Mitigation of Coherent Beam Instabilities in FCC-ee

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ICFA mini-Workshop MCBI-2019
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OUTLINE

1. Future Lepton Circular Collider: brief introduction and parameters

2. FCC-ee wake fields and coupling impedance

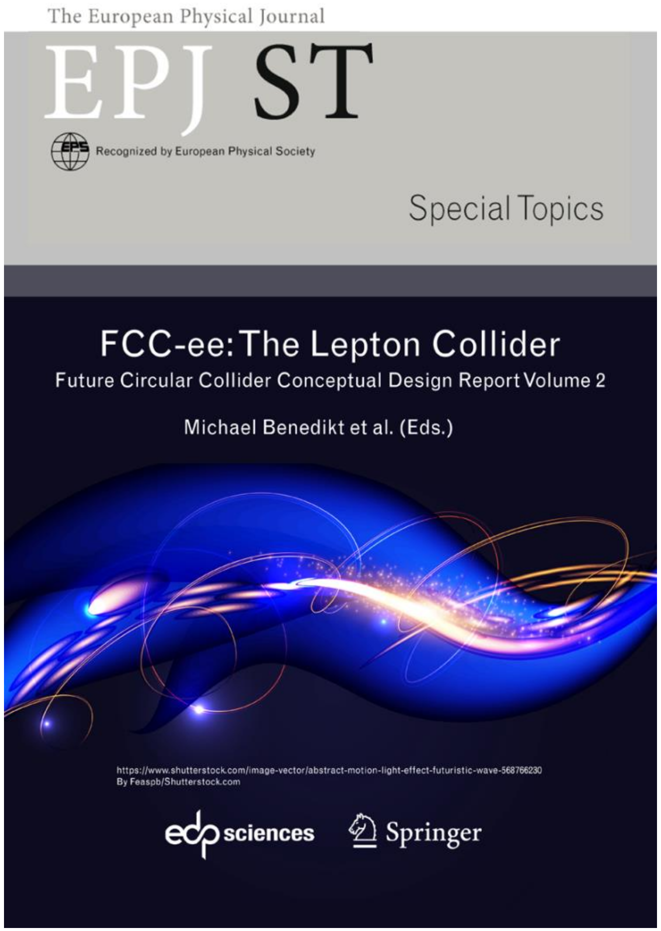
3. Impedance-related beam instabilities

4. Two stream instabilities: ion instabilities and e-cloud effects

5. Other effects

6. Summary

FCC-ee parameters



1364 contributors
from 351 institutes

	Z	W	H	tt	
Beam energy [GeV]	**45.6**	**80**	**120**	**175**	**182.5**
Circumference C [km]	97.75				
RF frequency f_{RF} [MHz]	400				
Arc cell	60°/60°	60°/60°	90°/90°	90°/90°	90°/90°
RF voltage V_{RF} [GV]	0.1	0.75	2.0	8.8	10.3
Momentum compaction α_c [10^{-5}]	1.48	1.48	0.73	0.73	0.73
Horizontal tune Q_x	269.14	389.124	389.13	389.108	389.108
Vertical tune Q_y	267.22	391.20	391.20	391.18	391.18
Synchrotron tune Q_s	0.025	0.0506	0.0358	0.0598	0.0622
SR energy loss/turn U_0 [GeV]	0.036	0.34	1.72	7.8	9.2
Longitudinal damping time τ_l [ms]	415	77	23	7.5	6.6
Beam current I [mA]	1390	147	29	6.4	5.4
Number of bunches/ring	16640	1300	328	40	33
Bunch population N [10^{11}]	1.7	2.3	1.8	3.2	3.35
Horizontal emittance ε_x [nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y [pm]	1	1.7	1.3	2.7	2.9
Energy spread - $\delta_{dp,SR}$ [%] - $\delta_{dp,BS}$ [%]	0.038 0.132	0.066 0.165	0.099 0165	0.144 0.196	0.150 0.2
Bunch length - $\sigma_{z,SR}$ [mm] - $\sigma_{z,BS}$ [mm]	3.5 12.1	3.0 7.5	3.15 5.3	2.75 3.82	2.76 3.78

Lower beam energy, longer damping times, higher beam intensities and highest number of bunches

FCC-ee is a particle factory with an unprecedented luminosity

LEP FCC-ee

$$L(45.6GeV) \rightarrow 3.4\times10^{31} cm^{-2}s^{-1} \rightarrow 2.3\times10^{36} cm^{-2}s^{-1}$$

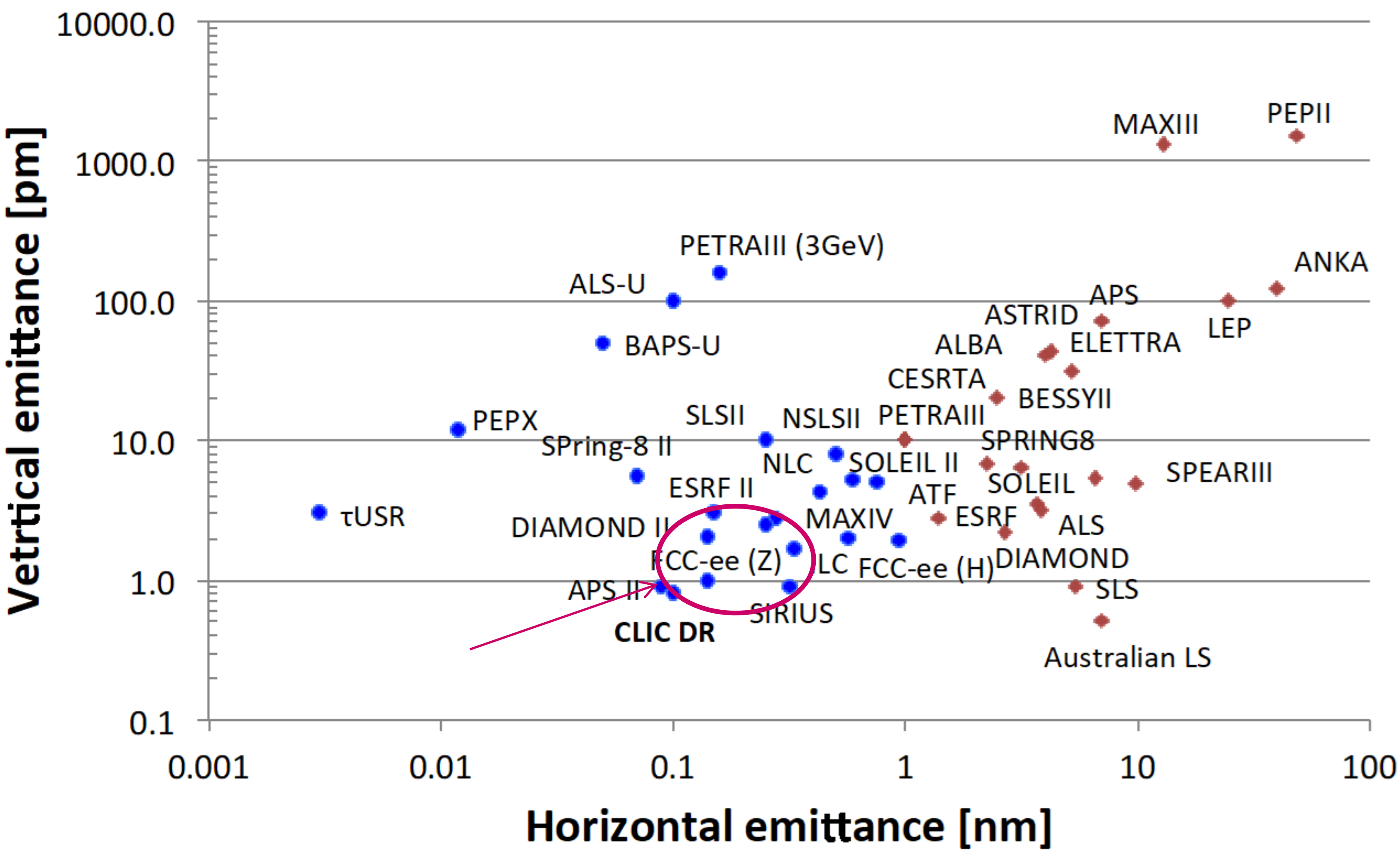
Main ingredients

1. Two separate rings allow colliding many bunches

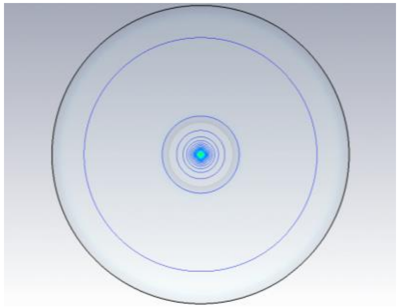
2. Crab waist collision concept (low emittance, low beta, high beam-beam parameter)

3. Longer perimeter allows storing higher intensity beams with the same synchrotron radiation losses

FCC-ee emittance is comparable with emittances of modern diffraction limited synchrotron light sources



Courtesy Yannis Papaphilippou



Beam Pipe Cross Section

The round cross section has been chosen in order to avoid the betatron tune shift with multibunch beam current due to quadrupolar resistive wall wake fields

$$\frac{dQ_\beta}{dI} = \pm\left(\frac{\pi\left(1+b^2/d^2\right)}{48Q_\beta}\right)\left(\frac{Z_0}{E_0/e}\right)\left(\frac{R}{b}\right)^2\left(\frac{L}{C}\right)$$

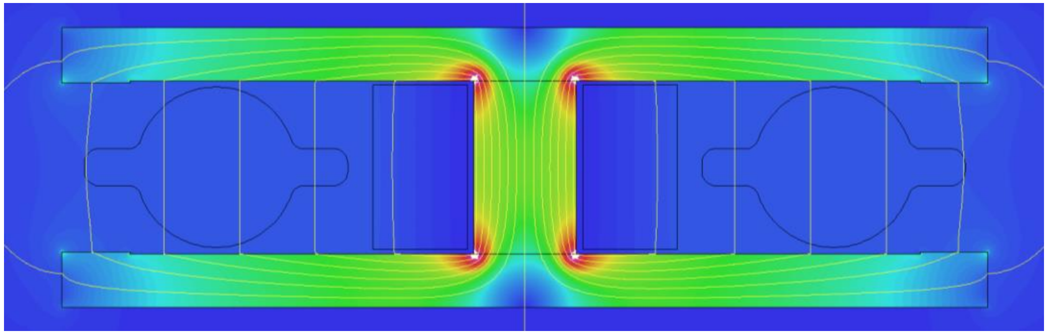
$\Delta Q_\beta \approx 0.42$

$I = 1.4A$

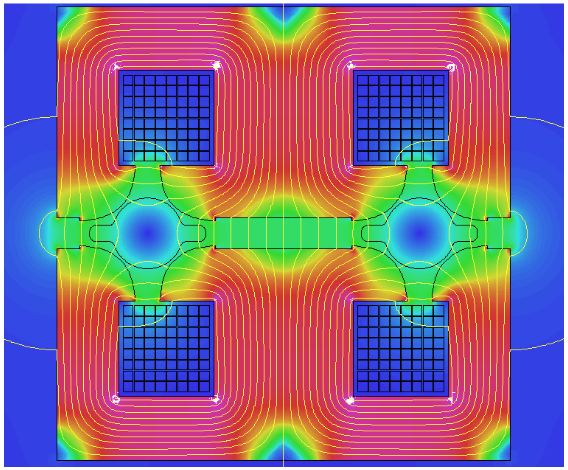
$2b \times 2d = 70 \times 120 mm^2$

Additional antechambers are foreseen for pumping purposes and installation of synchrotron radiation absorbers

