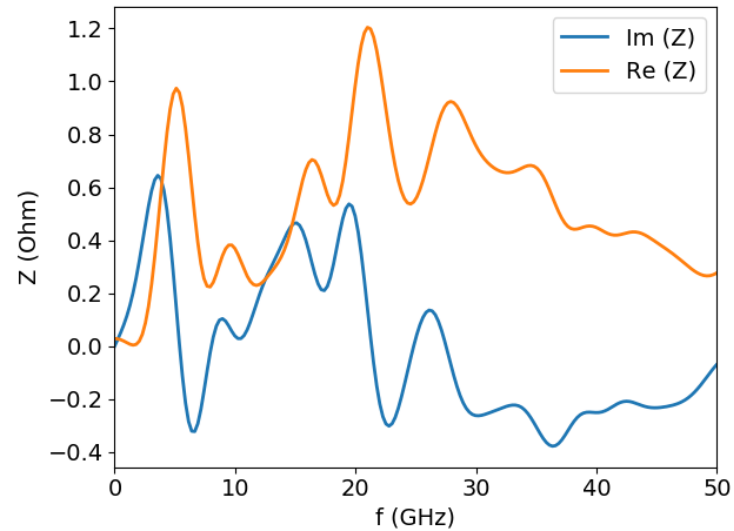
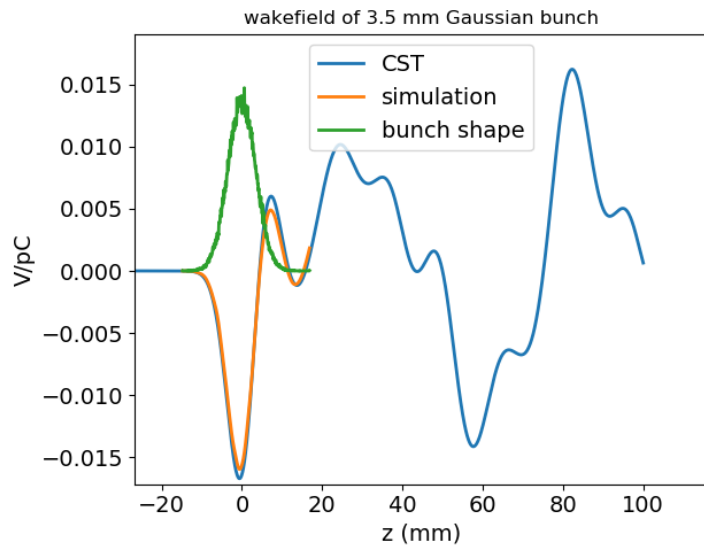
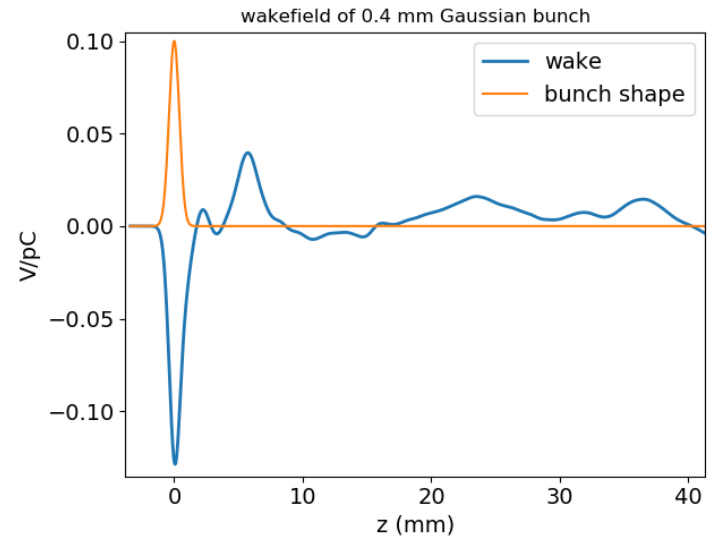
Tapers: transition from radius $a = 50$ mm outside the cryomodule to radius $b = 150$ mm inside the cryomodule (or vice-versa).



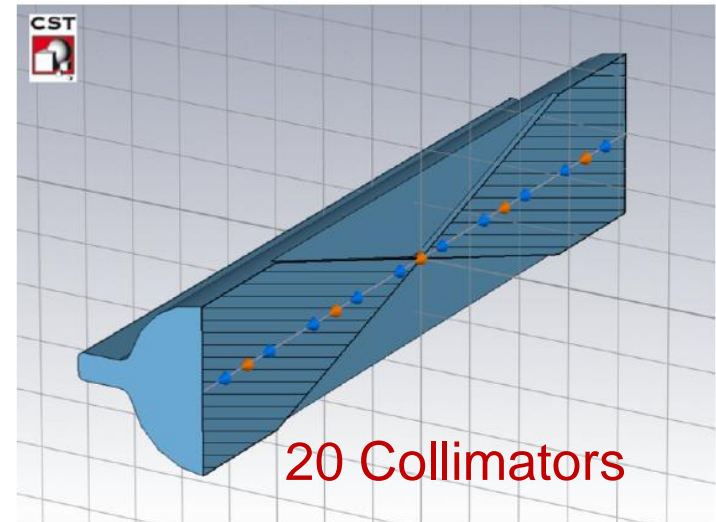
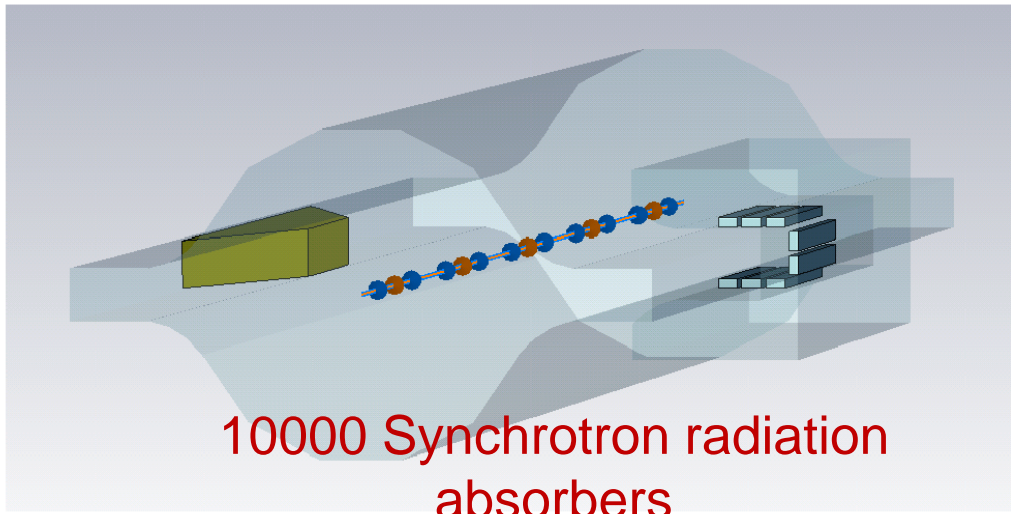
Overview of wakefields and coupling impedances



