Updated HE-LHC impedance model and implication on stability aspects

D.Amorim, S.Antipov, N.Biancacci, E.Métral, B.Salvant

Thanks to S.Arsenyev, R.Bruce, X.Buffat, M.Crouch, L.Mether, A.Oeftiger, T.Pieloni, C.Tambasco, F.Zimmermann

FCC Week 2019

25/06/2019

Outline

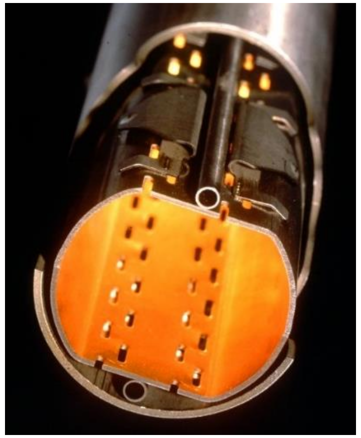
- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Outline

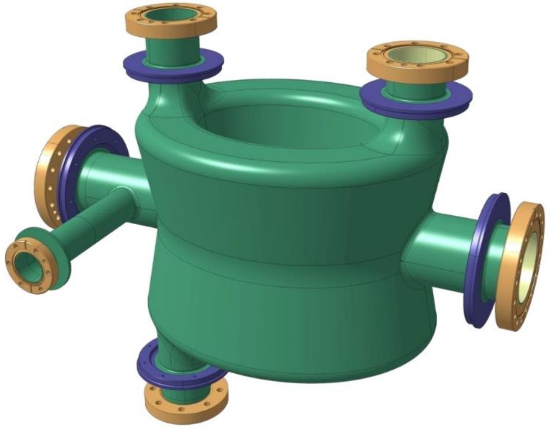
- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Wakefields and impedances

- The charged beam interacts with the elements it encounters on its path



Beam pipe



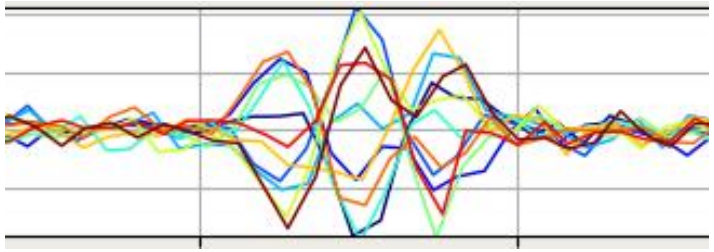
Crab cavity

Collimator

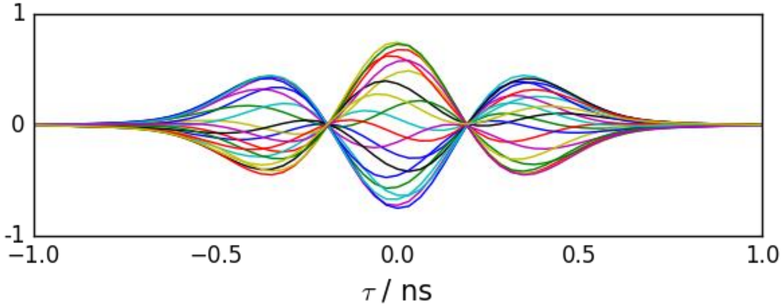
- An electromagnetic field is generated and perturbs the following bunches or the bunch itself

Impedance induced instabilities

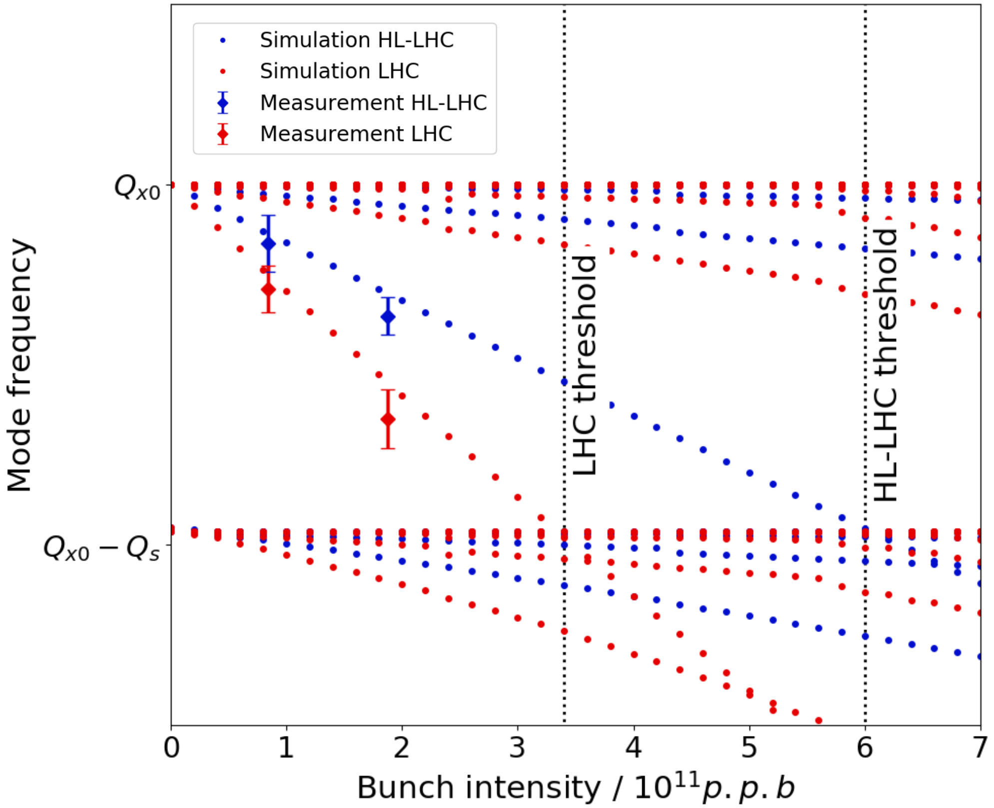
- Currently have an impedance model for LHC/HL-LHC
  - Used for transverse coherent stability studies
  - Prediction of stability thresholds /Reproduce machine observables
  - Reached factor 1.3 between measurements and simulations



Observed head-tail mode



Simulated head-tail mode



Tuneshift measurement in the LHC

- Model used as the basis for HE-LHC

Introduction

- Updated HE-LHC impedance model and stability simulations
  - **Old** collimator **gaps** from design review (**Dec. 2017**)
  - **New** collimator **gaps** from the CDR (**Dec. 2018**)
  - Beam parameters from the CDR when relevant

- Presented at HE-LHC design meeting in Dec. 2018 https://indico.cern.ch/event/781175/
  - Beam stability simulations and results were performed and presented by S.Antipov
  - Only the transverse impedance and single beam stability are addressed in this talk
    - For longitudinal considerations, see previous talk by E. Shaposhnikova

Outline

- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Impedance model: assumptions

- Based on HL-LHC impedance model
- Cold beam screen
  - 2017 FCC-hh beam screen impedance, scaled to HE-LHC length
  - No pumping holes (shielded by the beam screen)

S.Arsenyev *et al.,* "Traveling wave method for simulating geometric beam coupling impedance of a beam screen with pumping holes", PRAB **22**, 051002, 2019

- Warm beam screen
- Collimators
  - Assume the HL-LHC collimation layout
  - Primary (TCP) and secondary (TCSG) collimators in IR7 are MoGr with a Mo coating
  - The gaps are scaled with energy and normalized emittance
- Other elements
  - RF, ATLAS, CMS, ALICE, LHCb: broad-band impedance and resonant modes from RF cavities and experiments vacuum chambers
  - Other broad-band: recombination chambers, shielded bellows…

- HL-LHC injection or flat-top optics
- Crab cavities are not included: could have significant impact for multi-bunch stability

S.A.Antipov *et al.,* "Effect of crab cavity high order modes on the coupled-bunch stability of High-Luminosity Large Hadron Collider", PRAB **22**, 054401, 2019

Outline

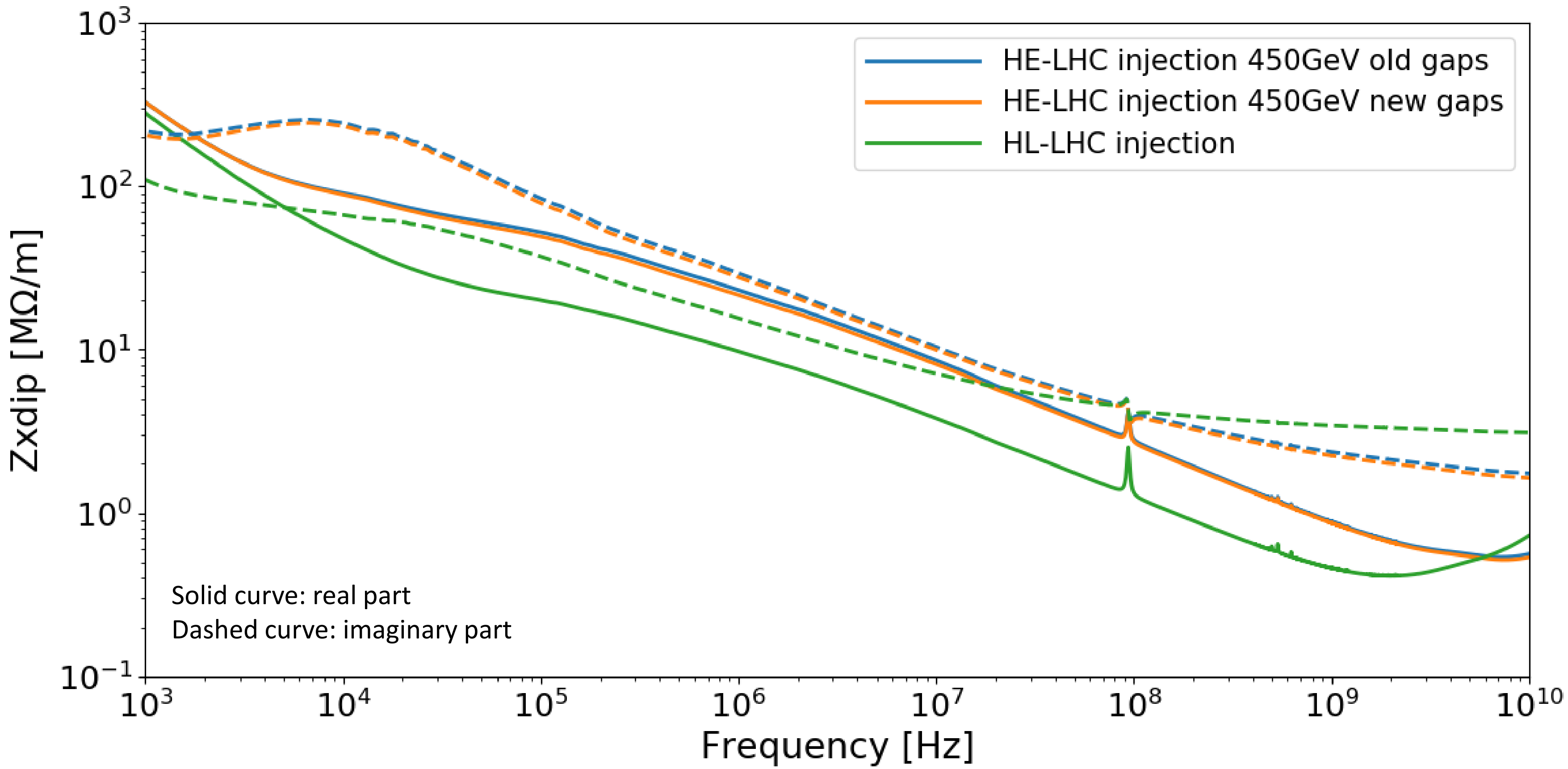
- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Cases studied for injection energy