Twin dipole magnet

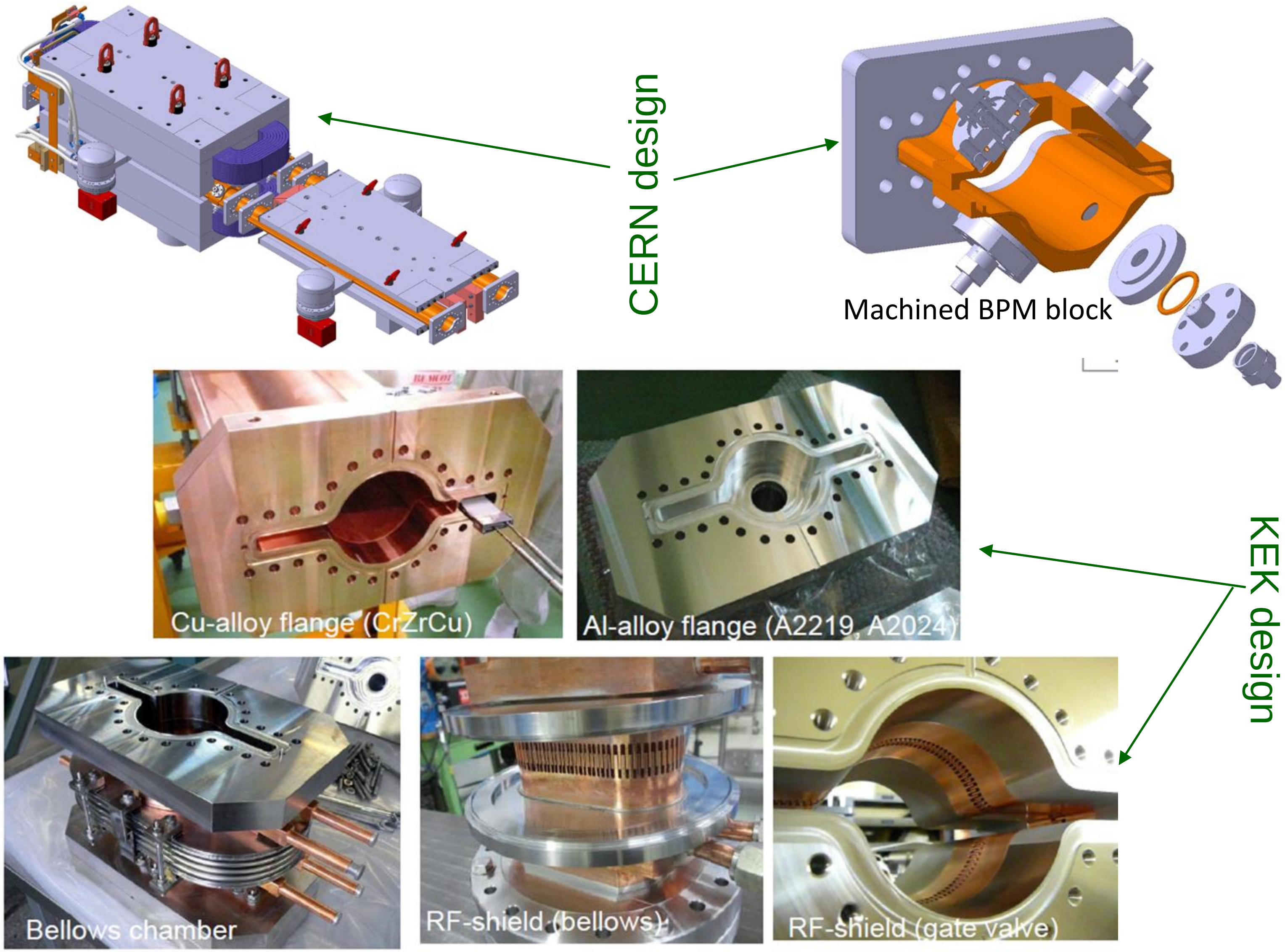


Quadrupole magnet



From Milanese's talk during FCC-ee Week, 2017

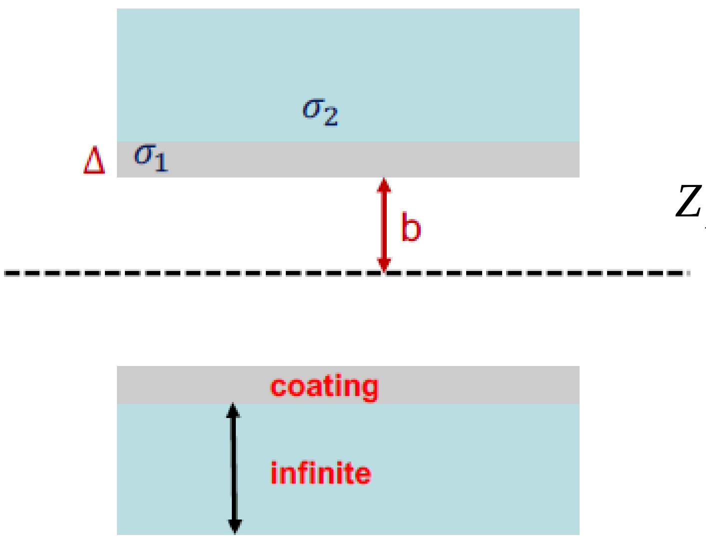
Beam pipes of other vacuum chamber components should possibly have similar shape



From R.Kersevan and C.C.Garion talk during FCC Week 2019

Impedance of a coated beam pipe

A coating is required to suppress the e-cloud (beam induced multipacting) in the positron ring and/or for pumping purposes in both rings: NEG, TiN, AC



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

Longitudinal impedance

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

Transverse impedance

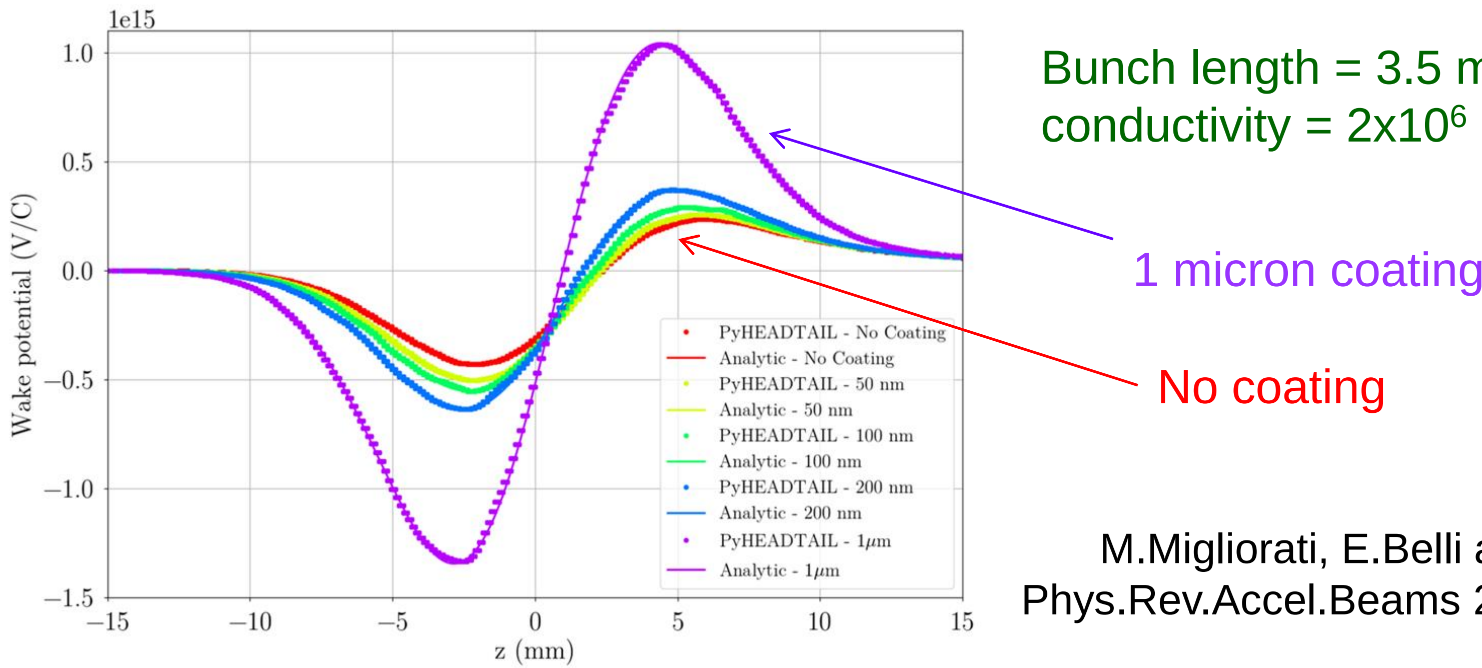
$$Z_T(\omega) = \frac{Z_0}{2\pi b^3}\left[1 - i\,\mathrm{sgn}(\omega)\right]\delta_1 \left[\frac{\alpha \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right] + 1}{\alpha + \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right]}\right]$$

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

For thin resistive coatings

1. The real part of the impedance does not depend on both the coating thickness and coating conductivity.
2. The imaginary part has an additional term depending on the coating thickness, while the dependence on the conductivity is very weak.

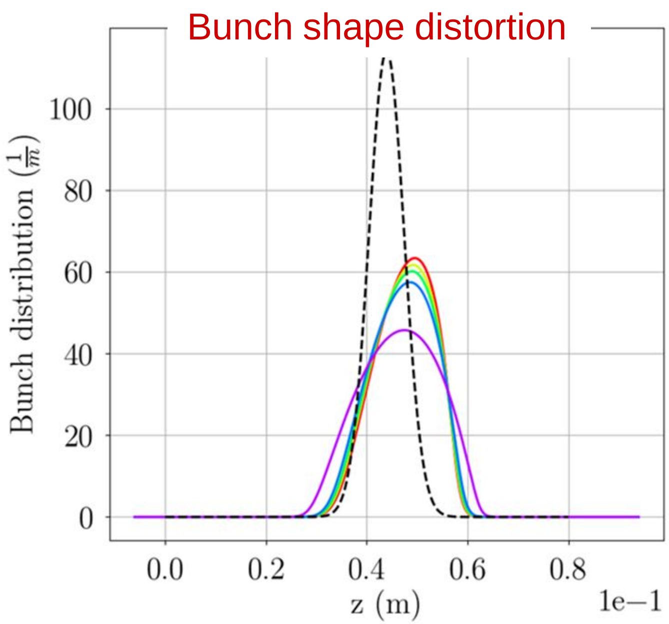
$$\frac{Z_L(\omega)}{C} = \frac{Z_0\omega}{4\pi cb}\frac{[\mathrm{sgn}(\omega)-i]\delta_2 - 2i\Delta}{1+\frac{\delta_2\Delta[1-i\,\mathrm{sgn}(\omega)]}{\delta_1^2}} \cong \frac{Z_0\omega}{4\pi cb}\left\{[\mathrm{sgn}(\omega)-i]\delta_2 - 2i\Delta\left(1-\frac{\sigma_1}{\sigma_2}\right)\right\}$$

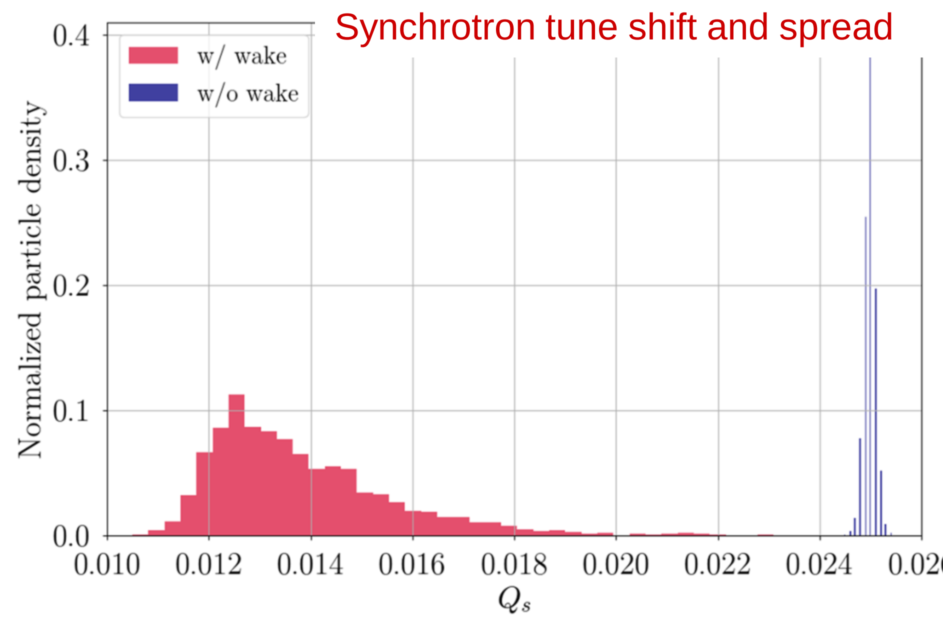


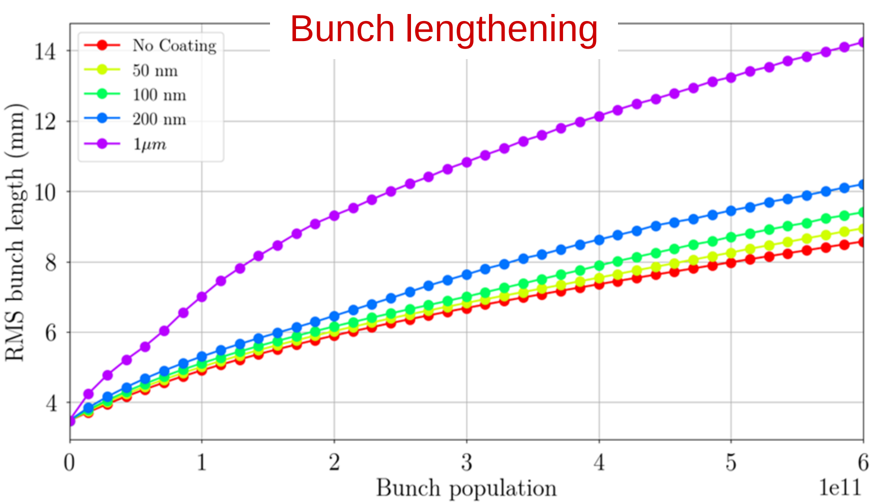
Bunch length = 3.5 mm, coating conductivity = 2×10^6 S/m