4000
BPMs

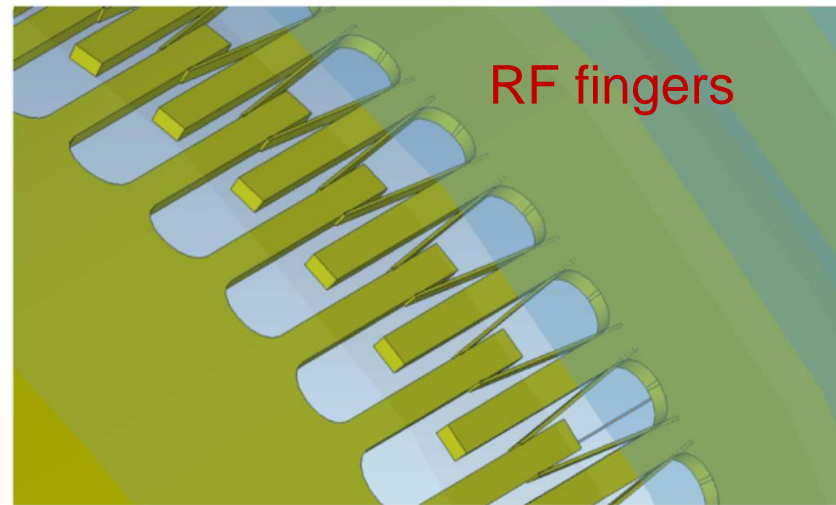
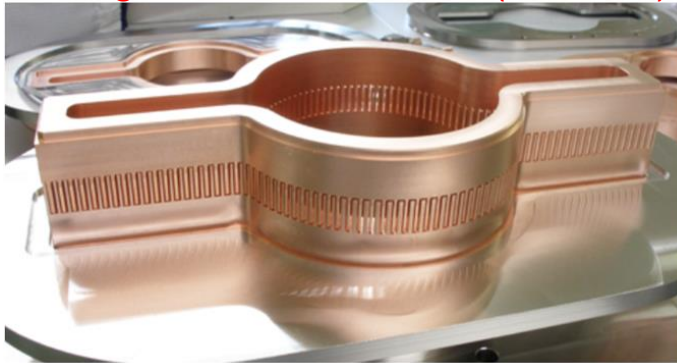


Overview of wakefields and coupling impedances



8000 bellows

Y. Suetsugu, Japan-Italy Collaboration Meeting "Crab Factories" 2008 (INFN-LNF)

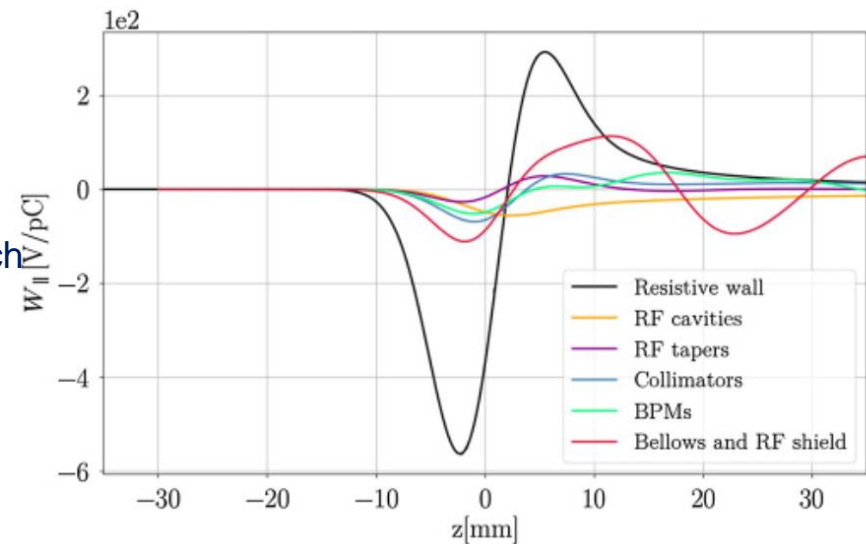


Overview of wakefields and coupling impedances

Component	Number	k_l (V/pC)	P_l (MW)
Resistive wall	97.75 km	210	7.95
RF cavities	56	18.5	0.7
RF double tapers	14	26.6	1.0
Collimators	20	18.7	0.7
Beam position monitors	4000	40.1	1.5
Bellows	8000	49	1.8
Total		362.9	13.7