Old (Dec. 2017) and **New** (Dec. 2018) gaps in σ_{coll}

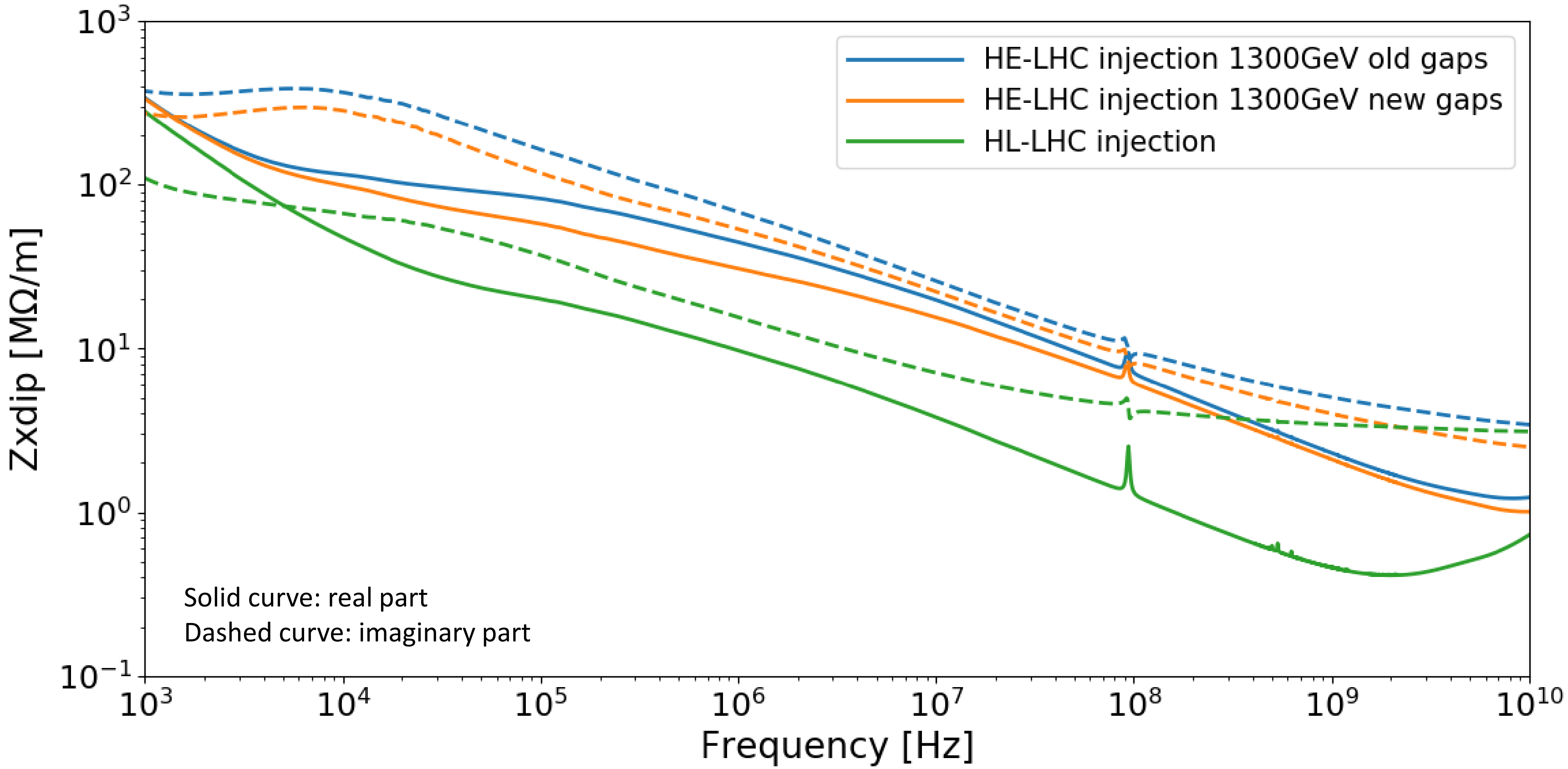
	450 GeV option		1.3 TeV option		HL-LHC Inj. 450 GeV
	Old	New	Old	New	
Reference emittance	2.5 um		2.5 um		2.5 um
Primary colls	5 σ	5.7 σ	5.7 σ	9.7 σ	6.7 σ
Secondary colls	6 σ	6.7 σ	6.7 σ	11.4 σ	7.9 σ
Injection protection	7.3 σ	8 σ	8 σ	13.6 σ	9.5 σ

Impedance at 450 GeV injection energy



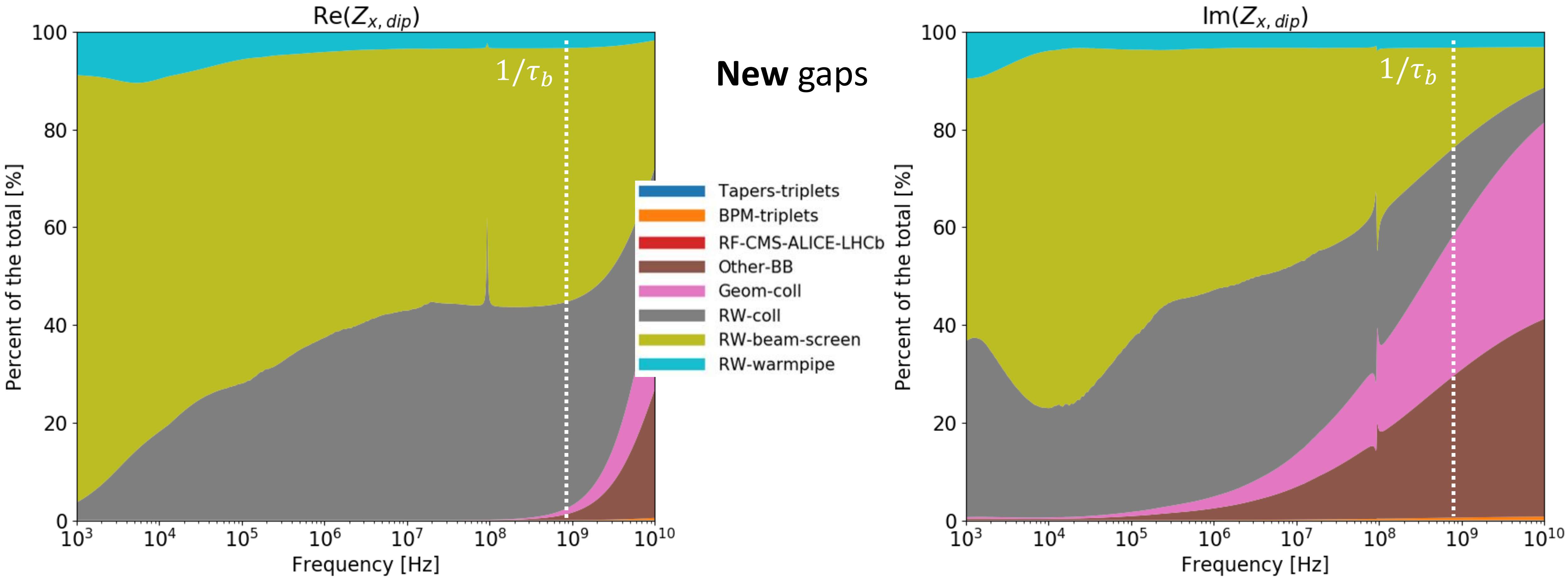
- At 450 GeV, beam screen and collimators are the main contributors
- Slight (~5% in the 100 kHz - 10 MHz range) impedance reduction thanks to the larger collimators physical gaps

Impedance at 1.3 TeV injection energy



- Collimators contribution dominate the frequency range of interest
- Visible impedance reduction thanks to the larger collimators physical gaps: ~30% in the 100 kHz - 10 MHz range

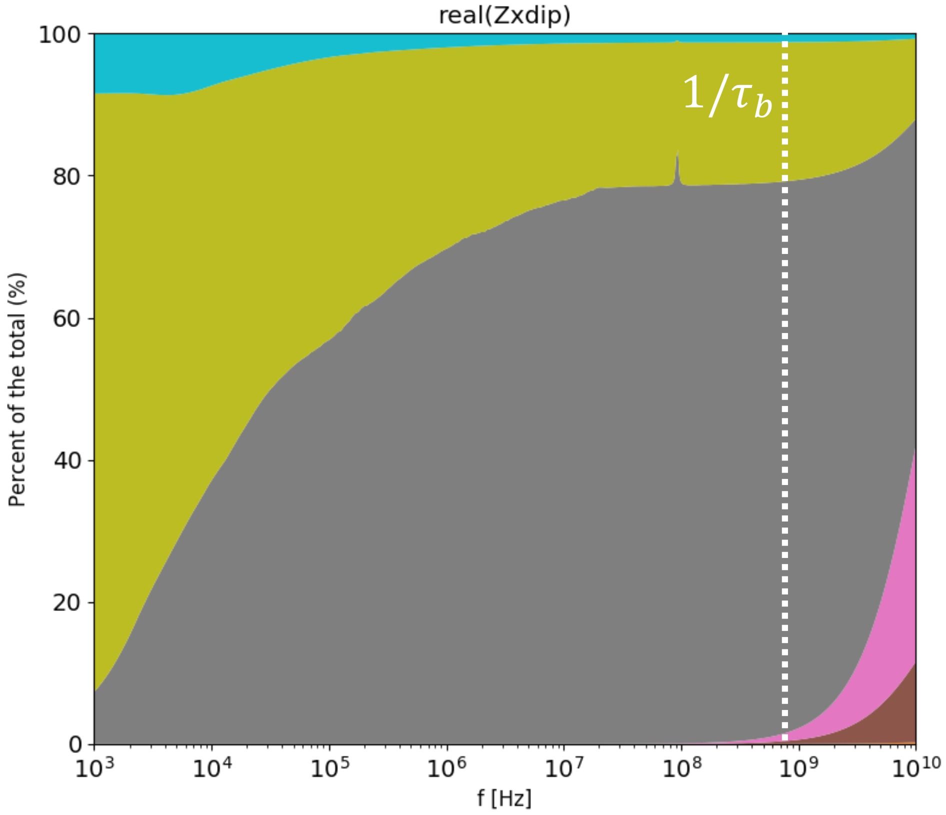
Contributors at injection energy: 450 GeV