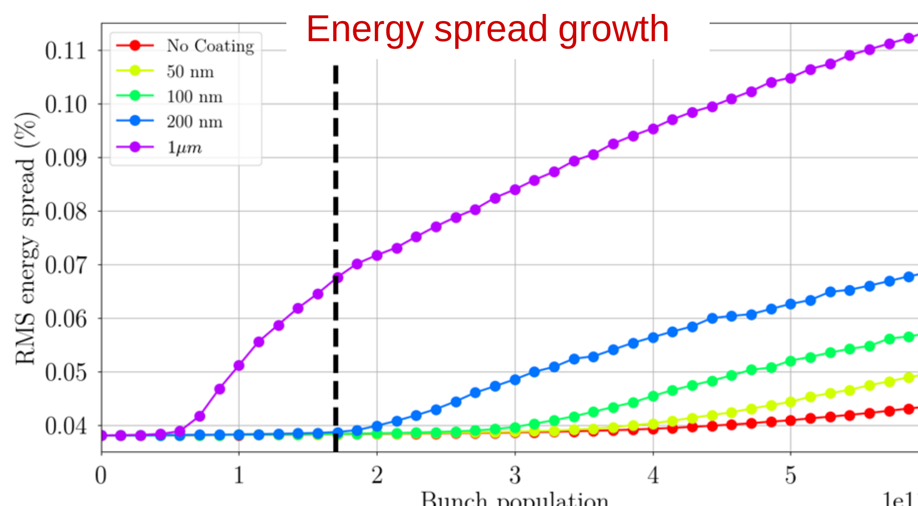
M.Migliorati, E.Belli and M.Zobov, Phys.Rev.Accel.Beams 21 (2018) 041001

Single bunch longitudinal dynamics





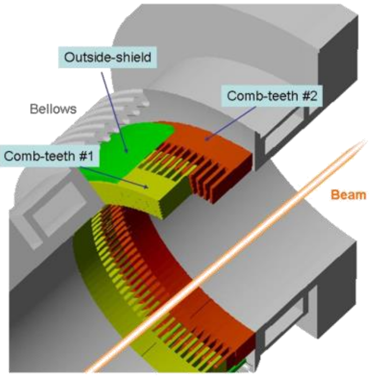




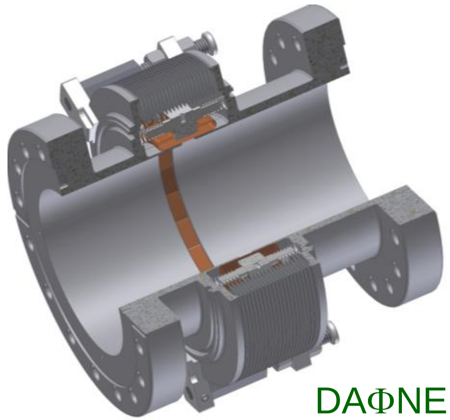
M.Migliorati, E.Belli and M.Zobov,
Phys.Rev.Accel.Beams 21 (2018) 041001

Best design solutions of vacuum chamber elements used in modern syncrotron sources and particle factories are considered for implementation in FCC-ee

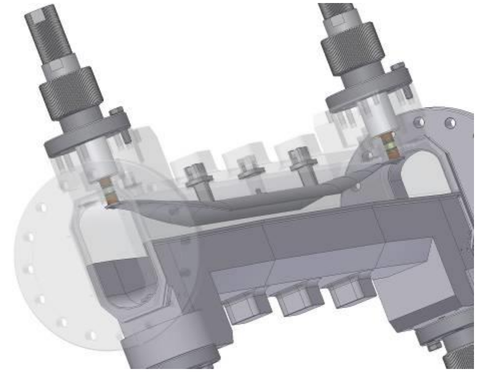
Some Examples



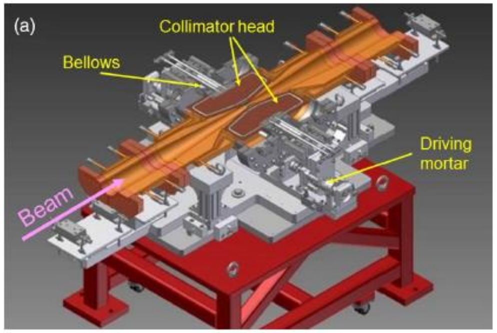
KEKB bellows



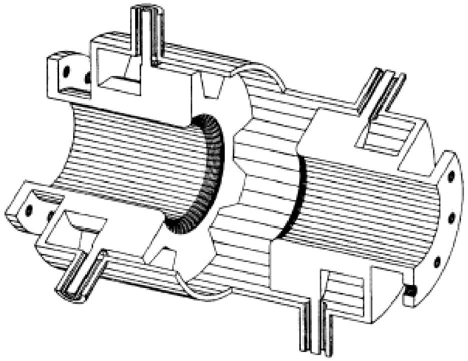
DAΦNE bellows



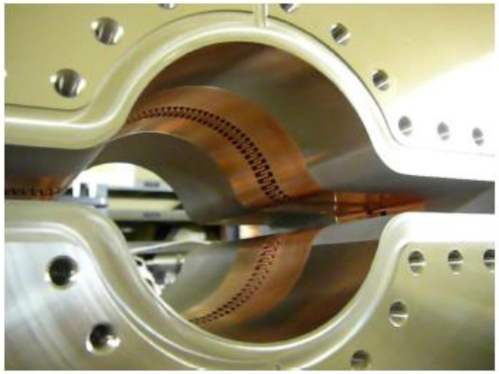
DAΦNEinjection kicker



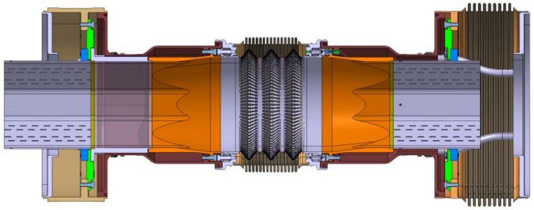
SuperKEKB collimator



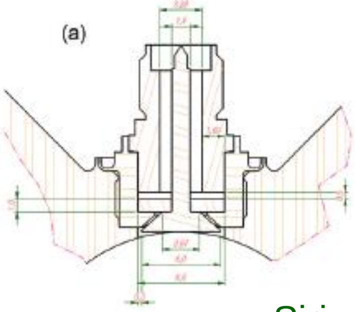
DAΦNE long. feedback kicker



SuperKEKB gate valve

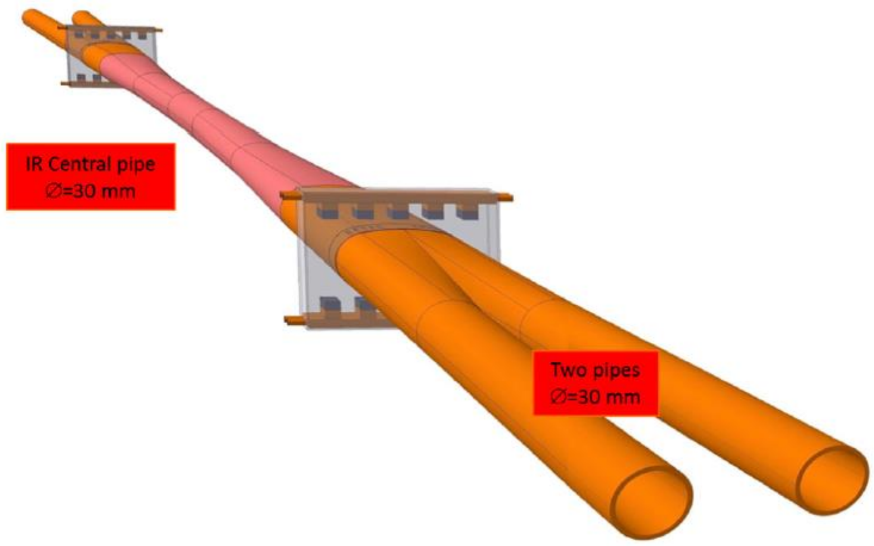


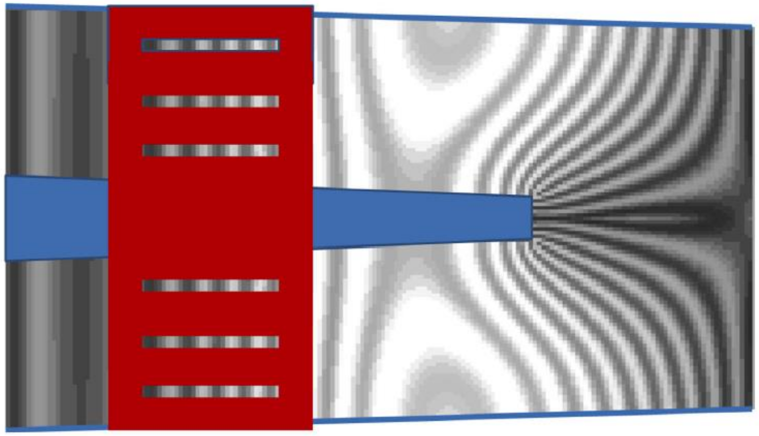
CERN bellows



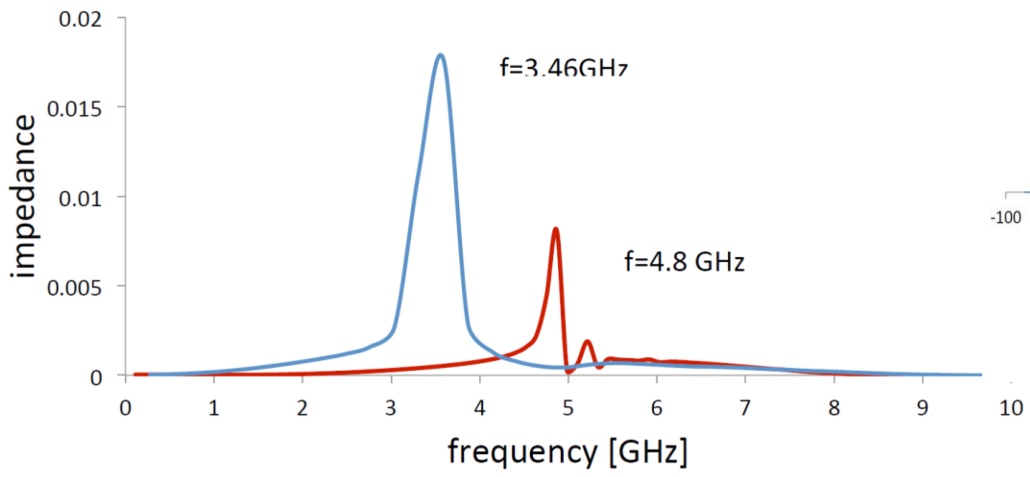
Sirius BPM

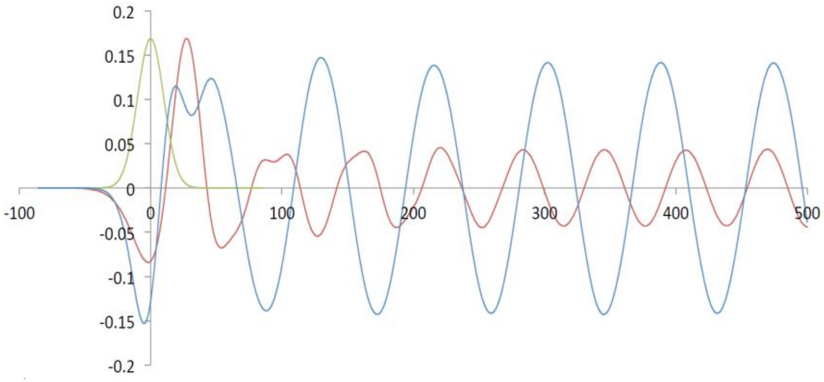
HOM absorbers in the IR





A.Novokhatski, E.Belli et al, PRAB, 20, 111005

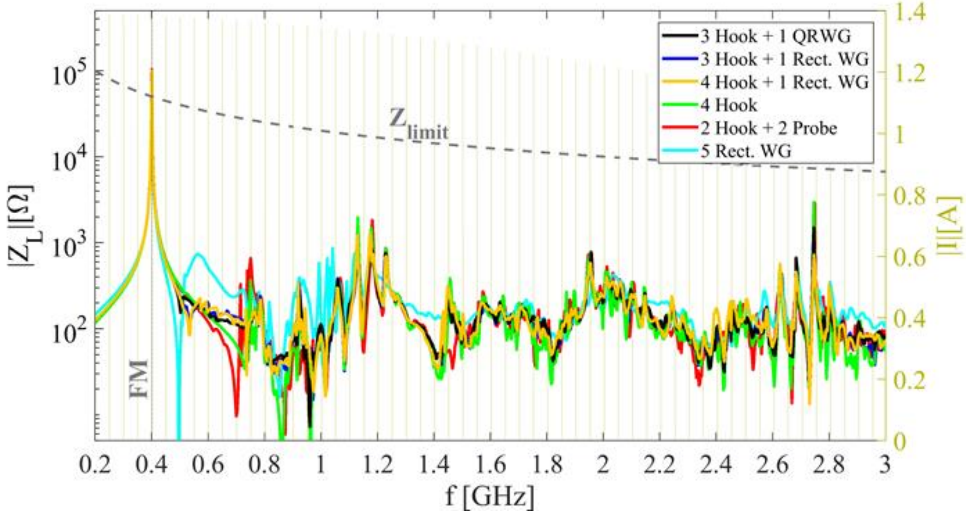


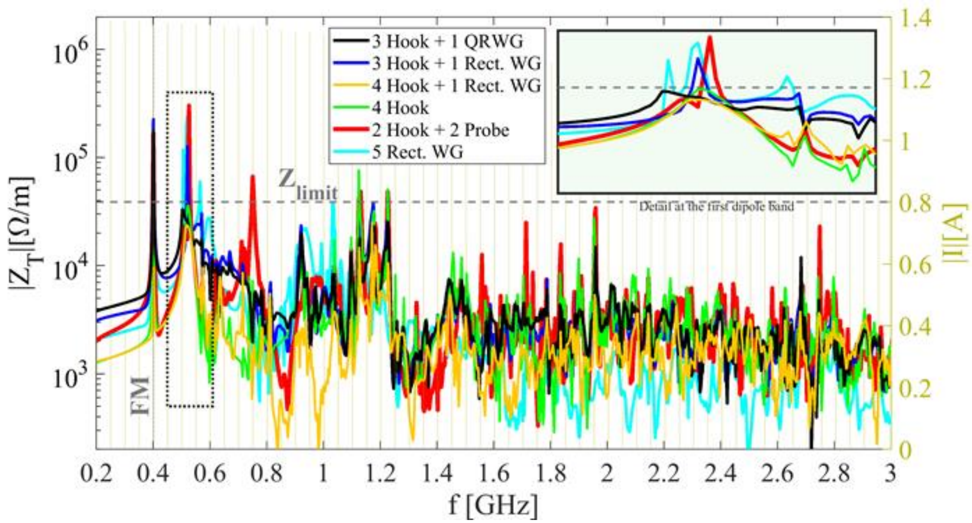


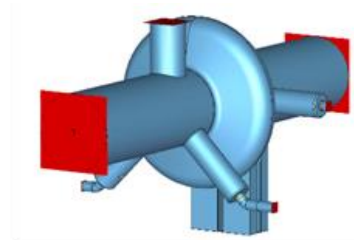
IR geometry optimisation is underway

From the talk of A.Novokhatski during FCC Week 2019

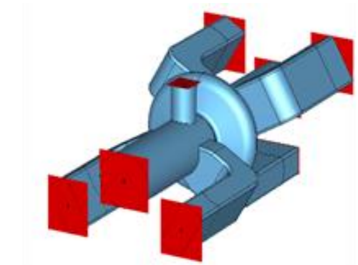
Different HOM damping techniques are considered for RF cavities