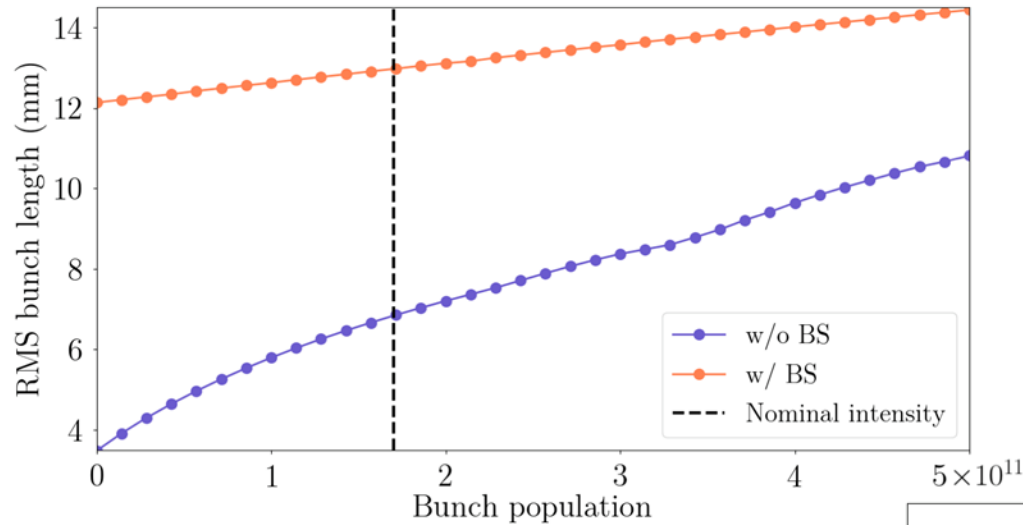
For nominal intensity and
3.5 mm Gaussian bunch
length

wake functions of 3.5 mm Gaussian bunch

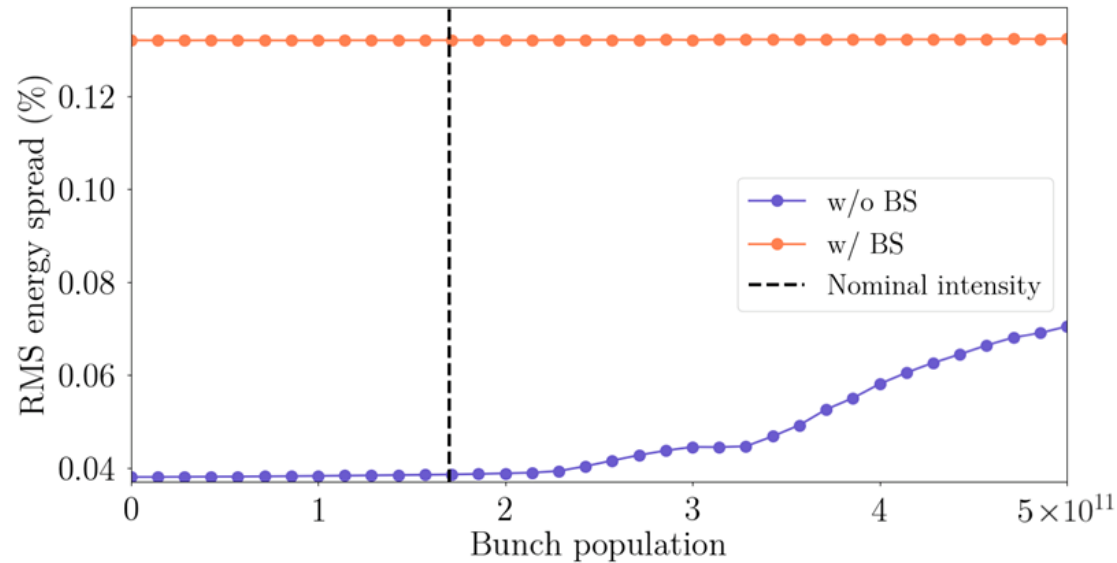


Single beam instabilities

Bunch length and energy spread versus bunch intensity

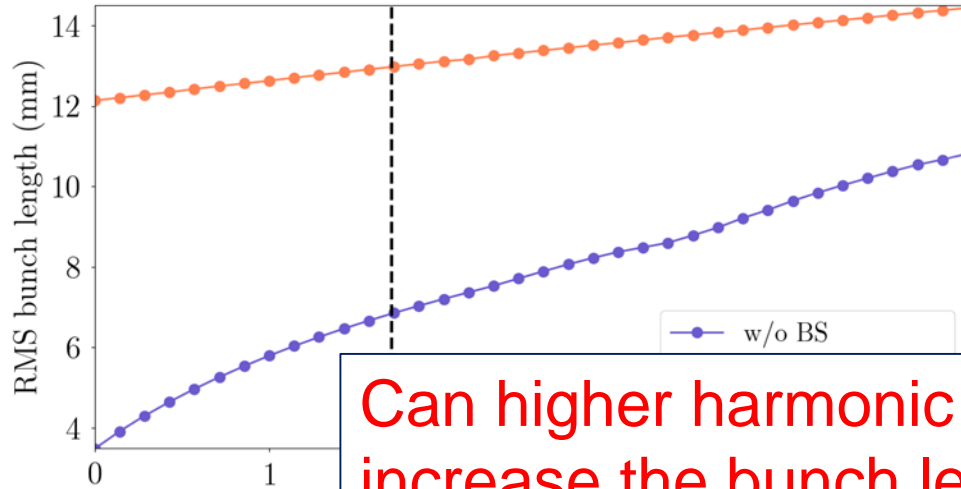


Beamstrahlung helps in mitigating microwave instability. What is the effect of the longitudinal impedance on the beam-beam interaction?