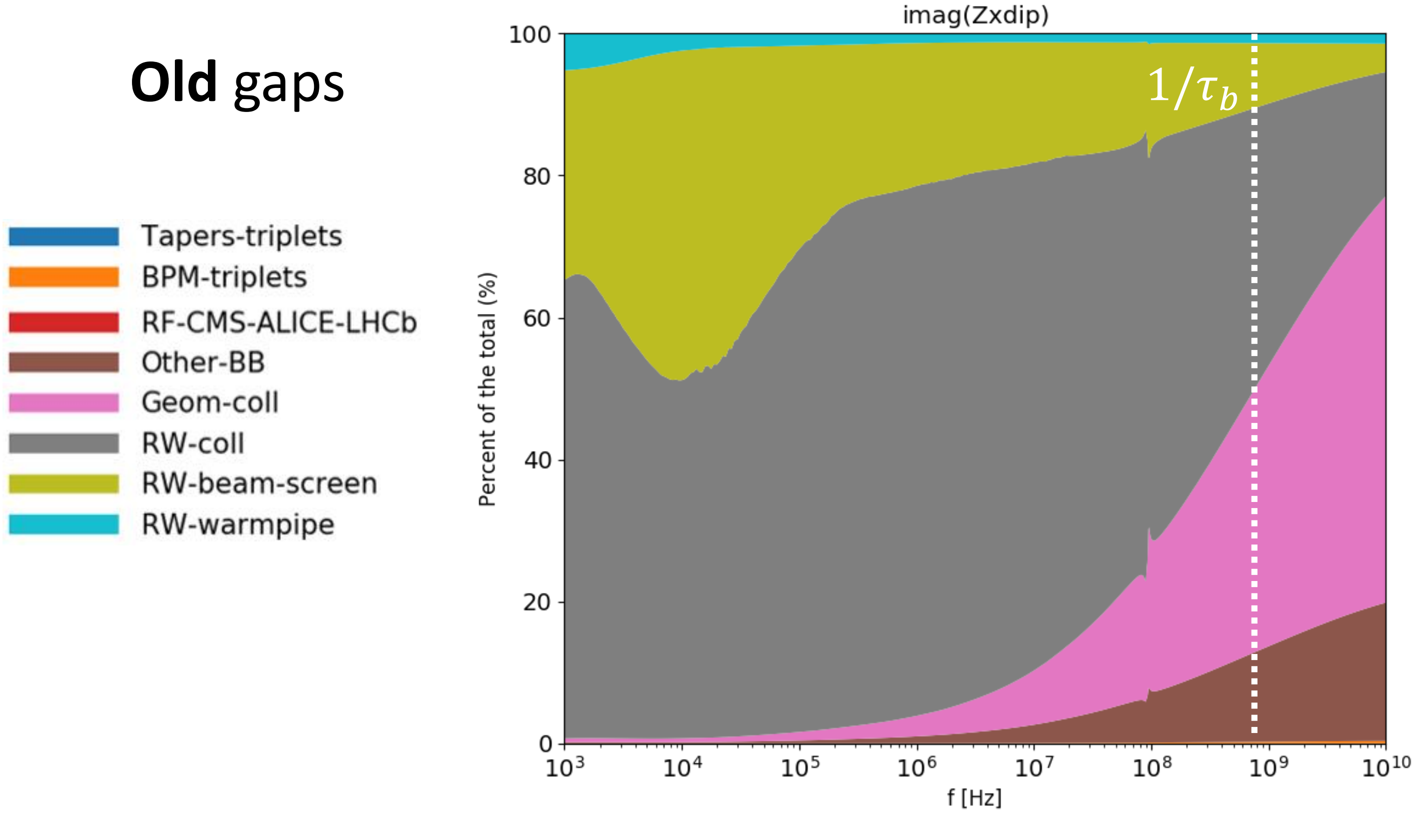


- Collimators and beam screen are the main contributors to the impedance

Contributors at injection energy: 1.3 TeV

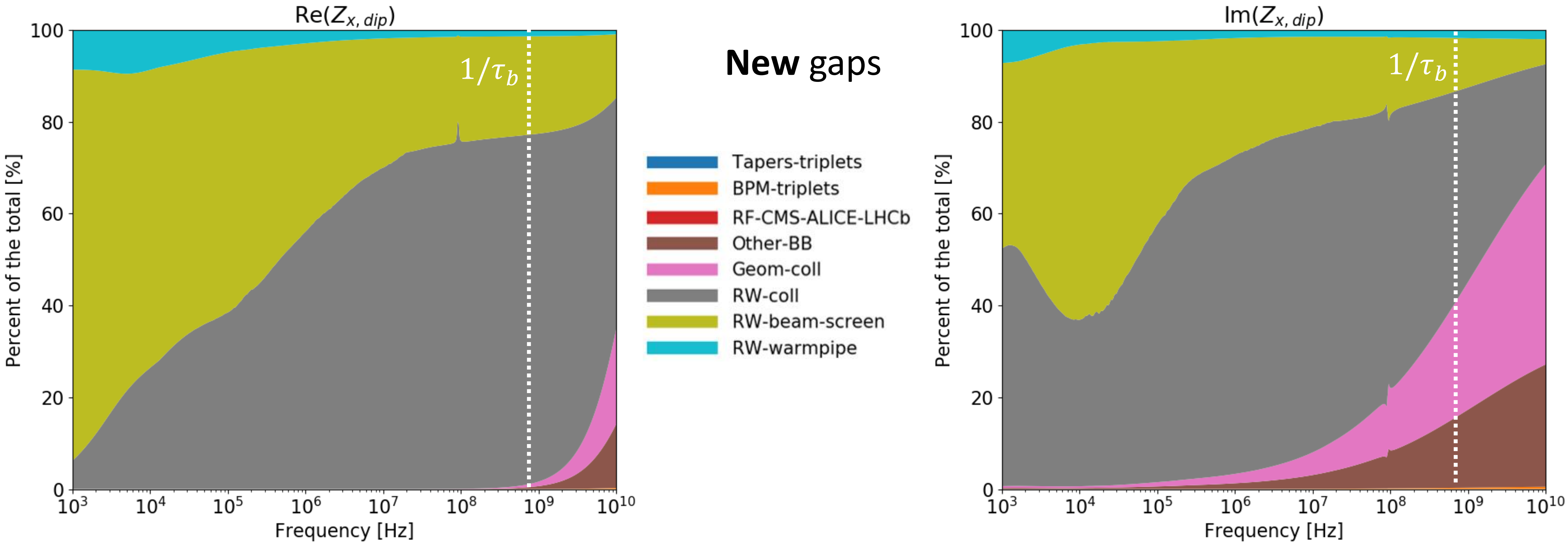
Old gaps





- The new collimator gaps reduce the total impedance
- Collimators still represent the largest share of the impedance

Contributors at injection energy: 1.3 TeV



- The new collimator gaps reduce the total impedance
- Collimators still represent the largest share of the impedance

Outline

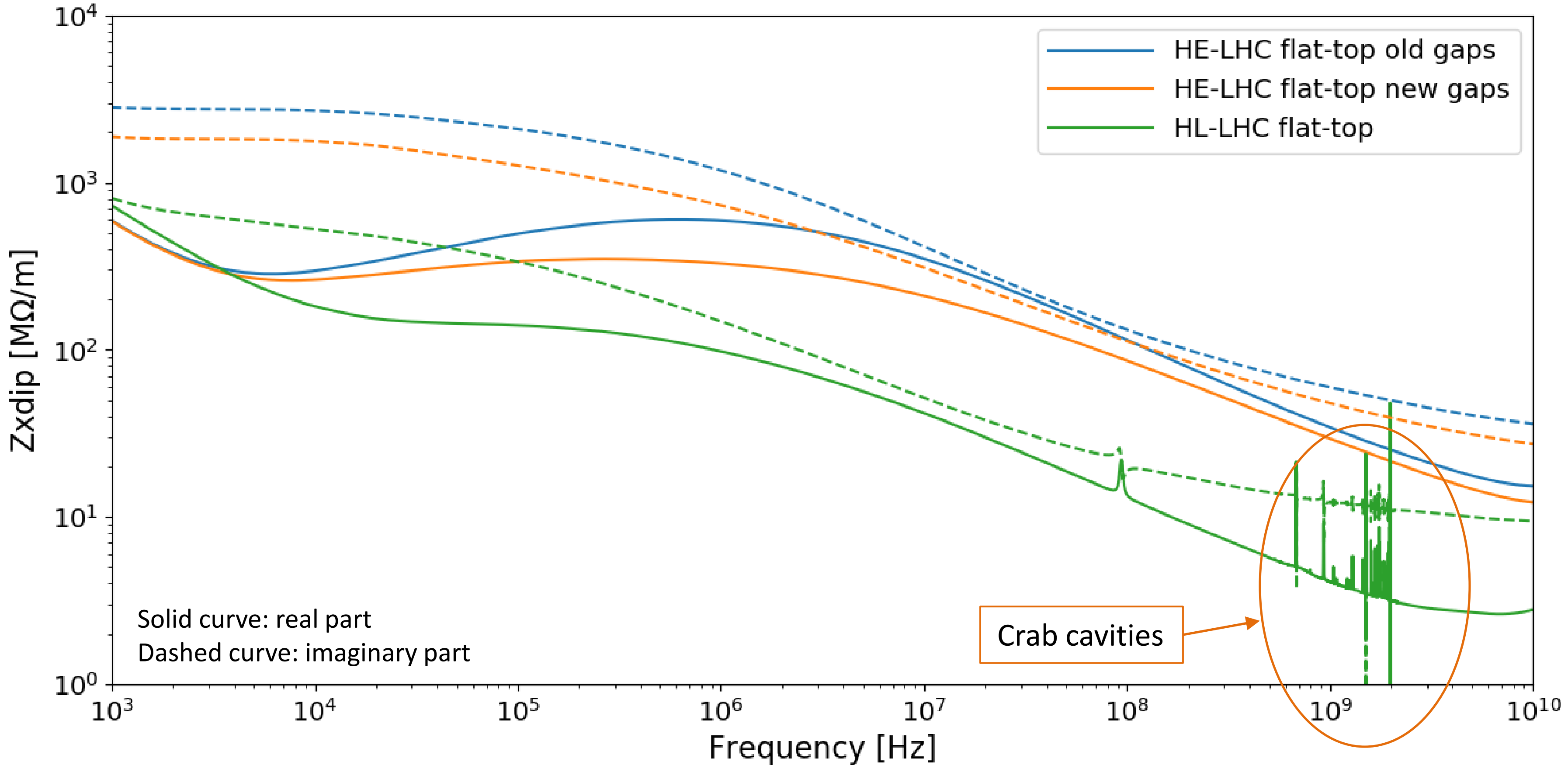
- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Case studied