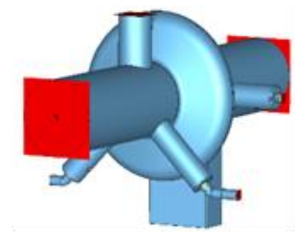




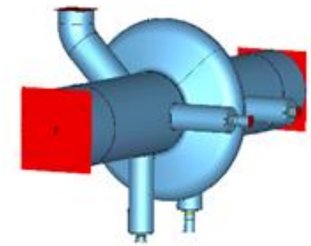
3 Hook-type couplers + 1 Quad ridged WG (3H1QRWG)



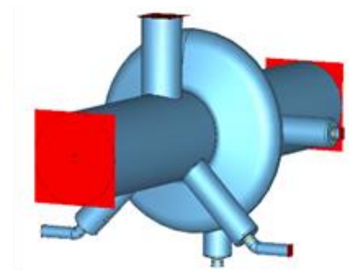
5 Rectangular Waveguide (5RecWG)



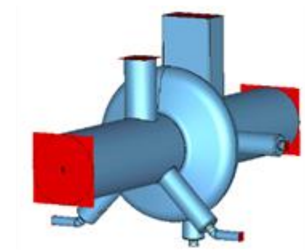
3 Hook-type couplers + 1 Rectangular WG (3H1RecWG)



LHC-type couplers 2 Probe+2 Hook (2H2P)



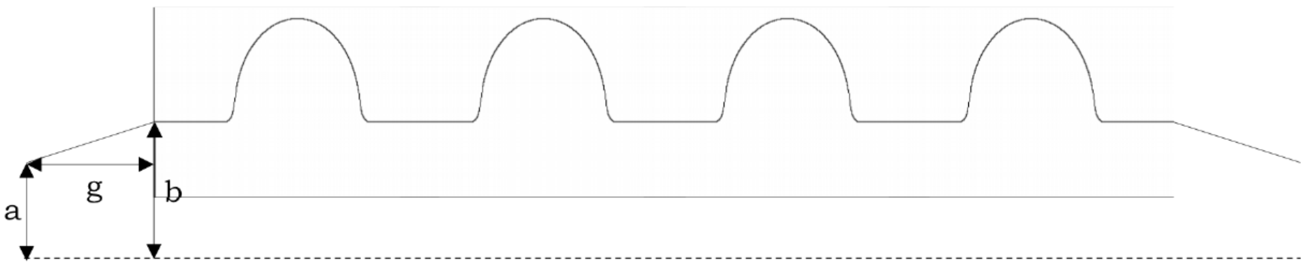
4 Hook-type couplers (4H)

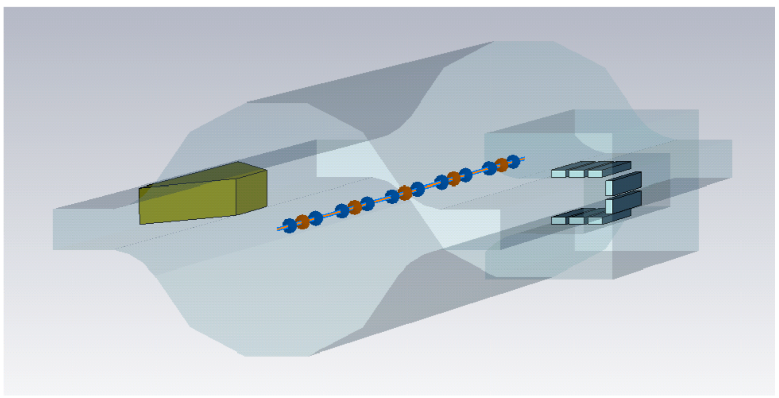


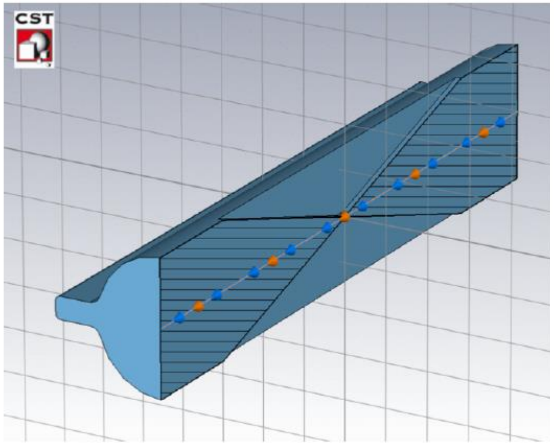
4 Hook-type couplers + 1 Rectangular WG (4H1RecWG)

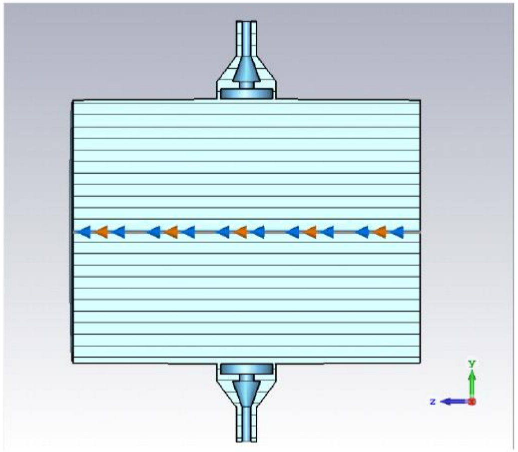
From the talk of Shahnam Gorgi Zadeh during FCC Week 2019

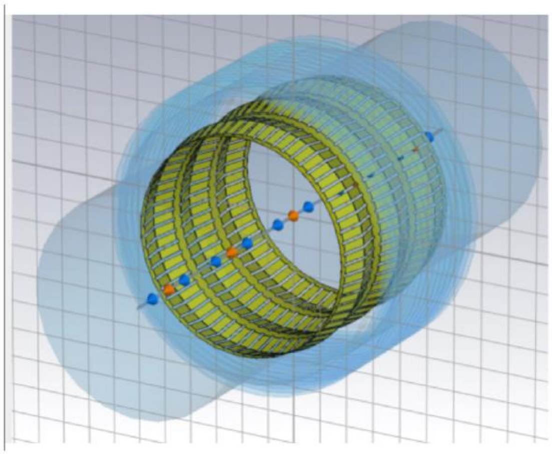
The wake fields and impedance have been evaluated for several most important vacuum chamber components