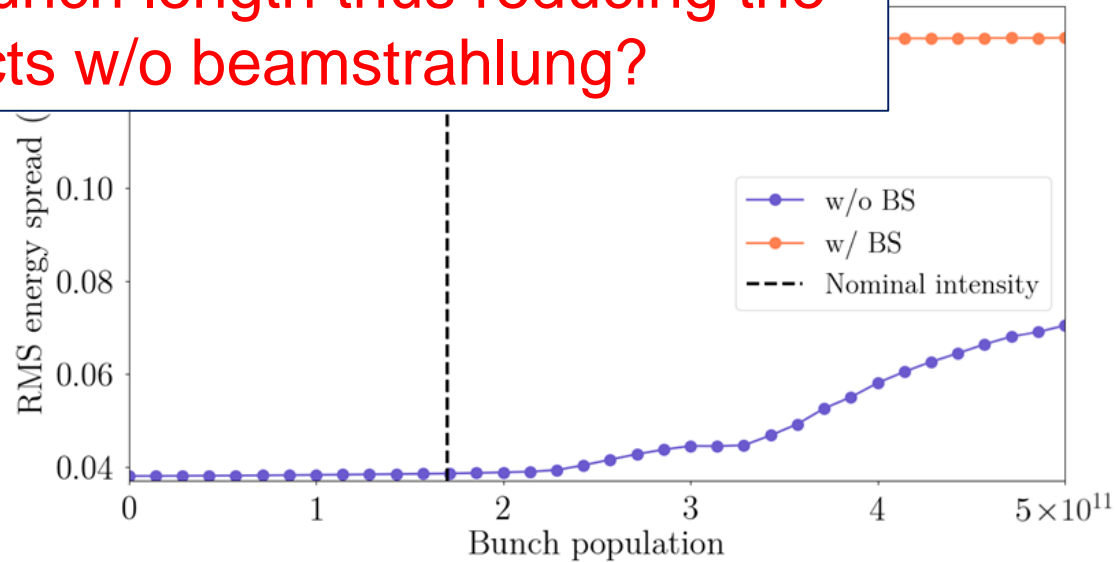
Single beam instabilities

Bunch length and energy spread versus bunch intensity



Can higher harmonic cavities be used to increase the bunch length thus reducing the wakefield effects w/o beamstrahlung?

Beamstrahlung helps in mitigating microwave instability. What is the effect of the longitudinal impedance on the beam-beam interaction?



Beam-beam and longitudinal impedance

PHYSICAL REVIEW ACCELERATORS AND BEAMS 23, 104402 (2020)

Self-consistent simulations of beam-beam interaction in future e^+e^- circular colliders including beamstrahlung and longitudinal coupling impedance

Yuan Zhang^{ⓧ,*,†}, Na Wang, Chuntao Lin^{ⓧ,‡}, Dou Wang[ⓧ], and Chenghui Yu^{ⓧ,§,||}

Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, Chinese Academy of Sciences, 19(B) Yuquan Road, Beijing 100049, China

Kazuhito Ohmi

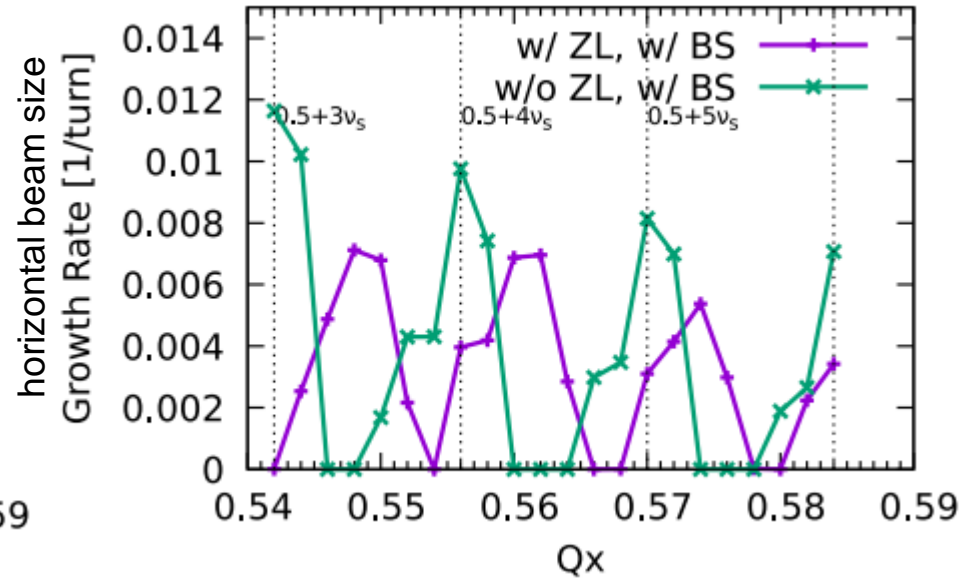
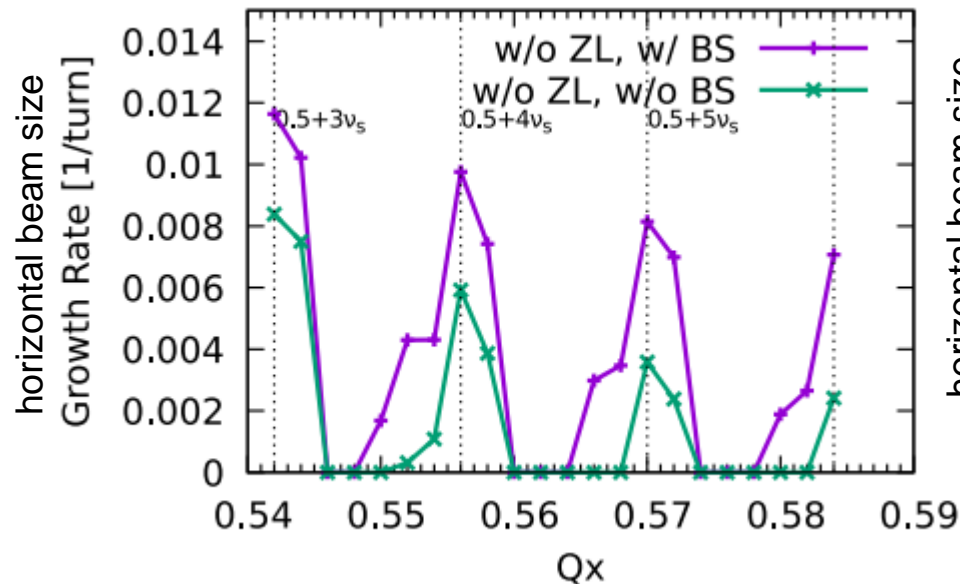
KEK, Tsukuba, Ibaraki 305-0801, Japan