	Old	New	HL-LHC 7 TeV
Reference emittance	2.5 um	2.5 um	2.5 um
Primary colls	**5 σ**	**6.7 σ**	6.7 σ
Secondary colls	**6 σ**	**9.1 σ**	9.1 σ
Dump protection	6.5 σ	10.1 σ	9.6 σ

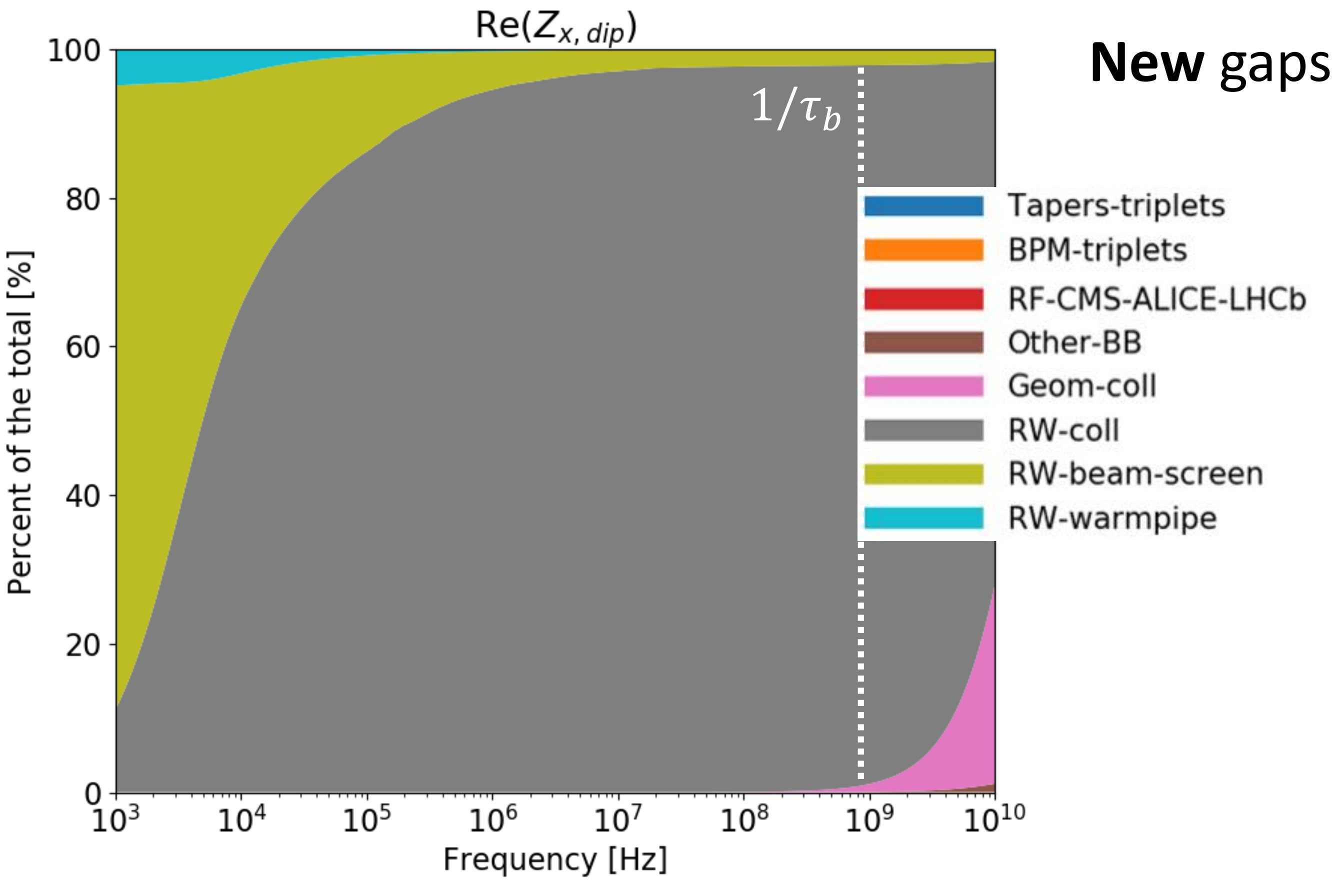
- New gaps have similar configuration to HL-LHC
- Tight settings (LHC 2018 with 1σ retraction) were used as old gaps
  - Showcased an ultimate scenario

Impedance at top energy

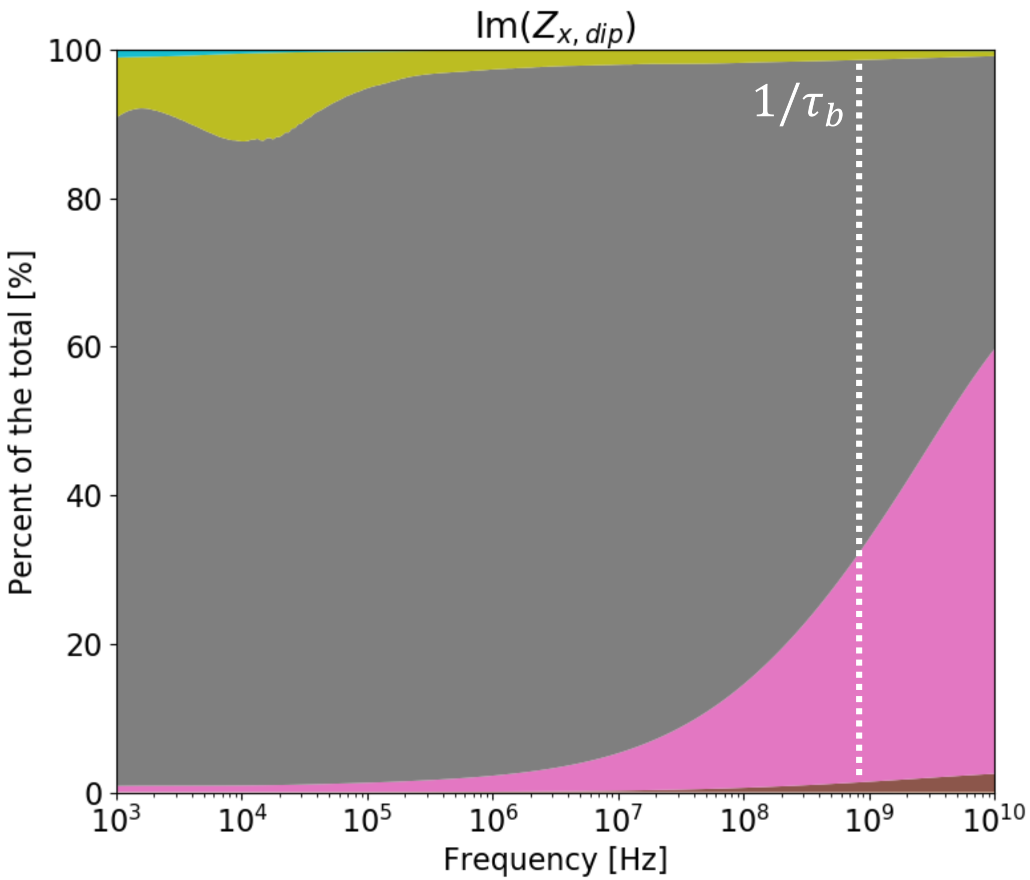


- Crab cavities not included in the HE-LHC model
- Significant impedance reduction thanks to the larger collimators gaps
  - In the horizontal plane: impedance reduced by a factor ~1.8 in the 100 kHz - 10 MHz range

Contributors at top energy



New gaps



- Collimators contribution dominate the whole frequency range

Outline

- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Beam stability simulations

- Check if there are constraints from the beam stability point of view

- Recommend parameters settings for the machine
  - Chromaticity
  - Damper gain
  - Octupole current

- Only the impedance is considered
  - No space charge
  - No electron cloud
  - No beam-beam

Machine and beam parameters

- HE-LHC CDR and Hi-Lumi beam parameters (tunes, bunch length, emittance)
- Hi-Lumi optics and Landau octupole magnets type were used