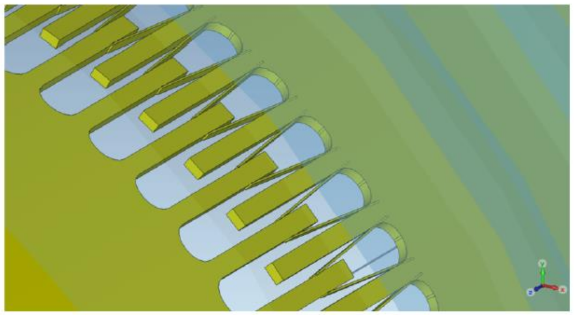


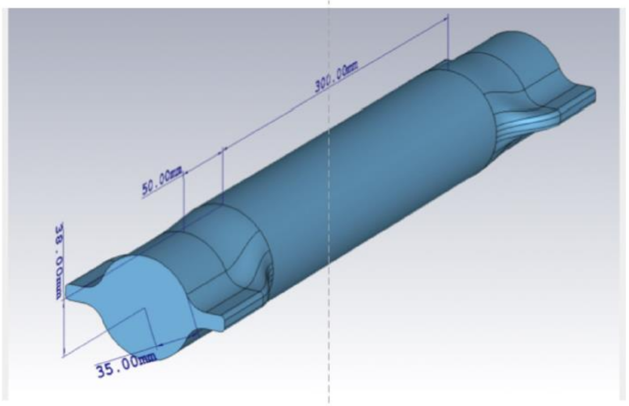








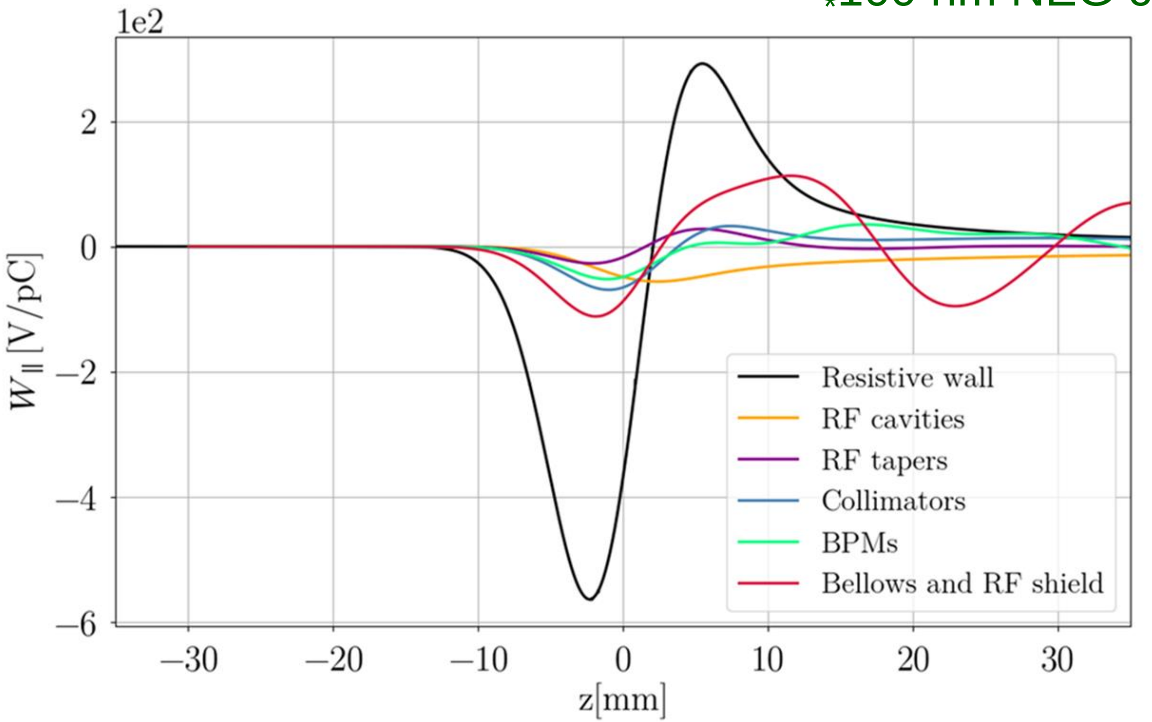




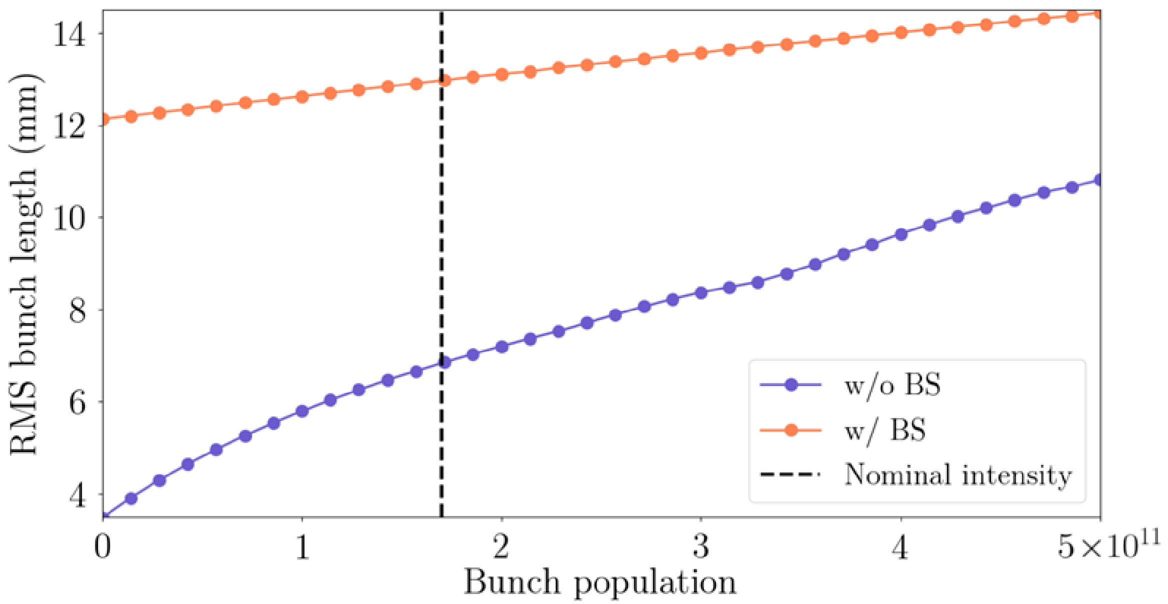
Longitudinal Impedance Budget

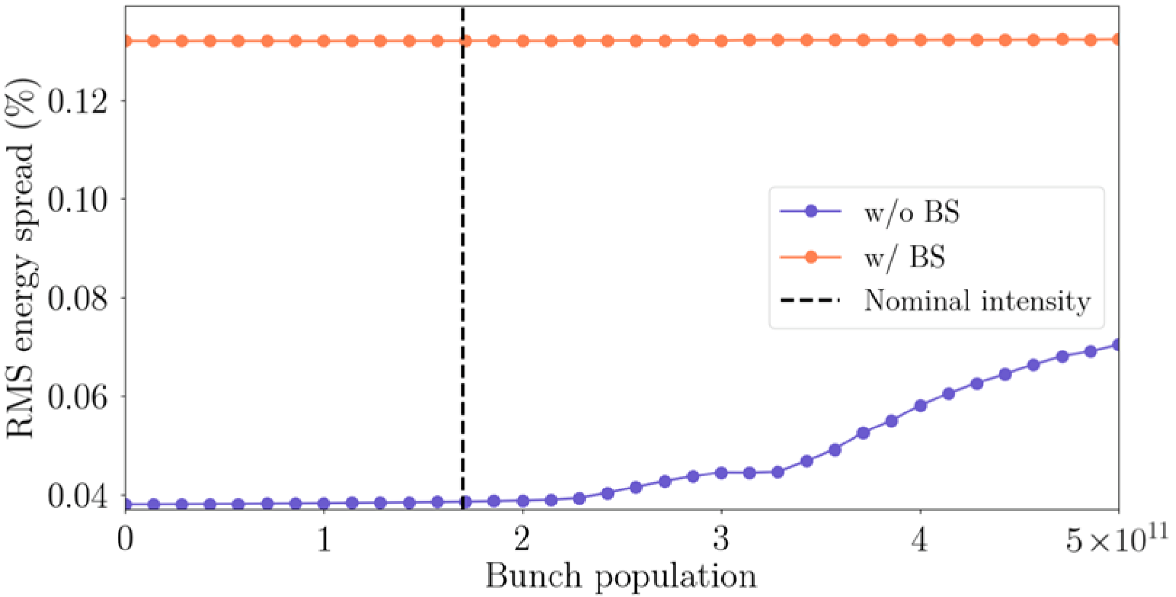
Component	**Number**	$k_l\ [V/pC]$	$P_l\ [MW]$
Resistive wall	97.75 km	210	7.95
RF cavities	56	18.46	0.7
RF double tapers	14	6.12	0.23
Collimators	20	38.36	1.45
Beam Position Monitors	4000	31.47	1.19
Bellows with RF shielding	8000	49.01	1.85
Total		**353.4**	**13.4**

*100 nm NEG coating is considered



Bunch length and energy spread versus bunch intensity

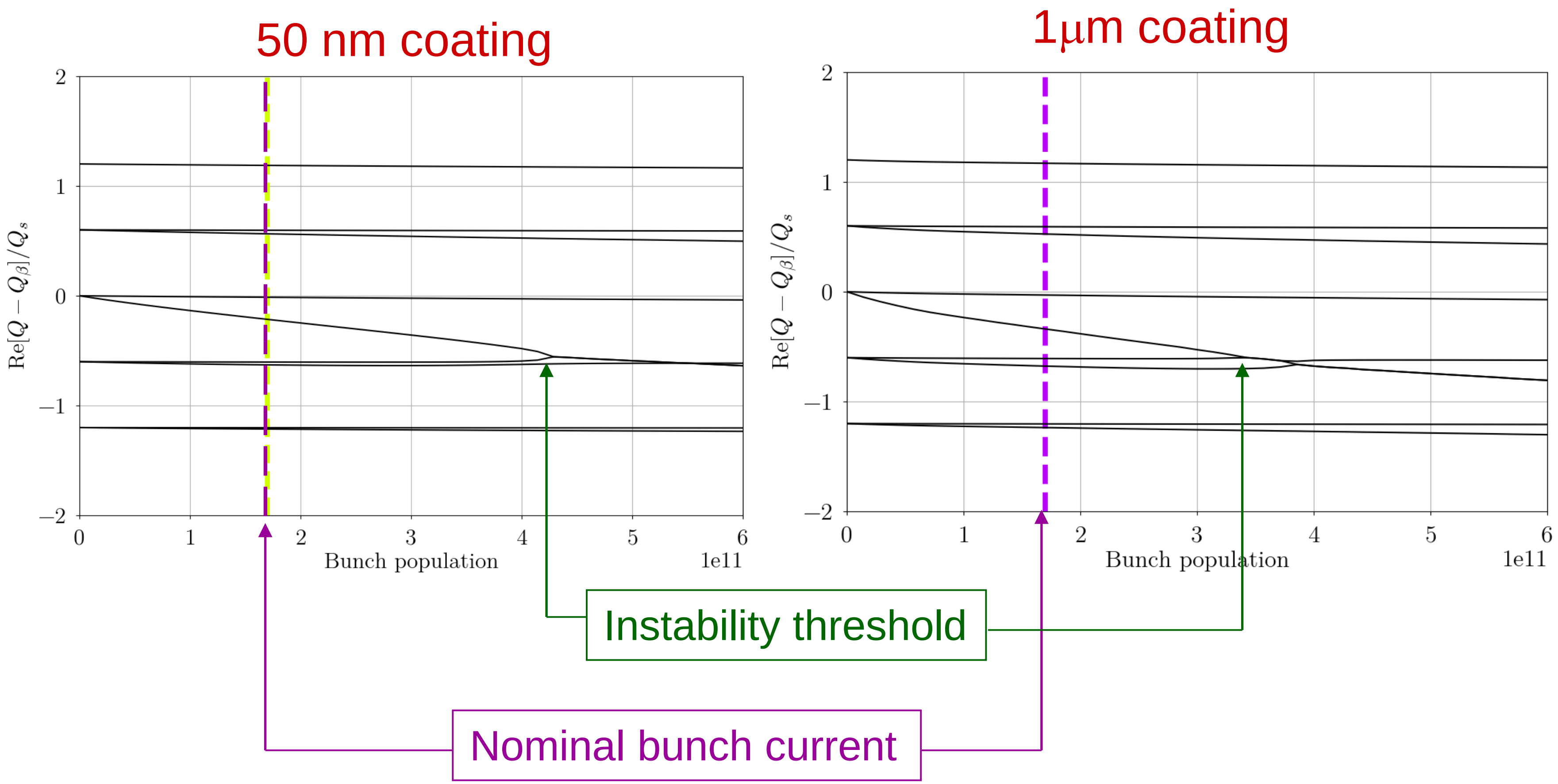




Transverse mode coupling instability (TMCI)

Differently from the longitudinal microwave instability TMCI is destructive.

It takes place when frequencies of different modes of transverse internal bunch oscillations merge



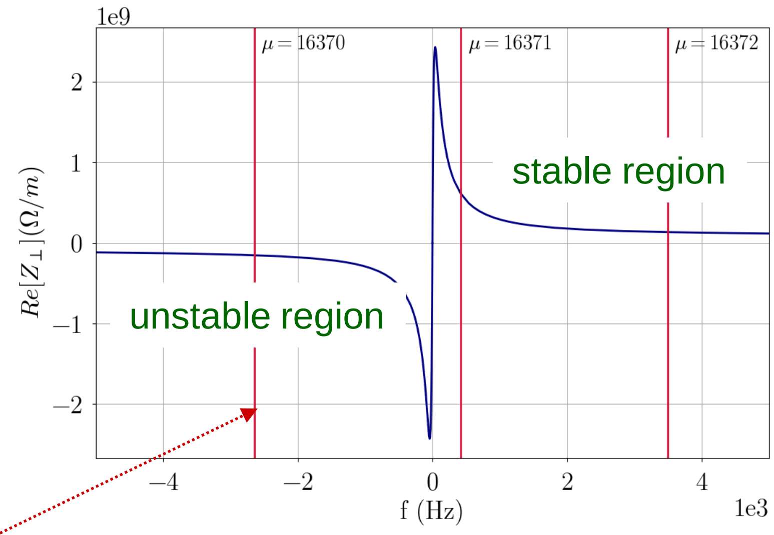
Transverse Coupled Bunch Instability

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

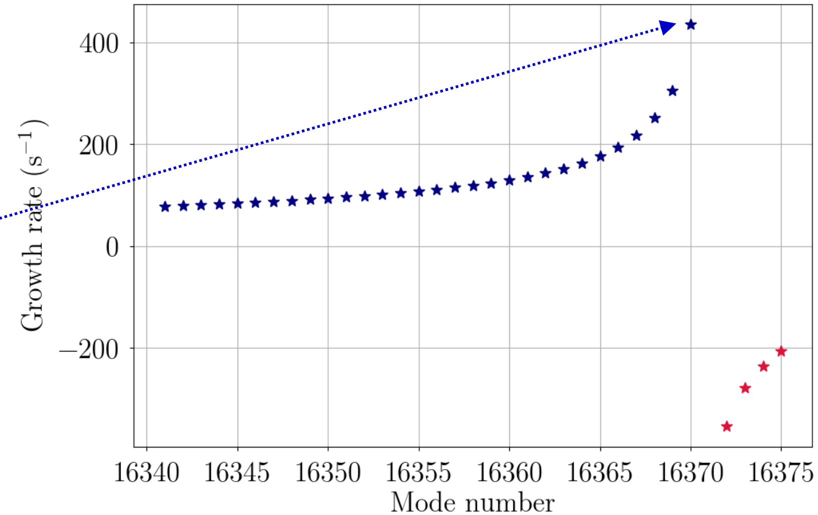
where $\mathrm{Re}\left[Z_\perp(\omega)\right] = \mathrm{sgn}(\omega)\frac{C}{2\pi b^3}\sqrt{\frac{2Z_0 c}{\sigma_c|\omega|}}$

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

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



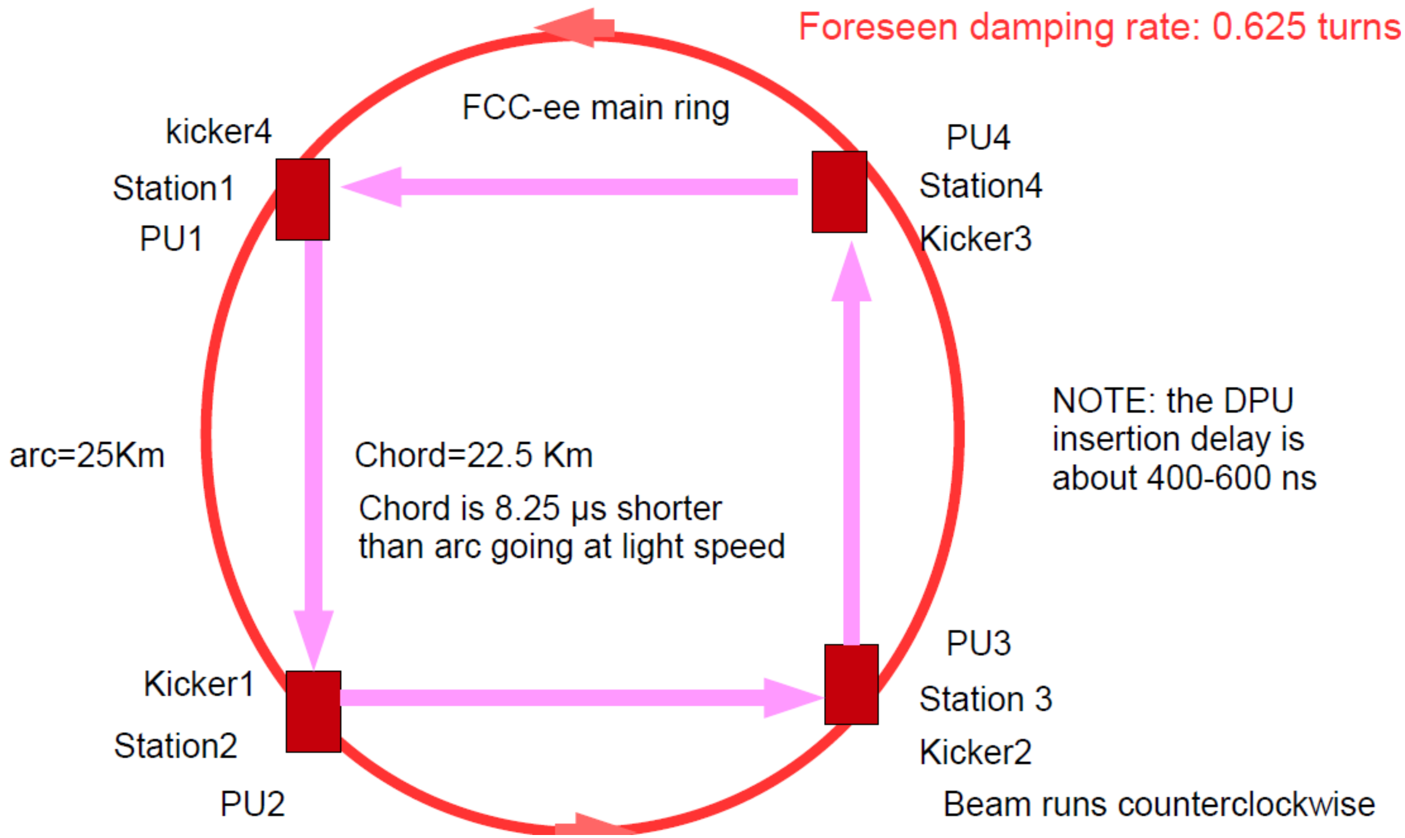
The most dangerous mode



Its growth time is about
7 revolution turns

A robust feedback is required for the instability suppression!