Mikhail Zobov[ⓧ]

INFN-LNF, Frascati, 00044 Roma, Italy

The X-Z instability is a novel coherent beam-beam instability appearing with a large crossing angle.

For CEPC the authors have investigated the effects of beamstrahlung and longitudinal coupling impedance on this instability.



Beam-beam and longitudinal impedance

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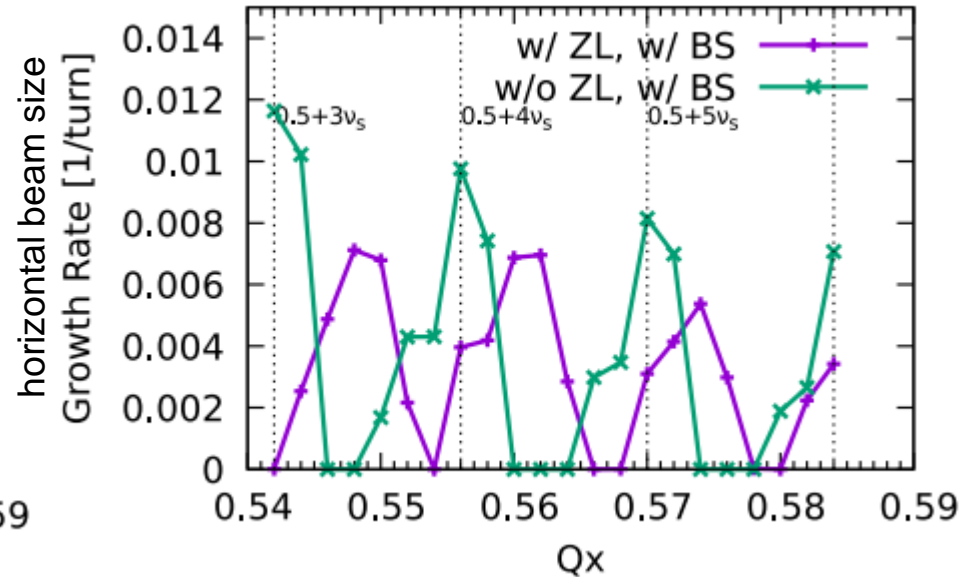
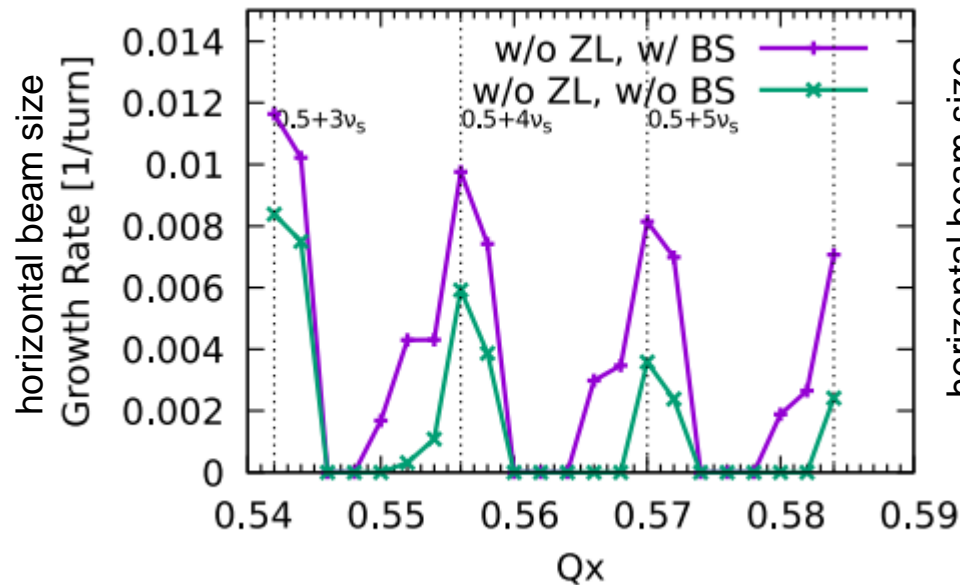
Kazuhiro
KEK, Tsukuba, Ibaraki

Mikhail Zobov[ⓧ]
INFN-LNF, Frascati, 00044 Roma, Italy

What about FCC-ee?