DELPHI code page: DELPHI

NHTVS code description:
A.Burov, PRAB **17**, 021007, 2014

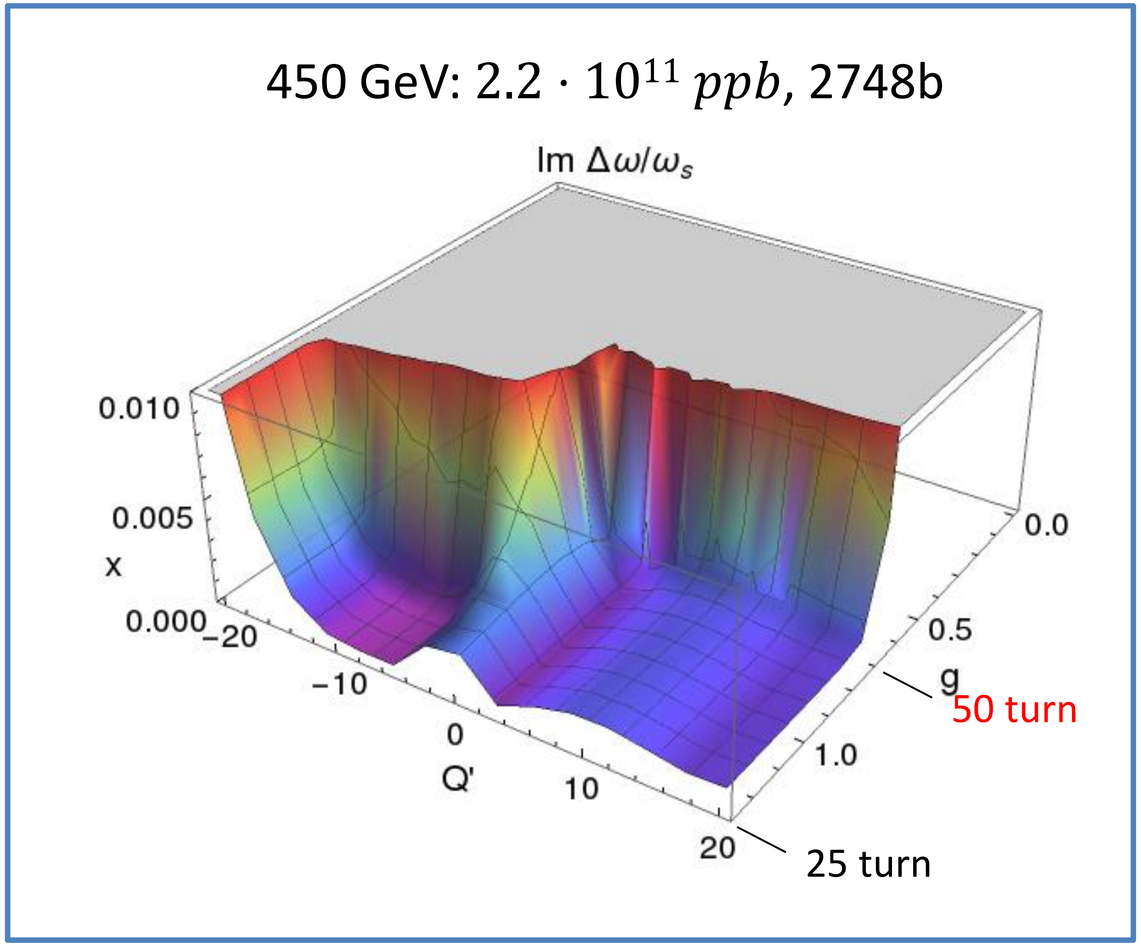
- Stability simulations made with NHT Vlasov Solver and DELPHI
  - Single-bunch and coupled-bunch simulations
- Scan over different parameters
  - Chromaticity: $Q' = -20 \ldots +20$
  - Damper gain: $g = 0 \ldots {}^{1}/_{25}\, turn^{-1}$
  - Intensity: $N_b = 0 \ldots 10 \cdot 10^{11}\, ppb$

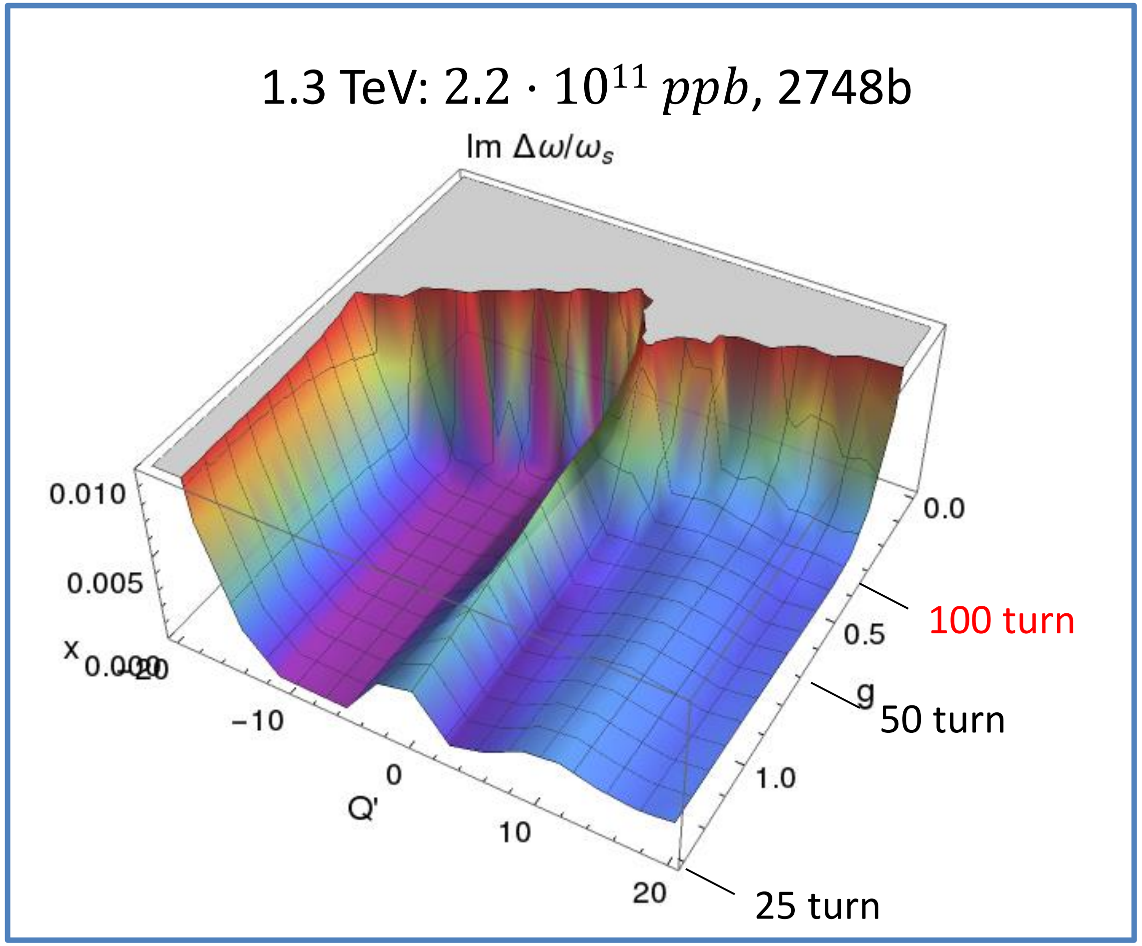
- Given a stability diagram and assuming the modes are uncoupled, the octupole current can be computed