Distributed feedback system

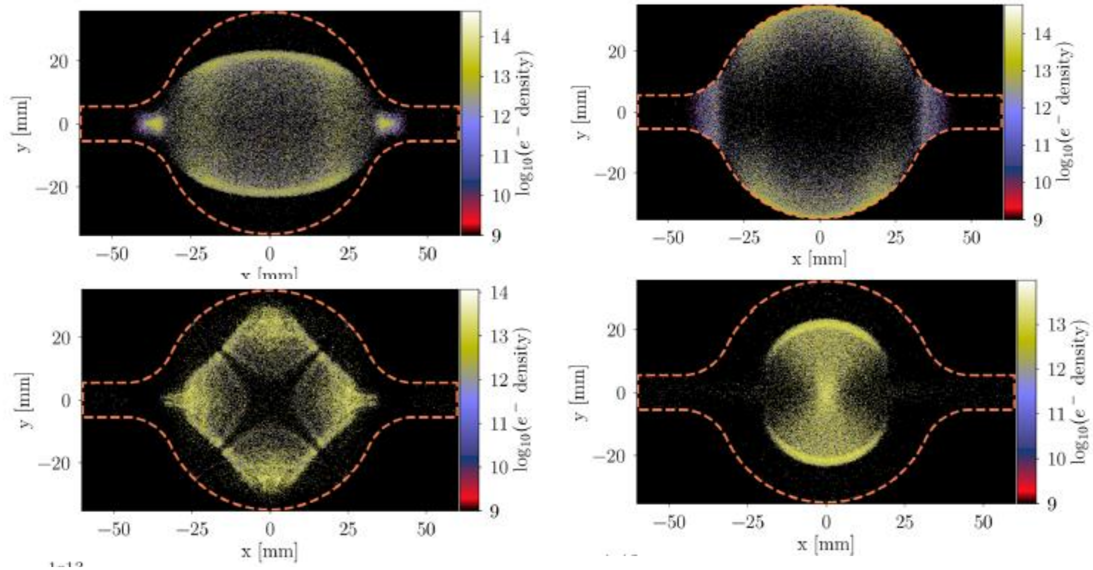


- However the FCC ring lenght gives a very interesting chance to build "*feeding forward*" systems, producing damping rate even faster than 1 revolution turn. This can be possible applying the correction signal quickly than one revolution period.

From A.Drago talk at ICFA mini-Workshop on Impedances and Beam instabilities, Benevento, 19-22 September 2017

Electron cloud buildup at 45.6 GeV

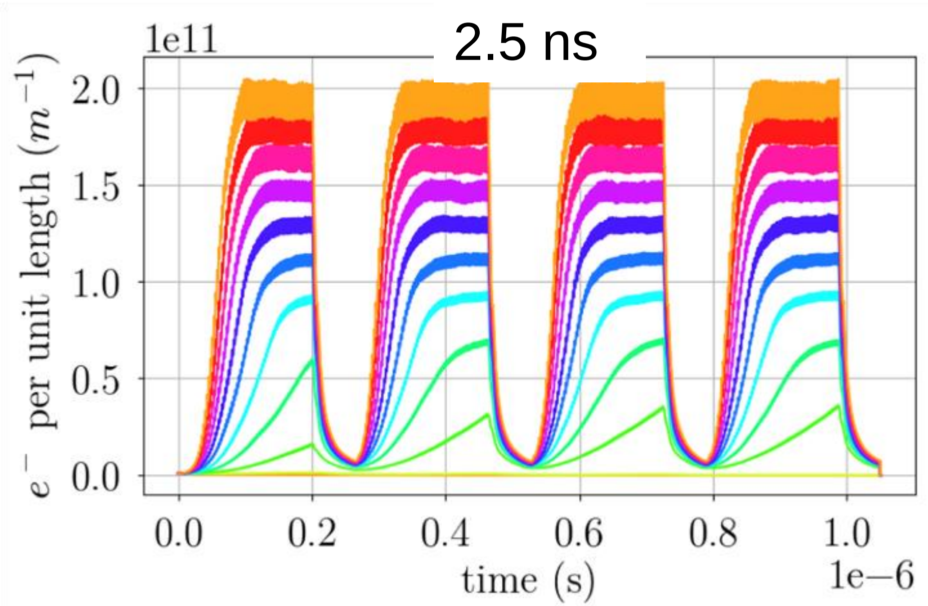
Element	L[m]	Magnetic field
Arc dipole	23.44	0.014 T
Arc quad	3.1	±5.65 T/m
Arc drift	-	-
QC1L1	1.2	-96.3 T/m
QC1L2	1	50.3 T/m
QC1L3	1	9.8 T/m
QC2L1	1.25	6.7 T/m
QC2L2	1.25	3.2 T/m

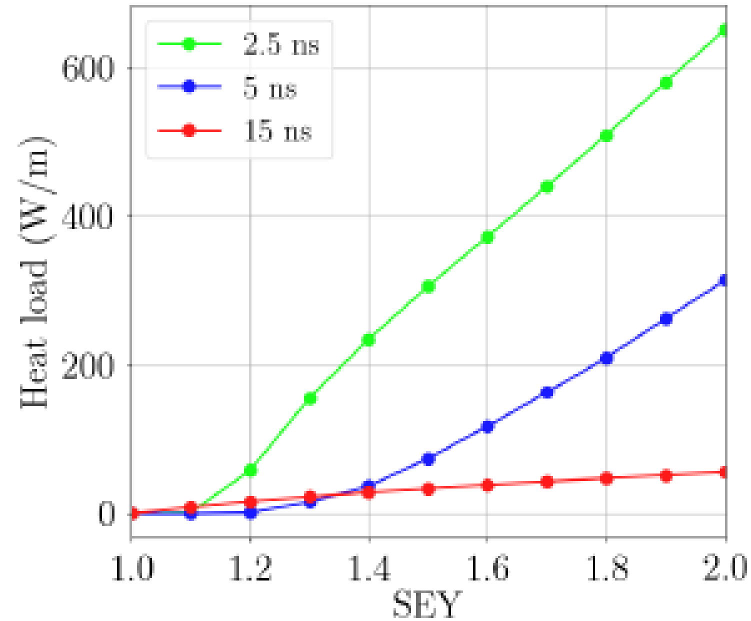


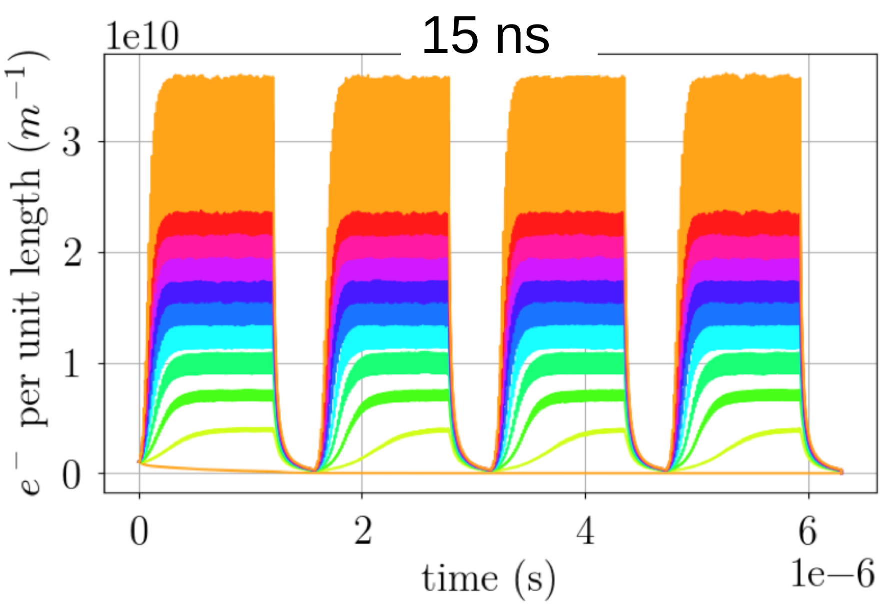
- Realistic shape of the vacuum chamber in the arcs
- Round chamber of 15 mm (20 mm) radius in Q1 (Q2)
- Electron cloud build-up in the arcs and IR magnets
  - Initial uniform distribution 10^9 e^-/m
  - SEY scan
  - Nominal bunch intensity
  - Filling pattern: 80b + 25e
  - Bunch spacing scan: 2.5 ns,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