The X-Z instability is a novel coherent beam-beam instability appearing with a large crossing angle.

For CEPC the authors have investigated the effects of coupling impedance and longitudinal coupling impedance on this instability

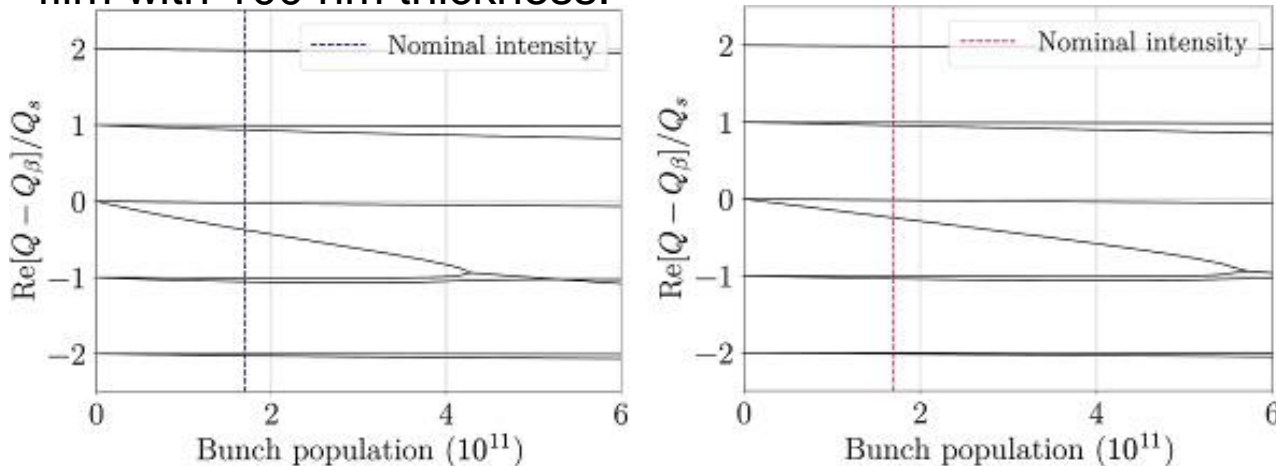


Single beam instabilities

Transverse Mode Coupling Instability

It takes place when frequencies of different coherent modes of transverse internal bunch oscillations couple.

Real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without (left) and with (right) beamstrahlung, by considering only the RW impedance produced by a NEG film with 100 nm thickness.



Results obtained with DELPHI (no tracking code) which uses a decomposition over orthogonal Laguerre polynomials for the radial modes. For each point in the plots, the bunch length at a given intensity, as obtained by PYHEADTAIL, has been used.

Single beam instabilities

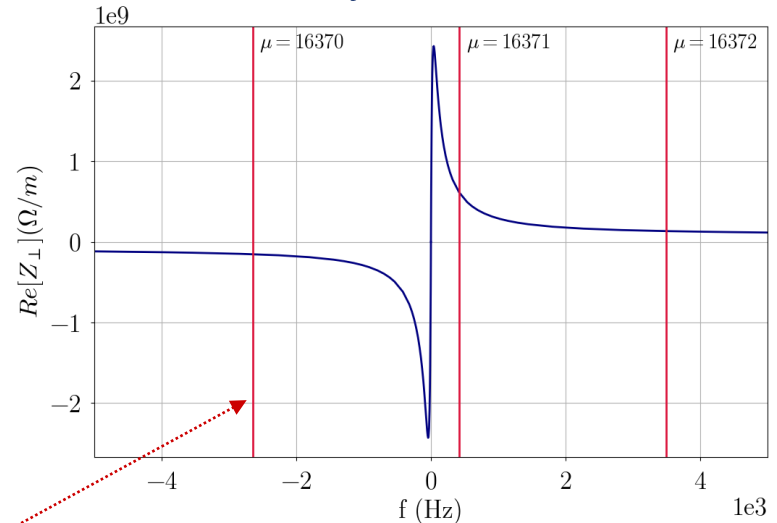
Differently from the longitudinal microwave instability TCBI is destructive.

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

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

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

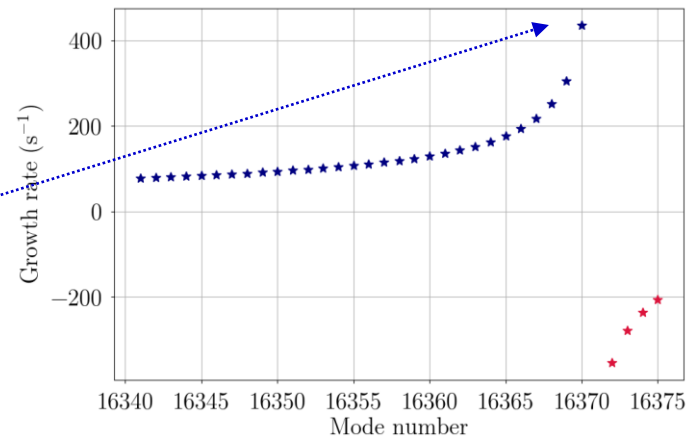
$$\omega'_q = \omega_q + \xi \frac{\omega_\beta}{\eta}$$



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

Its growth time is about 7 revolution turns

A robust feedback is required for the instability suppression!