Outline

- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Injection energy

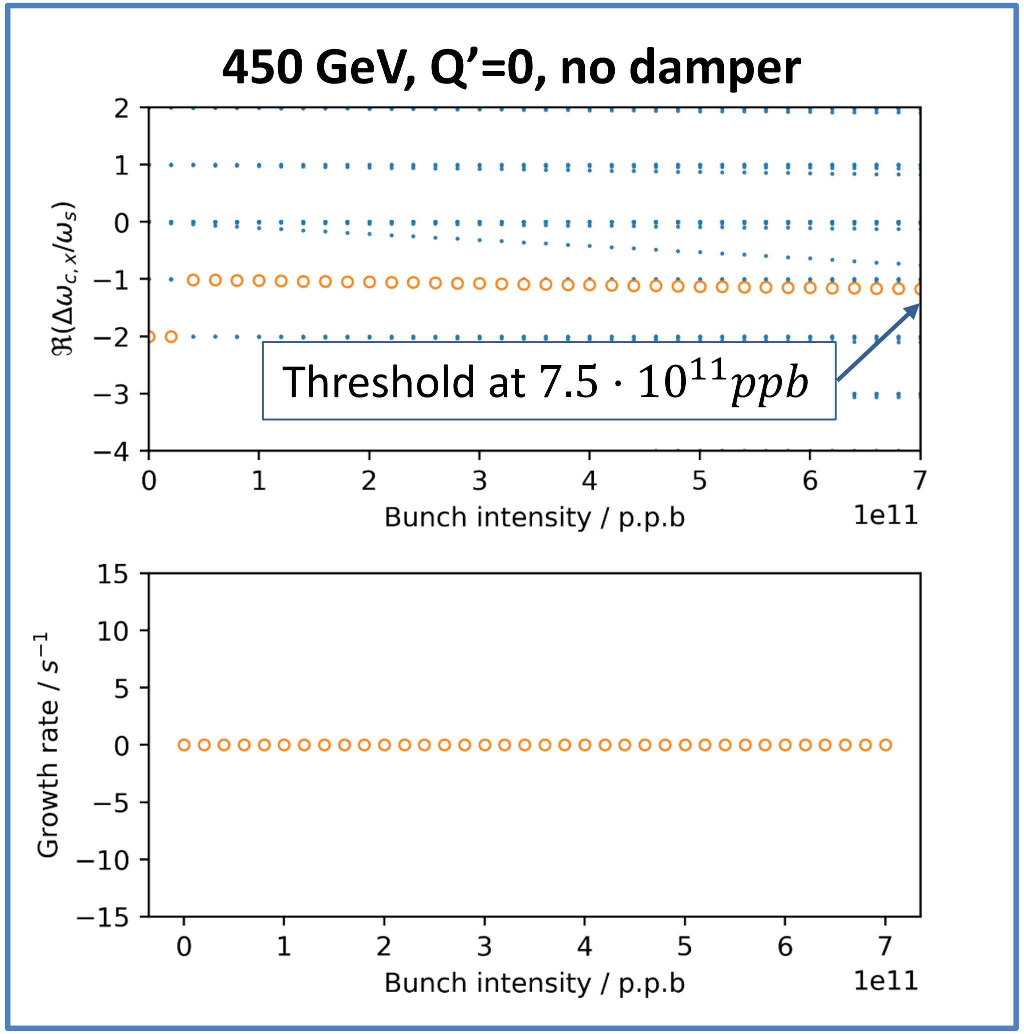


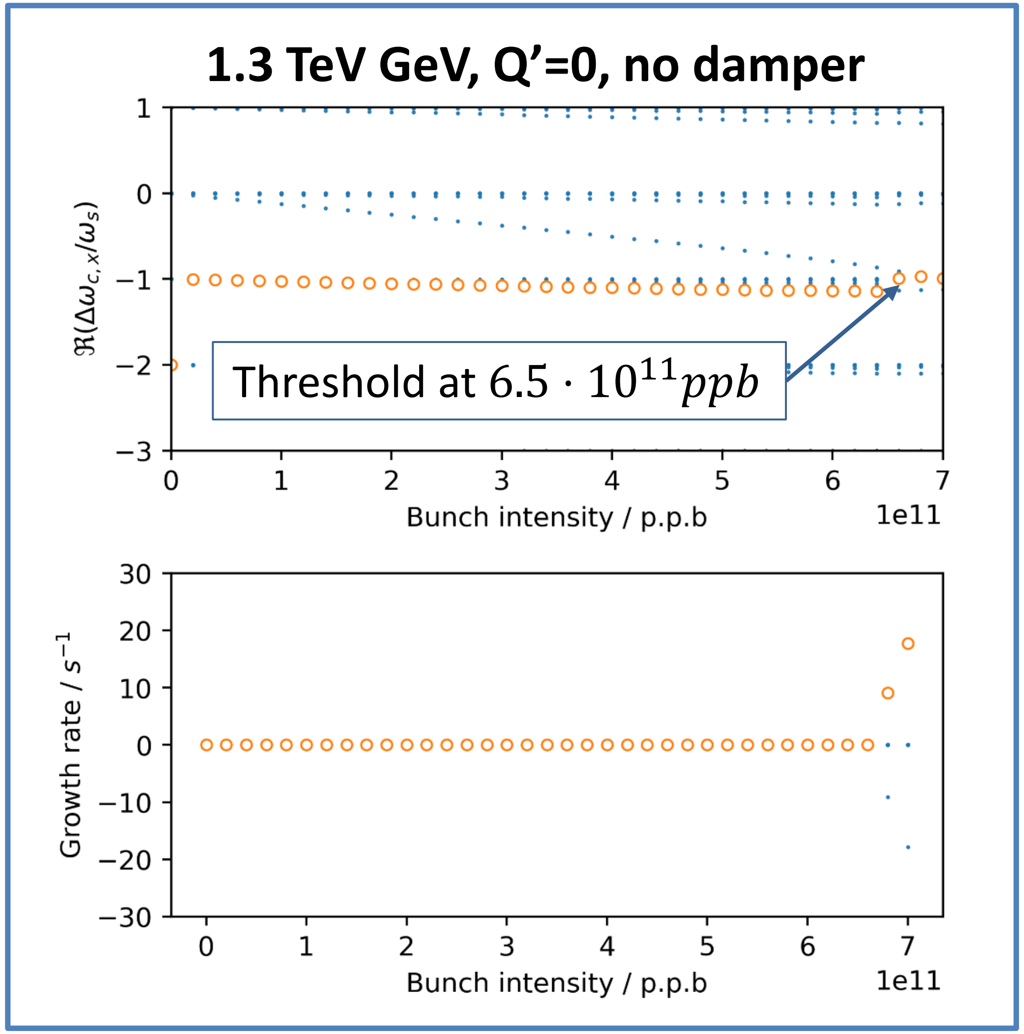


Damper gain: g = damping rate / ω_s

- 450 GeV option still requires 50 turns gain (with tight margin)
- 1.3 TeV option now requires 100 turns gain (was 75 turns with old gaps)

Single bunch TMCI

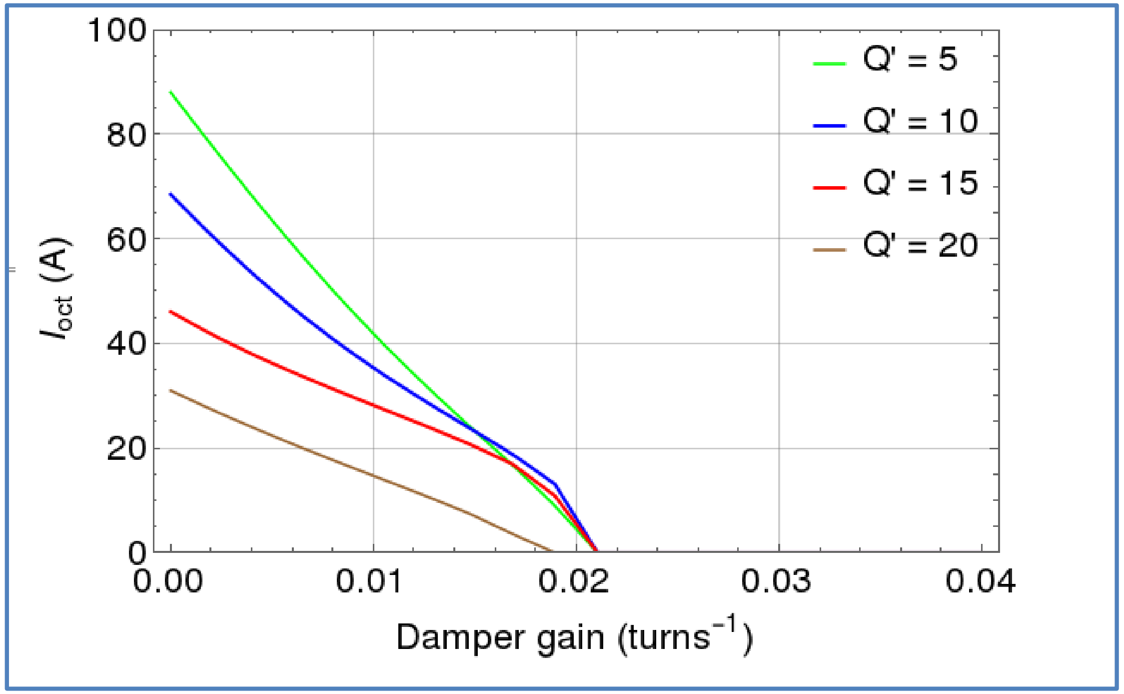




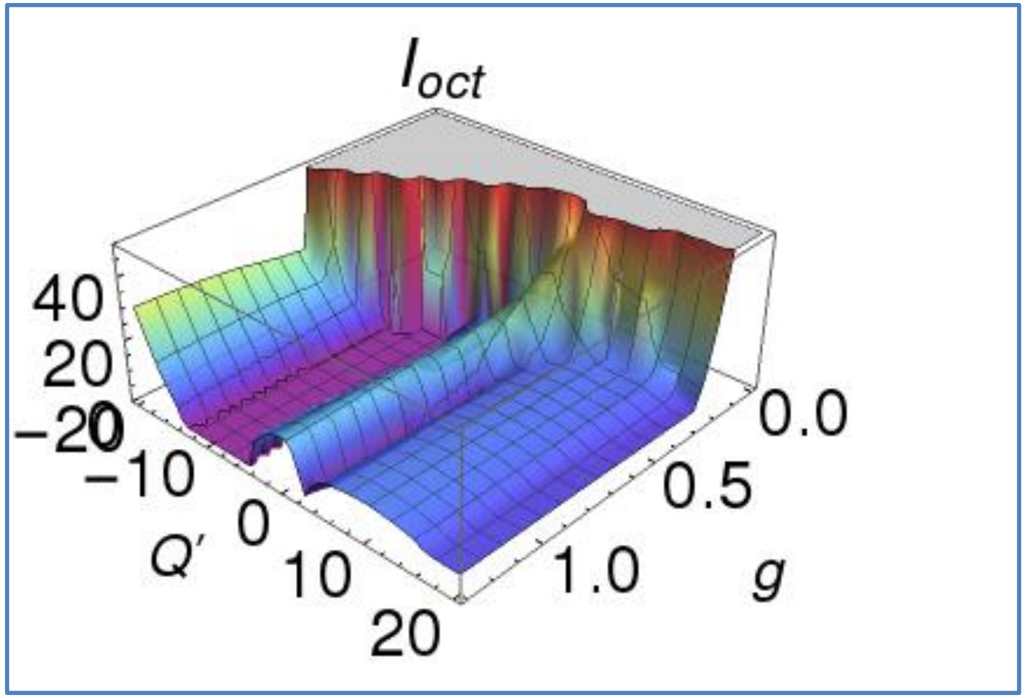
- Instability threshold can be lower in coupled bunch regime (as much as 50% for the 450GeV case, see last year presentation)

In multibunch, octupole current are still negligible

450 GeV: 2.2x10^{11} ppb, 2748 b, 2.0 μm



1.3 TeV: 2.2x10^{11} ppb, 2748 b, 2.0 μm



ε_n = 2.0 μm, σ_z = 9.0 cm, I_{oct} < 0, Gaussian

- Octupole current needed to stabilize the beam at injection is small if sufficient damper gain
- However the impact on dynamic aperture can be important