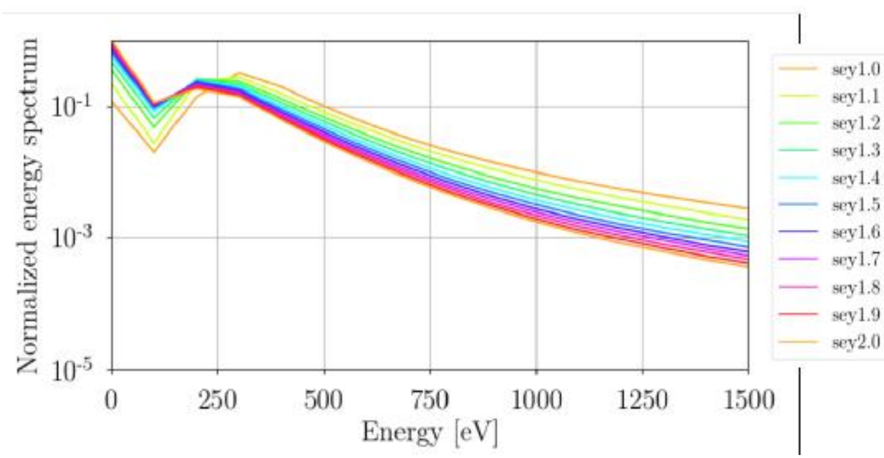
E.Belli's PhD thesis

e-cloud buildup and heat load in the arc dipoles

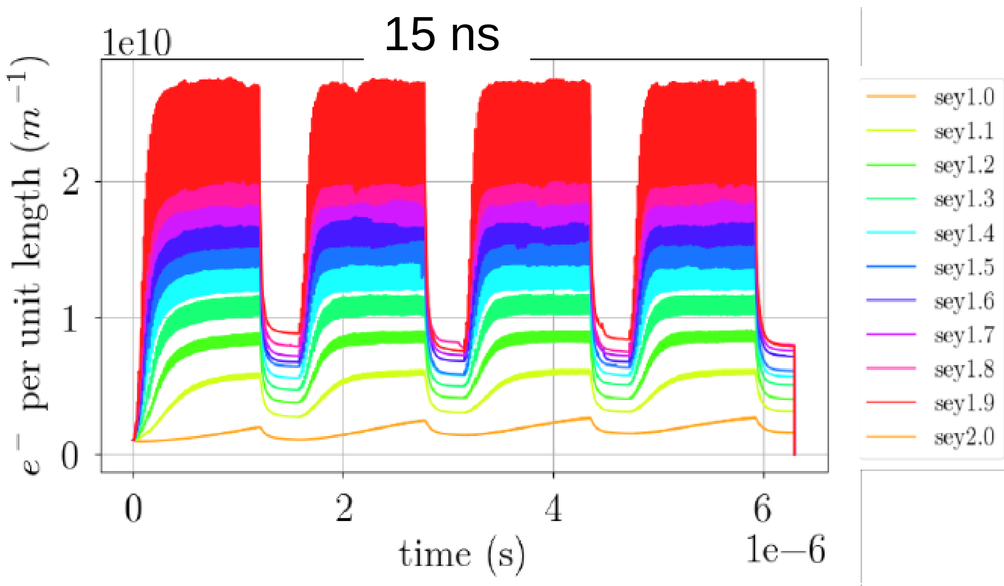


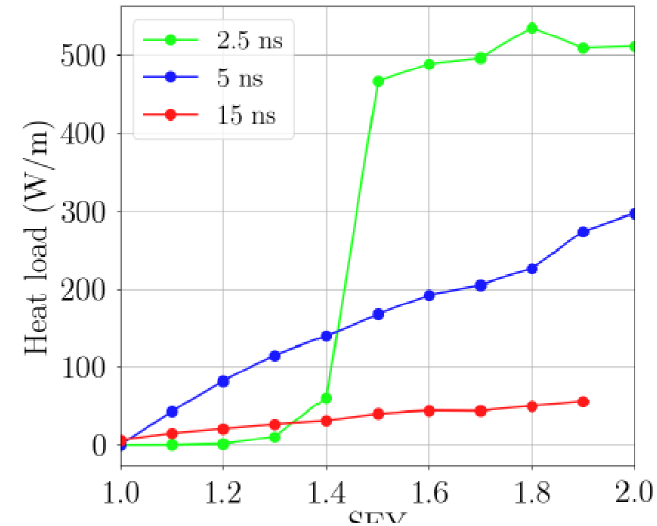


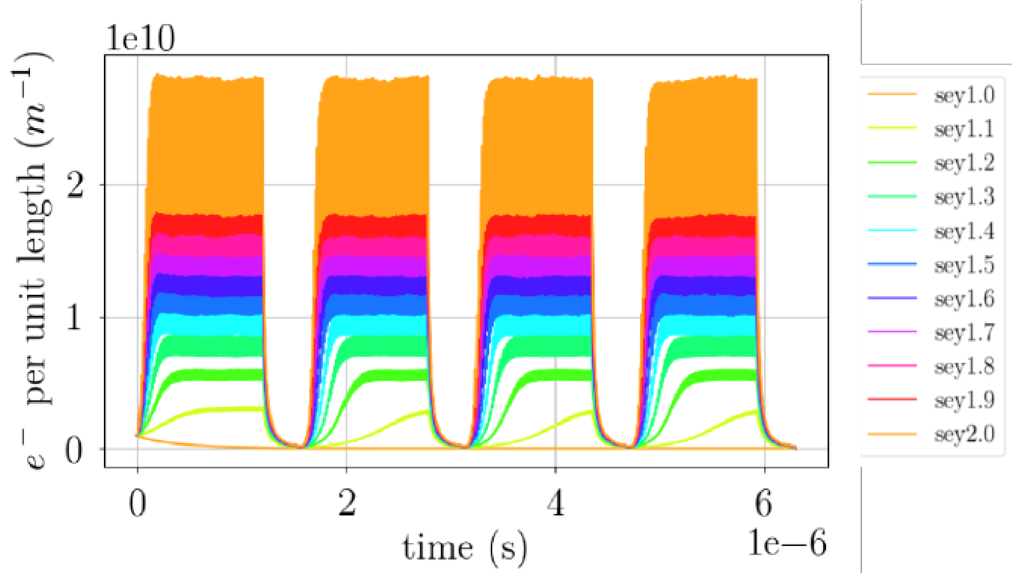


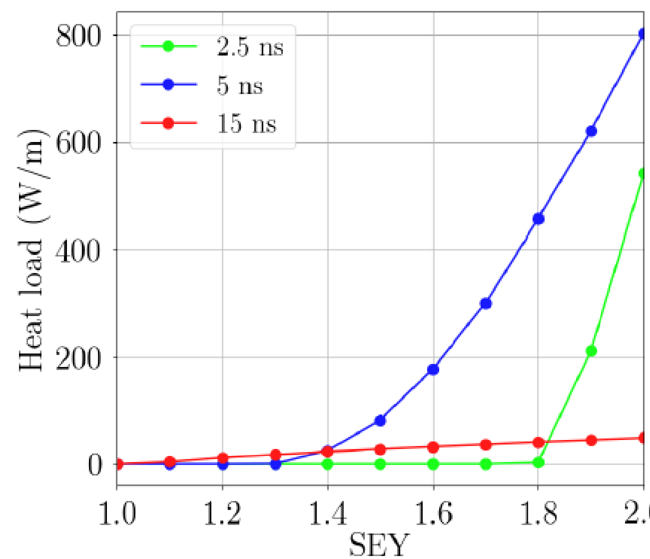


e-cloud buildup and heat load in the arc quadrupoles (top) and drifts (bottom)

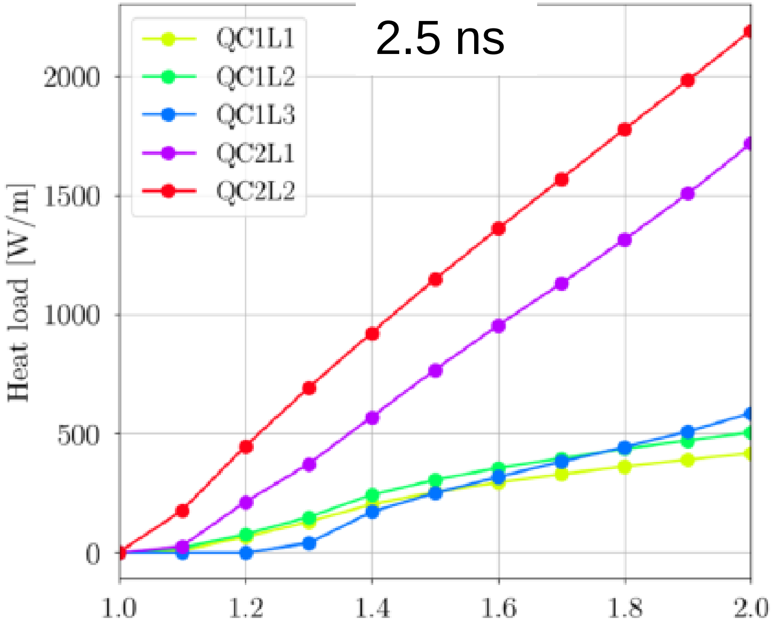


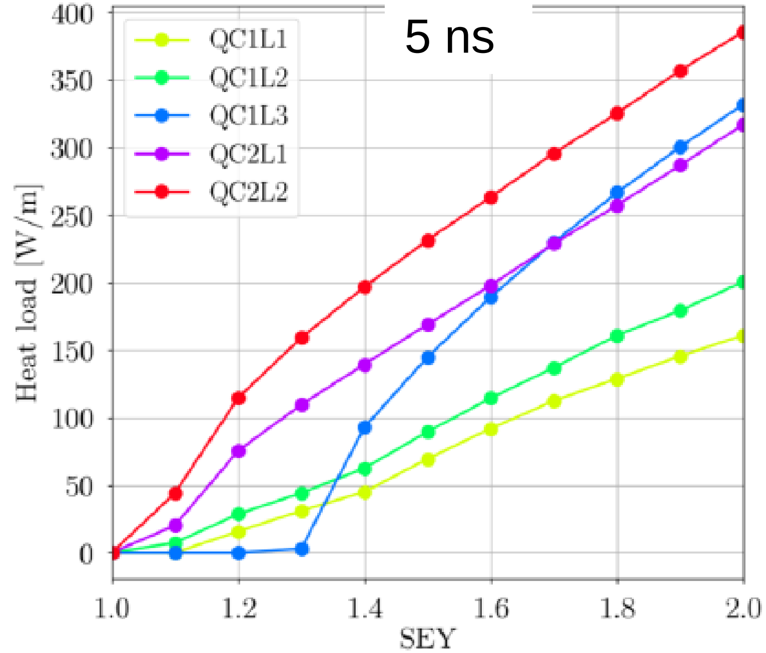


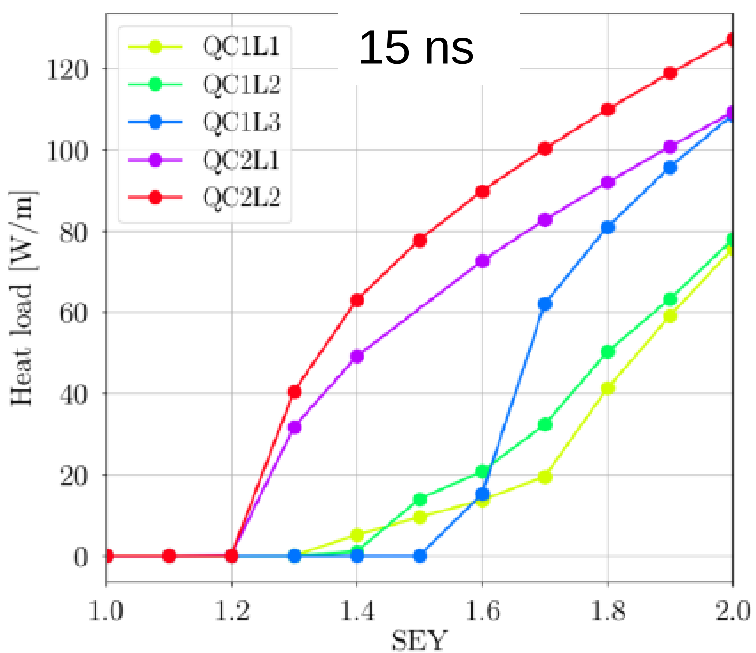




e-cloud heat load in the IR quadrupols



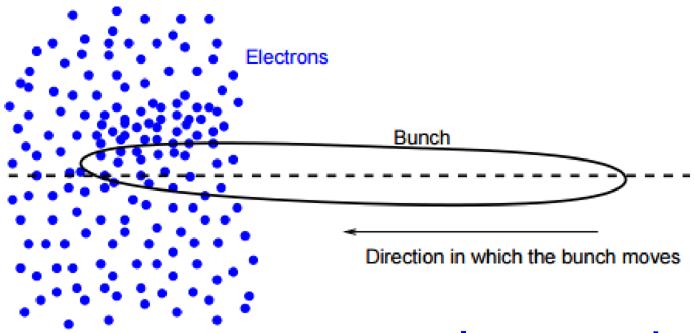


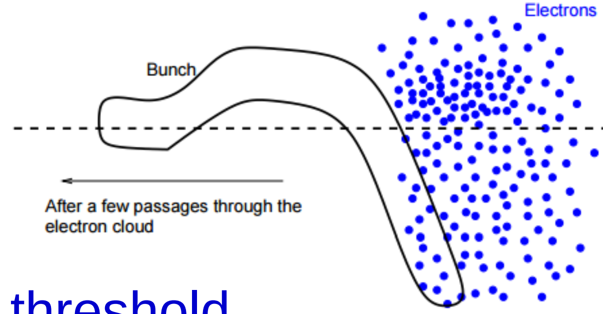


Element	2.5 ns	5 ns	15 ns
QC1L1	1.0	1.1	1.3
QC1L2	1.0	1.0	1.4
QC1L3	1.2	1.3	1.5
QC2L1	1.0	1.0	1.2
QC2L2	1.0	1.0	1.2

Threshold SEY for IR quadrupoles

e-cloud single bunch instability threshold





Electron density threshold

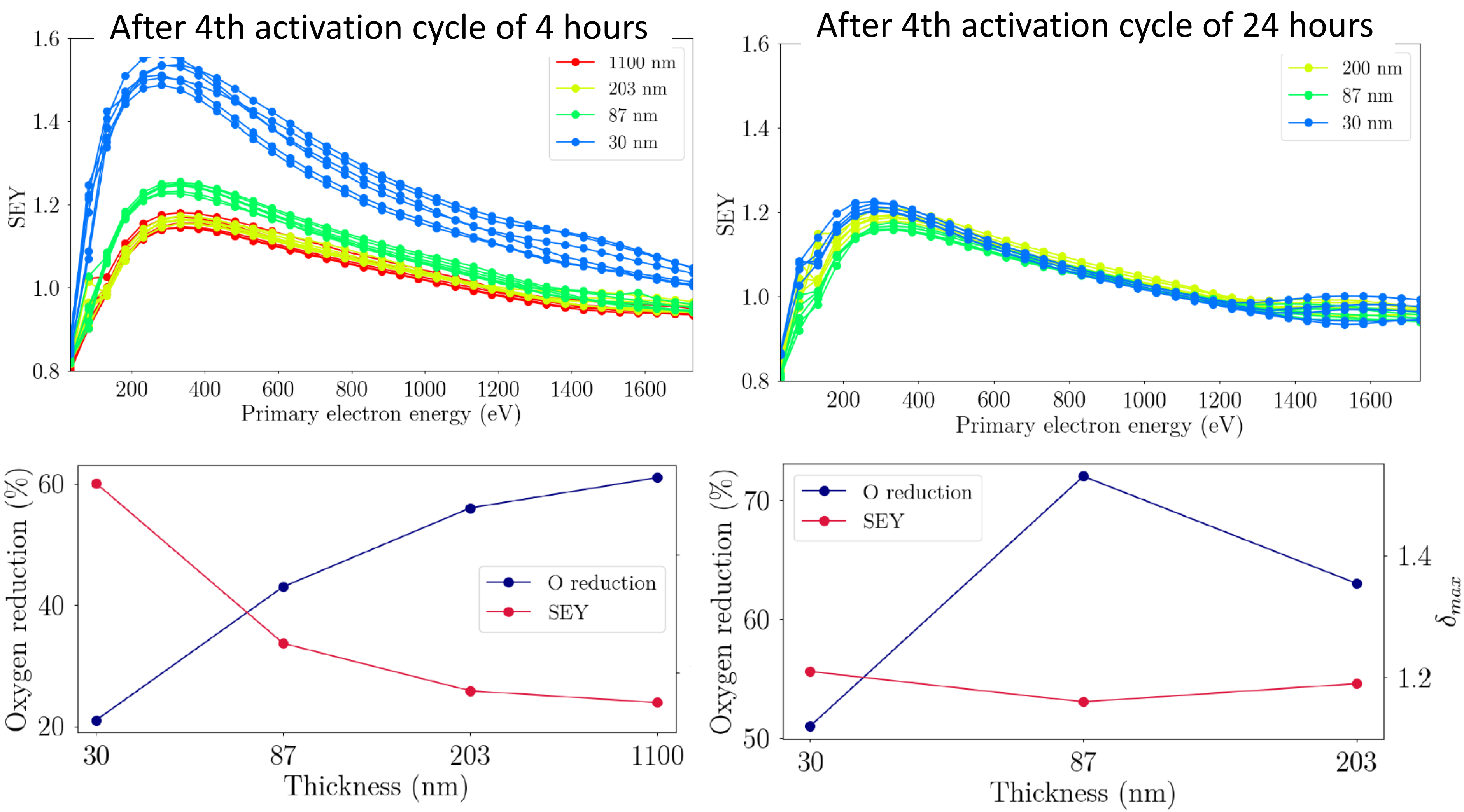
$$\rho_{th}^{e} = \frac{2\gamma Q_s}{\sqrt{3} Q r_e \beta_y C} \quad \textit{with} \quad \omega_e = \sqrt{\frac{2\lambda_p r_e c^2}{\sigma_y(\sigma_y + \sigma_x)}} \quad \textit{and} \quad Q = \min\left(\frac{\omega_e \sigma_z}{c}, 7\right)$$