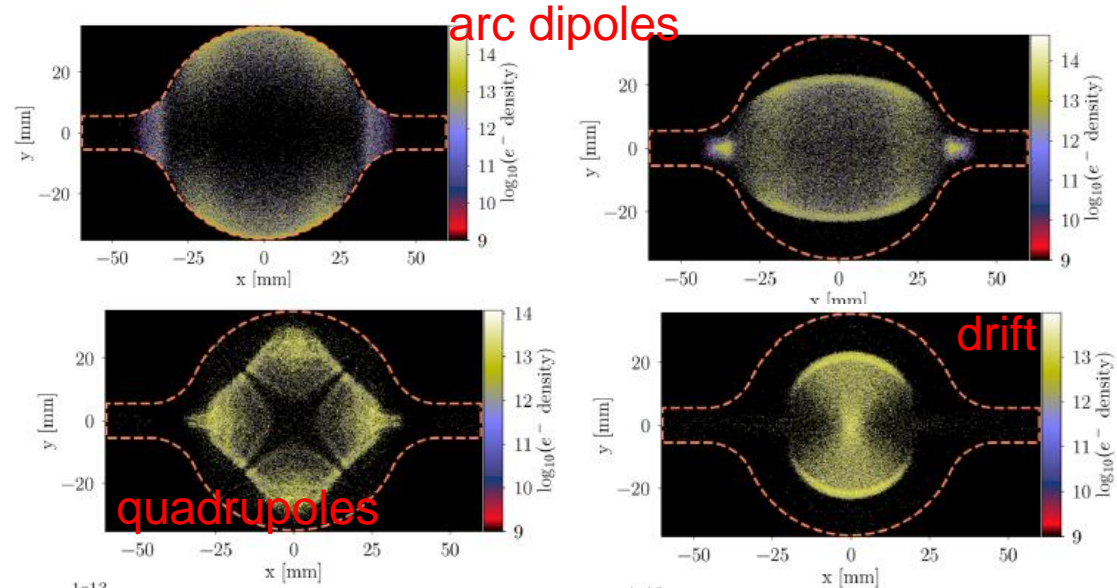


Single beam instabilities

Electron cloud build up

Simulations performed with PyECLOUD by E. Belli (PhD thesis)

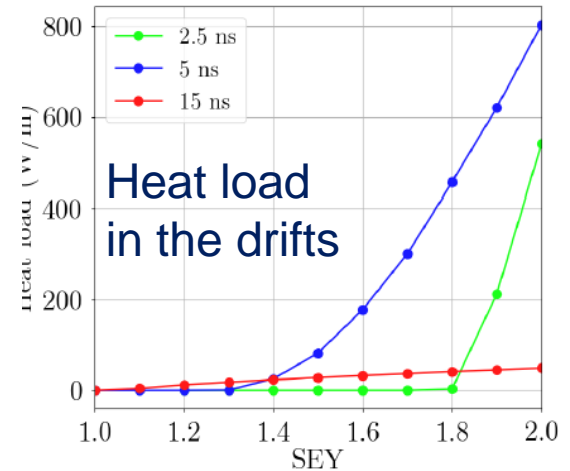
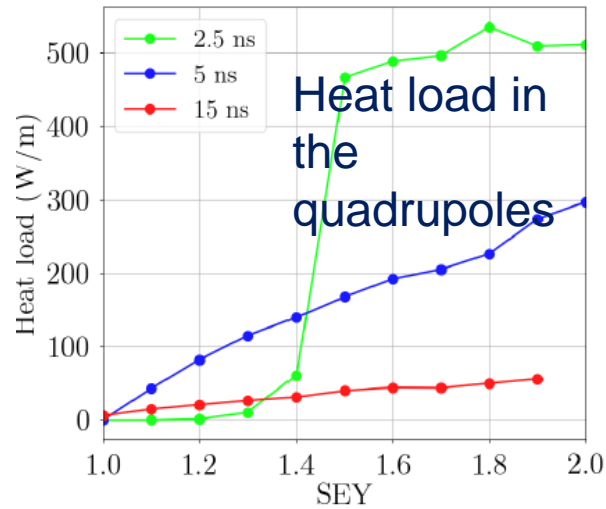
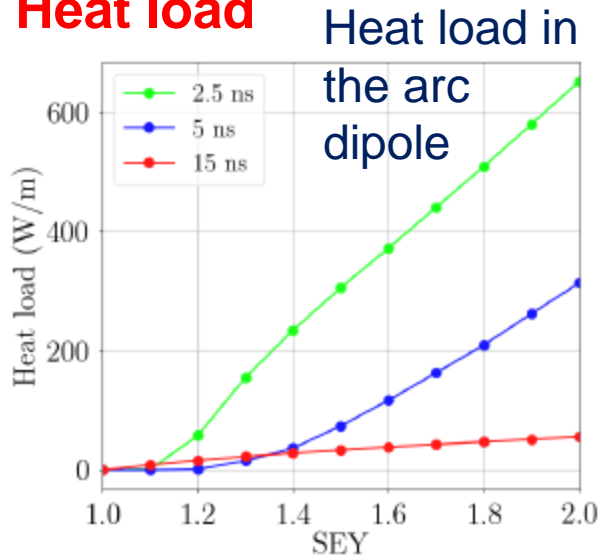
Element	L[m]	Magnetic field
Arc dipole	23.44	0.014 T
Arc quad	3.1	± 5.65 T/m
Arc drift	-	-
QC1L1	1.2	-96.3 T/m
QC1L2	1	50.3 T/m
QC1L3	1	9.8 T/m
QC2L1	1.25	6.7 T/m
QC2L2	1.25	3.2 T/m



- Realistic shape of the vacuum chamber
- Round chamber of 15 mm (20 mm) radius in Q1 (Q2)
- Electron cloud build-up in the arcs and IR magnets
 - ❑ Initial uniform distribution 10^9 e-/m
 - ❑ SEY scan
 - ❑ Nominal bunch intensity
 - ❑ Filling pattern: 80b + 25e
 - ❑ Bunch spacing scan: 2.5 ns, 5 ns, 15 ns