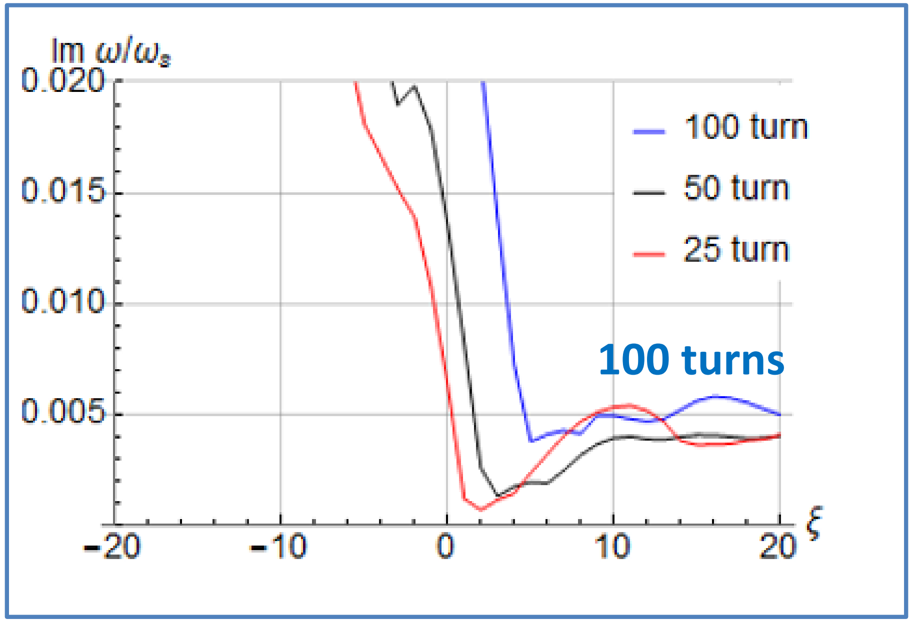
Damper gain: g = damping rate / ω_s

Outline

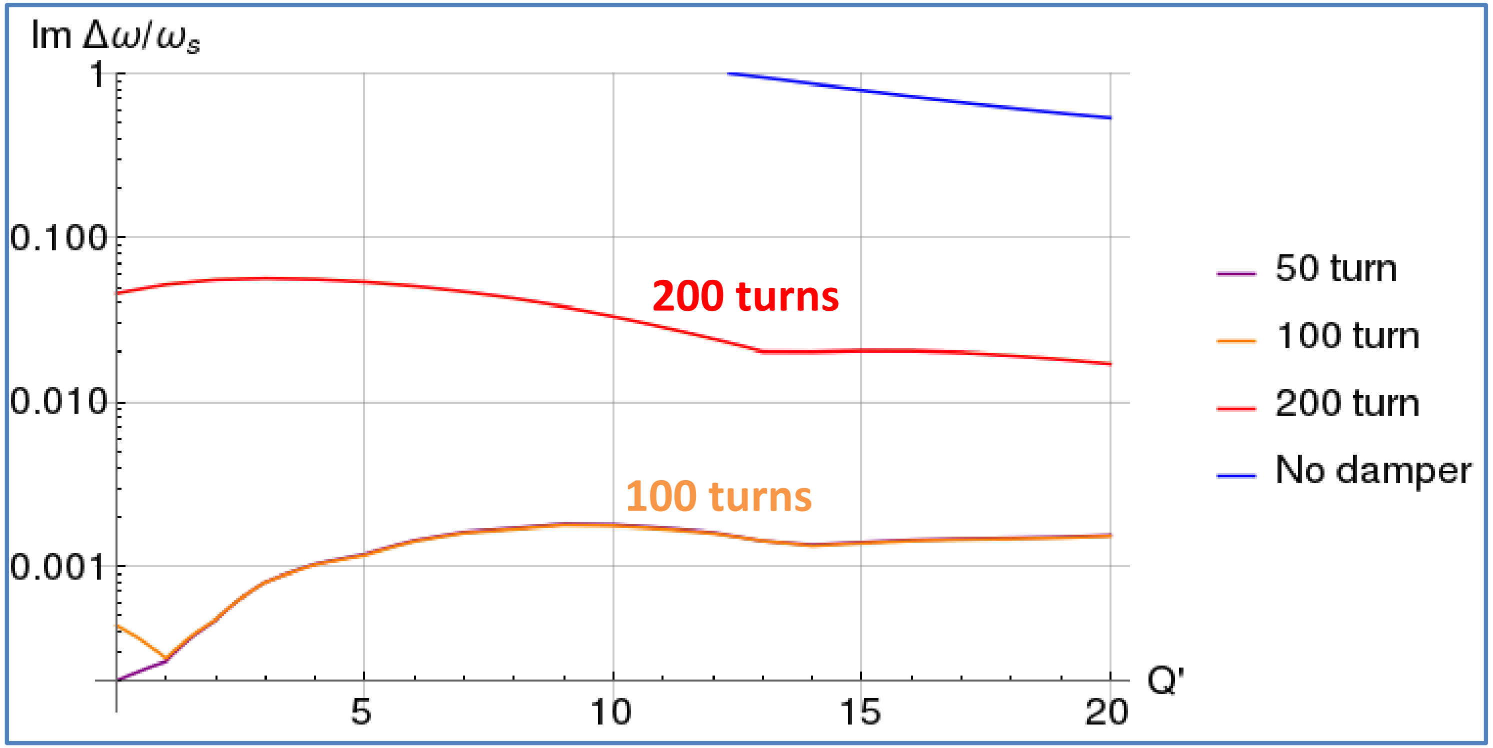
- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Growth-rates are reduced

Old gaps



New gaps

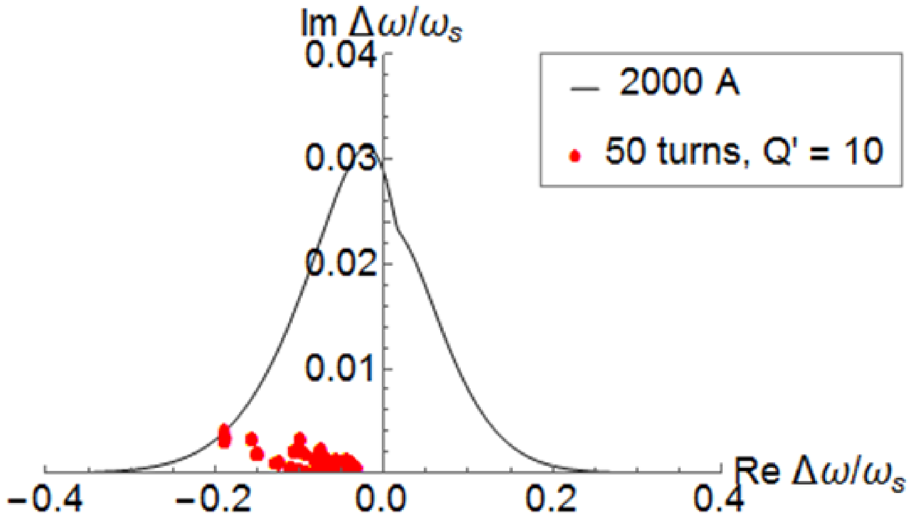


- Growth-rates are slightly reduced compared to previous model
  - For Q'~10, 100turns damper: $Im(\Delta\omega/\omega_s) \sim 5 \cdot 10^{-3}$ → $Im(\Delta\omega/\omega_s) \sim 2 \cdot 10^{-3}$
- Will help with instability damping

Landau damping

- Octupoles become less efficient for Landau damping at high energies
  - Octupole tune spread $\propto 1/\gamma^2$
  - Long range beam-beam might have a detrimental effect on Stability Diagram
    - Effect is considerable for some Hi-Lumi operational scenarios: see for example X.Buffat, 7th HL-LHC Meeting, Madrid, 2017
    - Not consider it in this talk

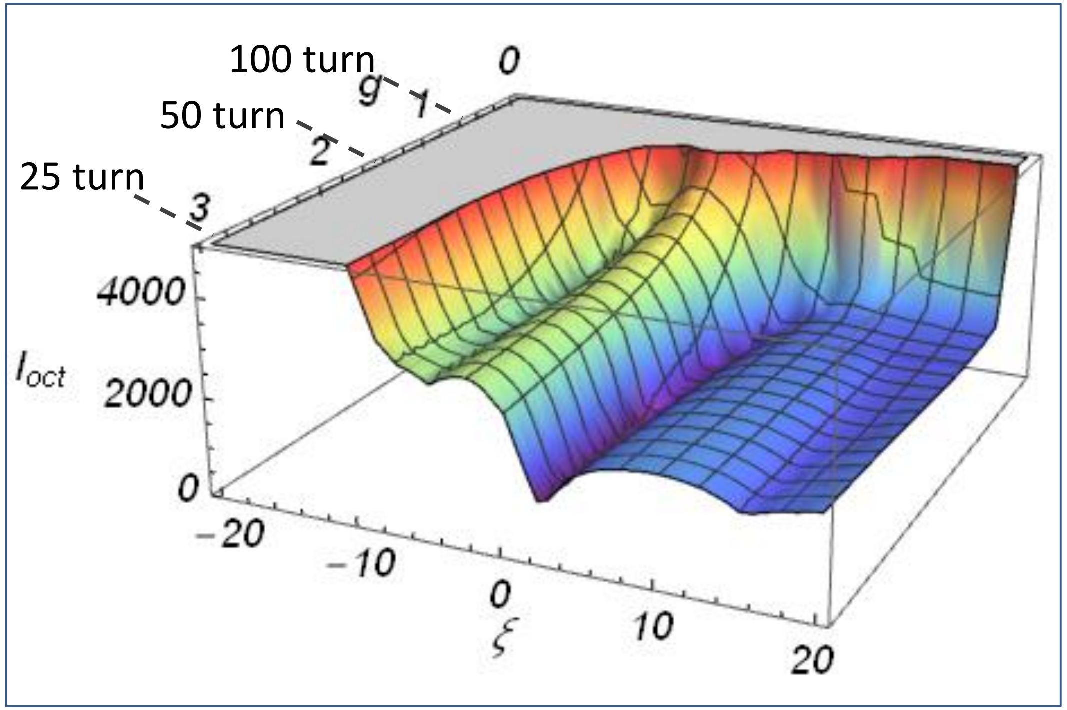
ε_n = 2.0 μm, σ_z = 9.0 cm, I_{oct} < 0, Gaussian

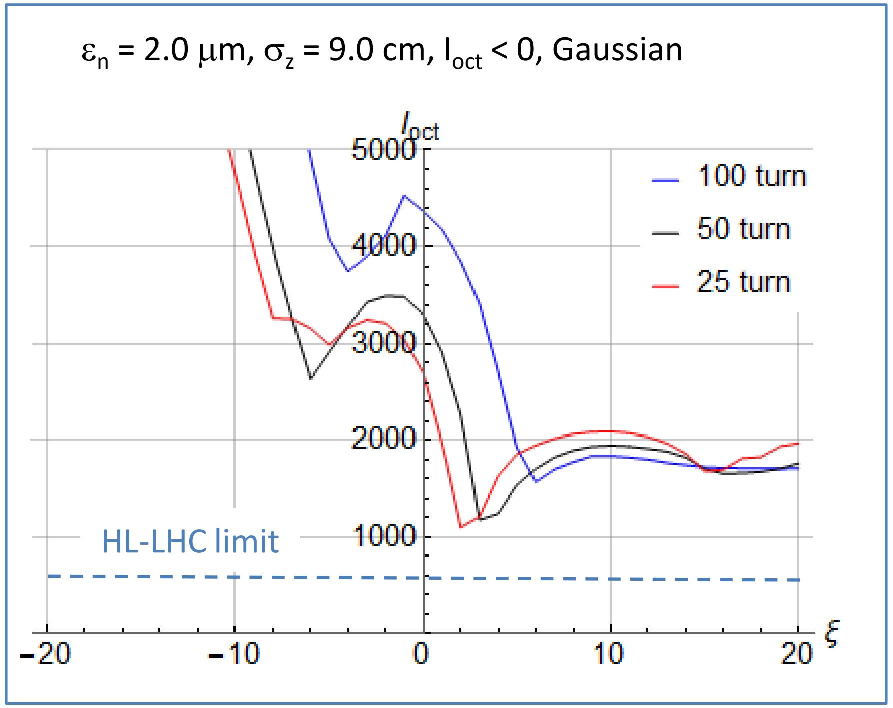


Old gaps required **~2000A** of Hi-Lumi octupoles to stabilize the beam

Old gaps: ~2000 A of octupole required

- Reminder: HL-LHC type octupoles are considered
- Optics can help provide more detuning
  - See ATS optic in Hi-Lumi for instance