K.Ohmi and F.Zimmermann, Phys.Rev.Lett.85 (2000) 3821

Energy E_0 [GeV]	**45.6**	**80**	**120**	**175**
Electron frequency $\frac{\omega_e}{2\pi}$ [GHz]	393.25	454.136	308.08	375.58
Electron oscillation $\frac{\omega_e \sigma_z}{c}$	28.847	31.41	20.34	19.28
Electron density threshold $\rho_{th}[10^{10}/m^3]$	**2.29**	**5.39**	**12.6**	**34.6**

To be compared with the average density of 1.64×10^{10} m^{-3} near the central area estimated by Ohmi-san for FCC-ee Z (Int.J.Mod.Phys. A34 (2019) 1940001): nominal intensity, 20 ns, no antechamber

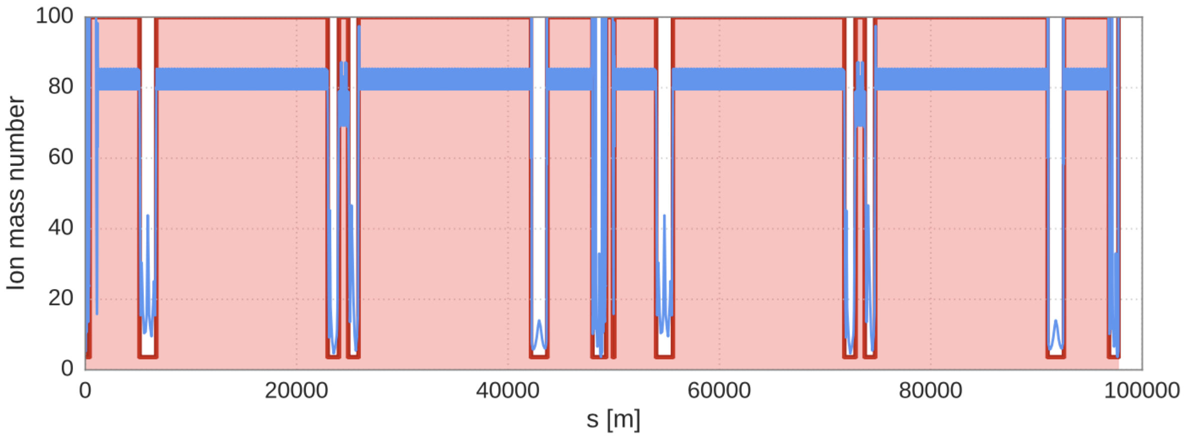
An extensive measurement campaign was performed at CERN to characterize TiZrV films with thickness below 250 nm



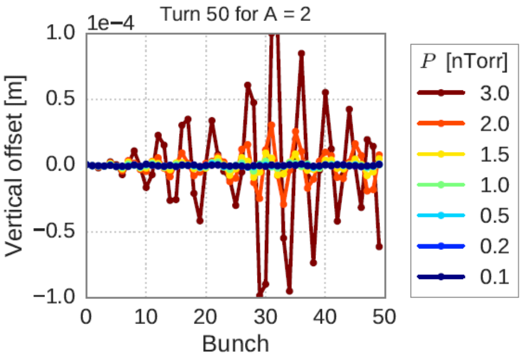
E.Belli et al., Phys.Rev.Accel.Beams 21 (2018) no.11, 111002

Ion instabilities in FCC-ee

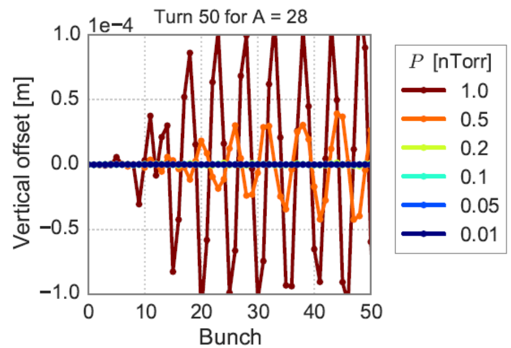
(Courtesy L.Mether, A.Oeftiger and G.Rumolo)



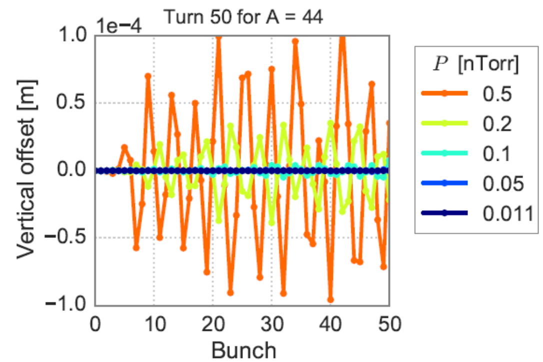
	Mass number, A	Ionization cross-section, σ [Mbarn]
H_2	2	0.5
N_2	28	2.0
CO	28	2.0
CO_2	44	2.0



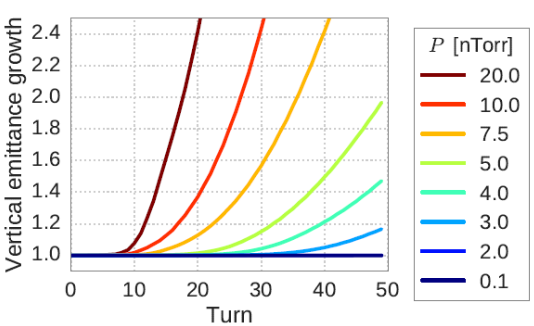
(a) Vertical bunch centroid offsets after 50 turns.

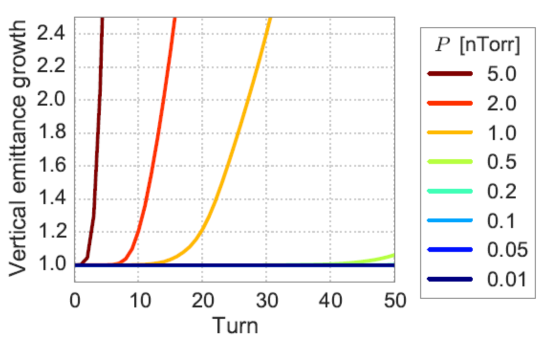


(a) Carbon monoxide (A = 28).

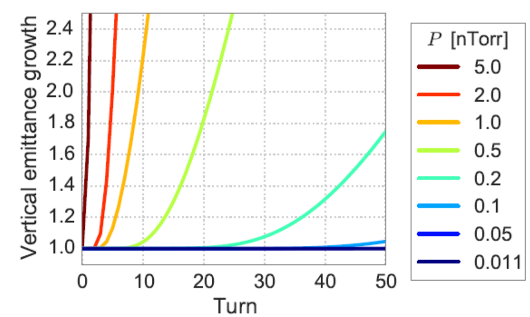


(b) Carbon dioxide (A = 44).





(a) Carbon monoxide (A = 28).



(b) Carbon dioxide (A = 44).

Partial pressure thresholds for residual gas species are probably tighter than vacuum specifications allow

	H_2	N_2, CO	CO_2
Arcs	–	0.1 nTorr	50 pTorr
Straight sections	0.5 nTorr	5 pTorr	5 pTorr

↓ Mitigation is required

Length of bunch train

Efficient only for heavier species in the straight sections, in the arcs would have to go to less than 10-20 bunches for an effect

Bunch spacing

A larger bunch spacing could increase thresholds in arcs and straight sections

Test for CO_2 in the arcs with 7.5 ns bunch spacing shows significant improvement pressure threshold increased at least by a factor of 20

Feedback

Generally efficient at suppressing coupled bunch instabilities

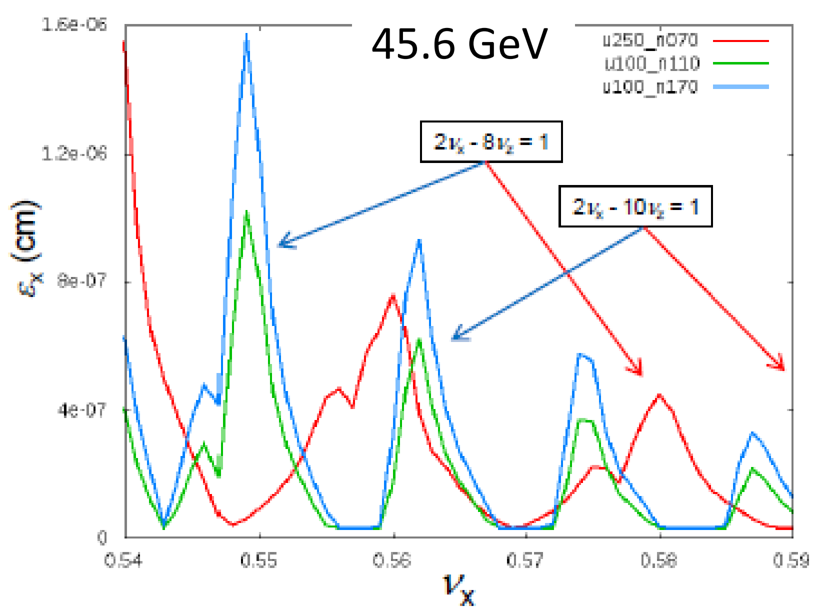
A damping time of ~10 turns → realistically achievable pressure thresholds

However, emittance growth may still occur

From the talk of L.Mether, A.Oeftiger and G.Rumolo at FCC Week 2018

Coherent beam-beam instability with a crossing angle

Coherent instability: ε_x dependence on ν_x and ν_z. Quasi-strong-strong simulations. U_{RF} = 250 MV (red) and 100 MV (green, blue).



The distance between resonances is ν_z. The width depends on ξ_x and the order of resonances.

We need to reduce ξ_x / ν_z ratio and increase the order of resonances near the working point.

- Increase the momentum compaction factor: ν_z and σ_z grow, ξ_x decreases.

  This is done by changing FODO arc cell, which also leads to an increase in ε_x. However, ε_y = 1 pm can be achieved. Besides, the threshold of microwave instability is raised.

- Decrease β_x^* (and thus ξ_x).

  This leads to a decrease in the energy acceptance. Eventually it can be reduced to 15 cm.

- Reduce the RF voltage.

  This decreases ν_z and ξ_x in the same proportion, but increases the order of resonances near the w.p.

- Neat choice of ν_x between synchro-betatron resonances.

From D.Shatilov's talk at EPS-HEP Conference 2019

References

1. K.Ohmi et al., Phys.Rev.Lett. 119 (2017) no.13, 134801
2. D.Shatilov, ICFA Beam Dyn.Newslett. 72 (2017) 30-41

Interplay of different effects

1. Instabilities in a real lattice: tune, chromaticity, betatron functions, coupling, nonlinear detuning etc. (several talks at this Workshop)
2. Beam-beam interaction and impedance, both transverse and longitudinal.
   For example:
   a) beamstrahlung helps to suppress the microwave instability in FCC-ee (this talk)
   b) collisions with a crossing angle can provide Landau damping of the longitudinal multibunch instabilities (A.Drago's talk)
   c) damping of transverse instabilities in beam-beam collisions (known experience)
3. Beam-beam interaction and ion related instabilities (see, for example, Beam-beam damping of the ion instability, M. Blaskiewicz, TUPLM11, NAPAC2019)
4. e-Cloud effects and beam-beam interaction (observations at several colliders)
5. Space charge and beam-beam interaction (should be important for SuperKEKB)
6. Other effects

Summary of mitigation techniques

1. Impedance and impedance-related instabilities

a) choice of the vacuum chamber shape to eliminate the quadrupolar wakes
b) the vacuum chamber pipe should have the same cross-section almost everywhere in order to reduce the geometric impedance
c) thin coating to reduce the RW impedance
d) vacuum chamber component design using the experience from other high current colliders and synchrotron radiation sources
e) novel designs: IR HOM absorbers, HOM suppressors in the RF cavities, other
f) distributed feedback systems
g) special bunch patterns to reduce lost HOM power

2. e-Cloud effects

a) choice of the bunch patterns and bunch separation
b) coating with low SEY to reduce the heat load and stay under the instability threshold
c) antechambers
d) fast feedback systems

3. Ion related instabilities: lower pressure, dedicated beam patterns, lattice parameters, feedbacks

4. Interplay between different effects/instabilities can be important and should be studied in detail