Single beam instabilities

Heat load



New electron cloud studies and simulations are now being performed by Fatih Yaman with different bunch spacings (10, 15 and 20 ns). Work in progress. See:

Fatih Yaman, 'Electron -Cloud Simulations for the FCC-ee Collider Arcs and for the e+ Damping Ring' 121st FCC-ee Optics Design Meeting, July, 2020

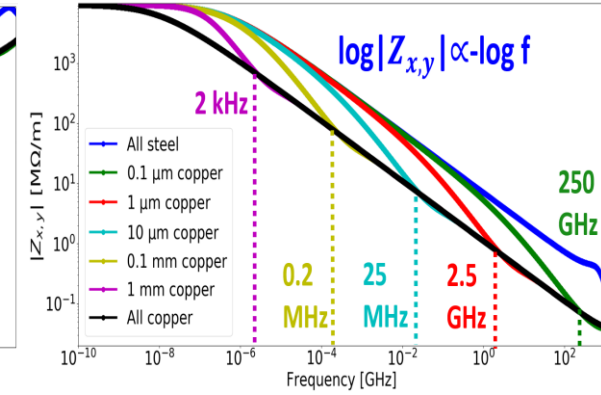
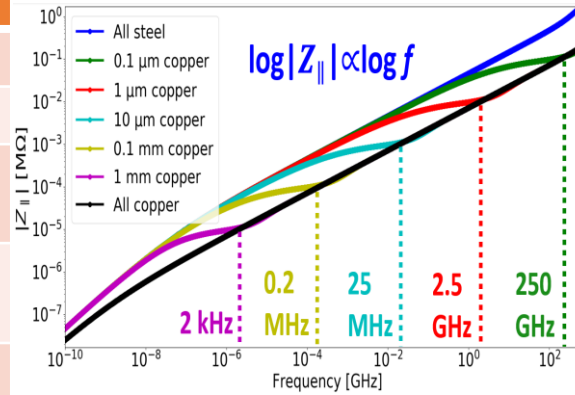
Fatih Yaman, 'Electron cloud build up in the collider: towards lower density', 123rd FCC-ee Optics Design Meeting, July, 2020

FCCee-Booster Beam Dynamics Studies

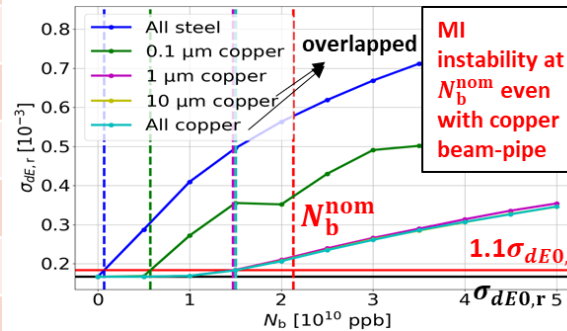
1) Simulated parameters

Parameters	Value
Machine circumference (C_r)	97.756 km
Beam energy at injection (E_0)	20 GeV
Bunch population (N_b^{nom})	2.13×10^{10} ppb
SR 1σ rel. energy spread ($\sigma_{dE_{0,r}}$)	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)	0.0304
SR 1σ bunch length (σ_{z0})	1.26 mm

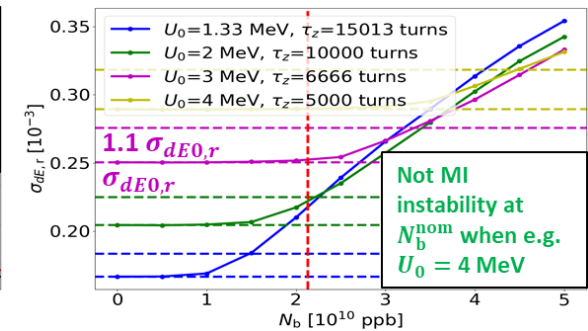
2) RW-impedance evaluation with IW2D adding a copper layer to beam-pipe



3) BLoND longitudinal beam dynamics simulations



4) BLoND simulations using 1 μm copper-layer increasing SR power-loss



5) DELPHI shows no presence of TMCI at N_b^{nom} when $U_0 = 4$ MeV.

6) Analytical considerations indicate that the TCBI rise-time is of about 2 revolution turns (fast feedbacks are required).

Challenges and future plan

- Impedance and wakefield evaluation of other machine devices (e. g. flanges)
- Include the interaction region in the broadband impedance model
- Update of some impedance sources (e. g. collimators, RW?) with more realistic models
- Create an impedance repository
- Evaluate the transverse wakefields and impedances and perform PyHEADAIL simulations
- Investigate the interaction between beamstrahlung and longitudinal coupling impedance
- Study the possible effect of higher harmonic cavities

Challenges and future plan

- Continue the study related to electron cloud, including the multi-bunch effects
- Continue the work on ion instabilities
- Continue the study of impedance evaluation (and create a repository) and collective effects for the Booster, in both the longitudinal and transverse planes
- Collaborate for the determination of a feedback system for coupled bunch instabilities (in particular, for the transverse plane, also in the Booster)
- ... maybe I'm missing some other important argument.

Challenges and future plan

- Continue the study related to electron cooling, including the multi-bunch effects
- Continue the work on ...
- Continue the study on ... (and create a review on ... effects for the Booster) ... and transverse plane
- Collaborate on the determination of a feedback system for longitudinal bunch instabilities (in particular, for the transverse plane, also in the Booster)
- ... maybe I'm missing some other important argument.

**Thank you for
your attention**