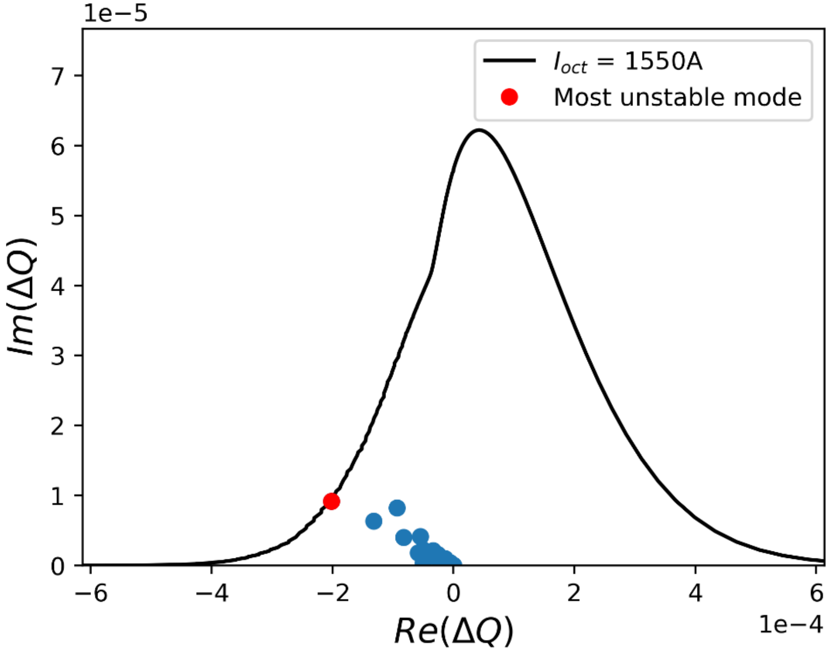


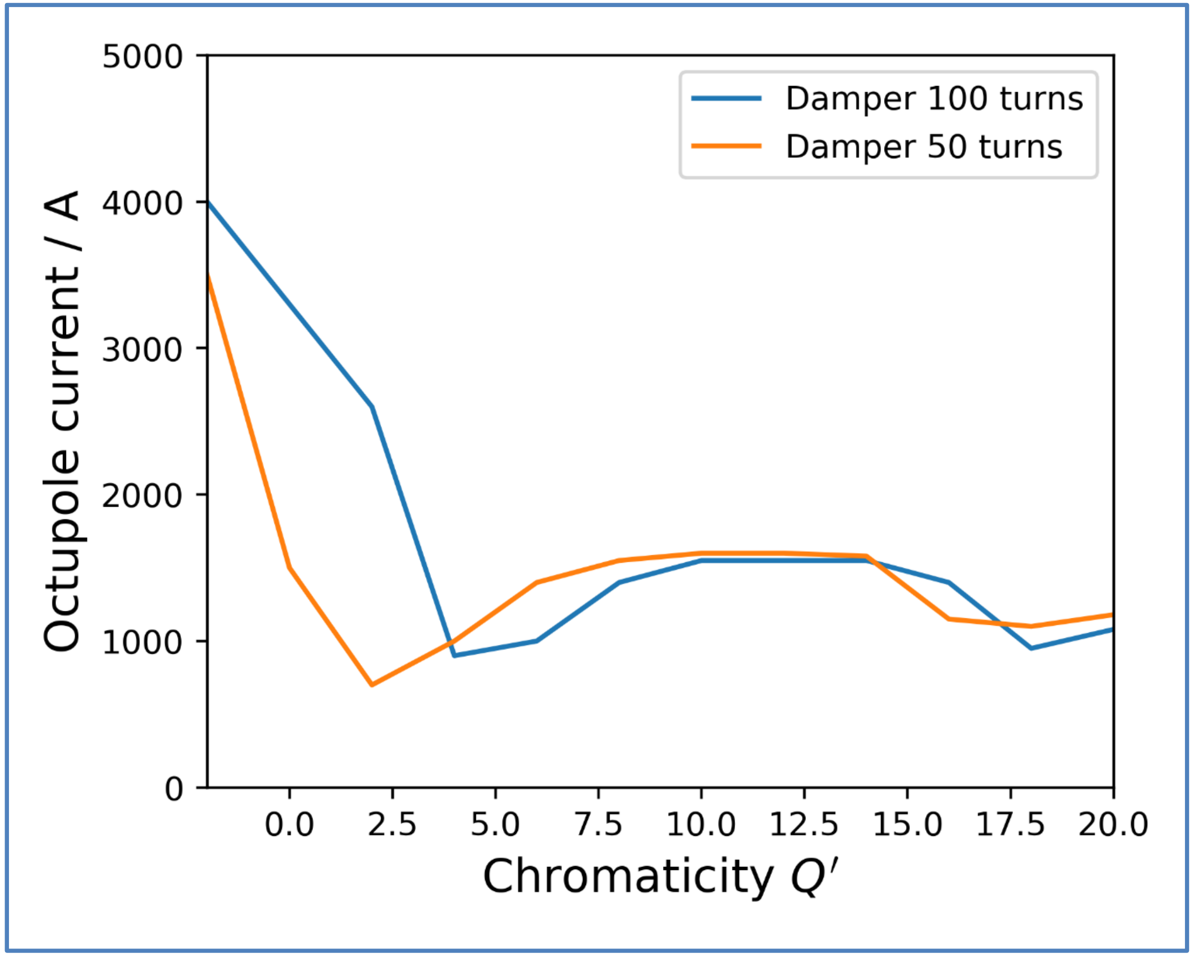
New gaps: ~1500 A of octupole required

- Impedance reduction helps to Landau damp the modes

Most unstable CB modes

2.2x10^{11} ppb, 2748 b, 2.0 μm





Alternative methods may be required:

- Gaussian Electron Lens — V. Shiltsev, *et al.*, Phys. Rev. Lett. **119**, 134802, 2017
- RFQ — M. Schenk, *et al.*, IPAC’17, Copenhagen, 2017

Outline

- Introduction
- HE-LHC impedance model
  - Assumptions on the impedance model
  - Results for injection energy
  - Results for top energy
- Beam stability simulations
  - Parameters for the stability simulations
  - Results for injection energy
  - Results for top energy
- Conclusions

Conclusions

- HE-LHC impedance model updated with CDR parameters
  - All contributors included, except for the crab cavities
  - The FCC-hh beam screen was used
- At 1.3 TeV injection and 13.5TeV top energy, impedance is dominated by the collimators
- Impedance was reduced in all scenarios thanks to larger collimator gaps
  - Smaller impact at 450 GeV
  - Visible reduction at 1.3 TeV and 13.5TeV

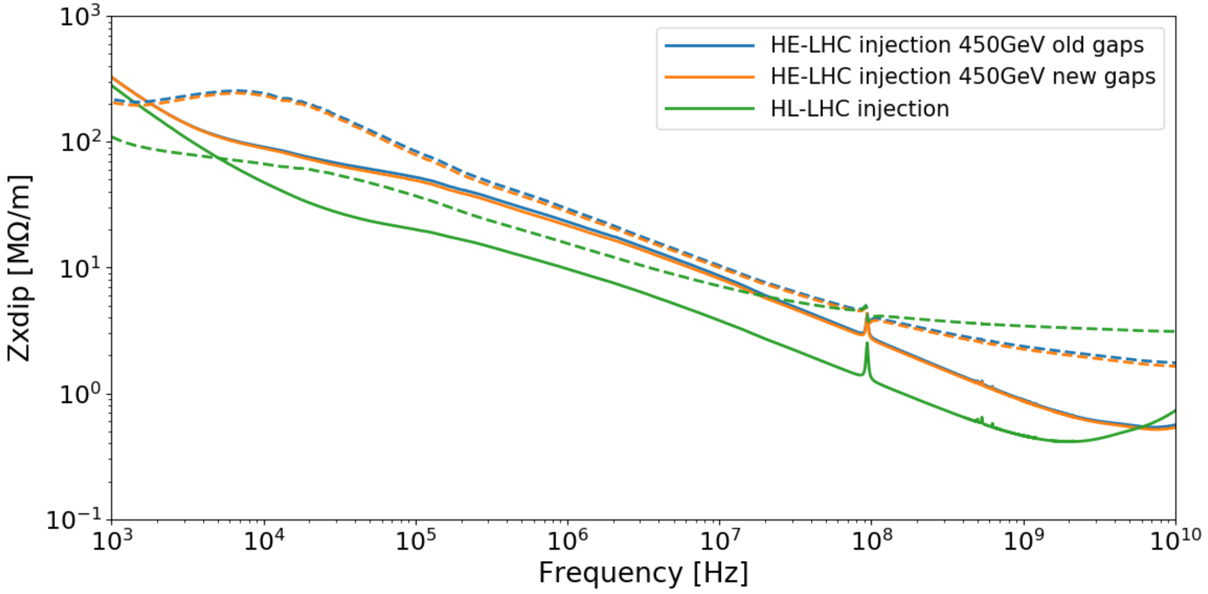
- The stability estimates include impedance effects only
- For all injection energy options the beam is stable for a damper gain of 50-100 turns
  - Impedance reduction mainly helped for the 1.3 TeV scenario
  - Still small octupole currents needed for stabilization (~10 A or below)
  - The 450 GeV option has less margin in intensity threshold and damper gain
- Top energy still challenging for beam stability
  - Impedance reduction significantly helped: ~~2000 A~~ → 1500 A
  - Still assuming the Hi-Lumi optics

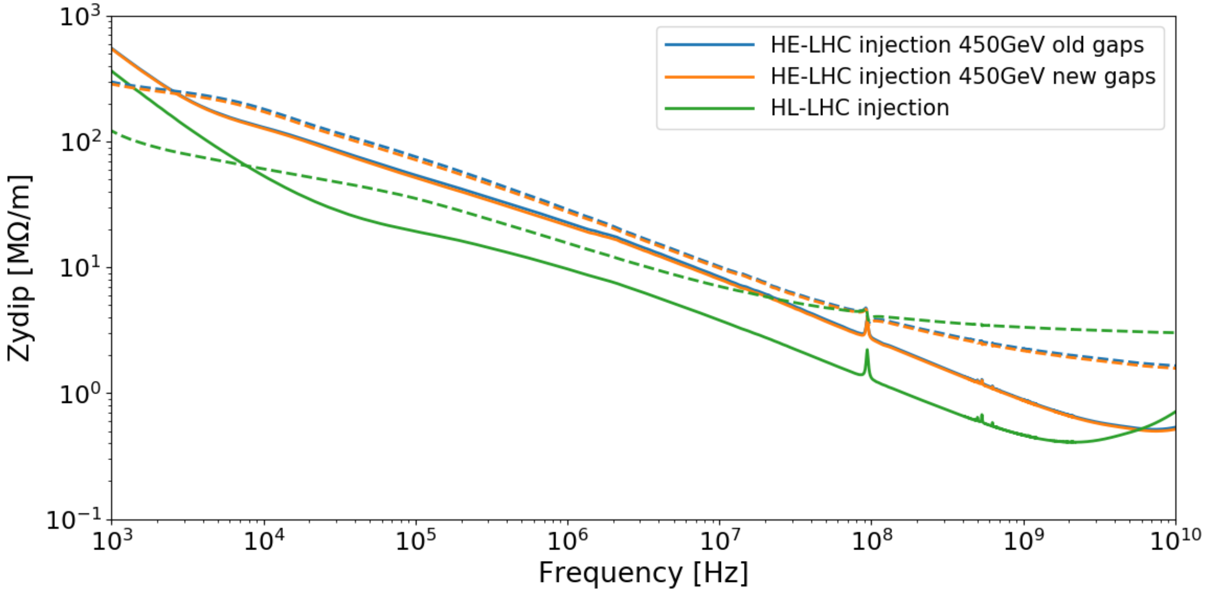
- The impedance models are available at https://gitlab.cern.ch/IRIS/HLLHC_IW_model

Thank you for your attention!

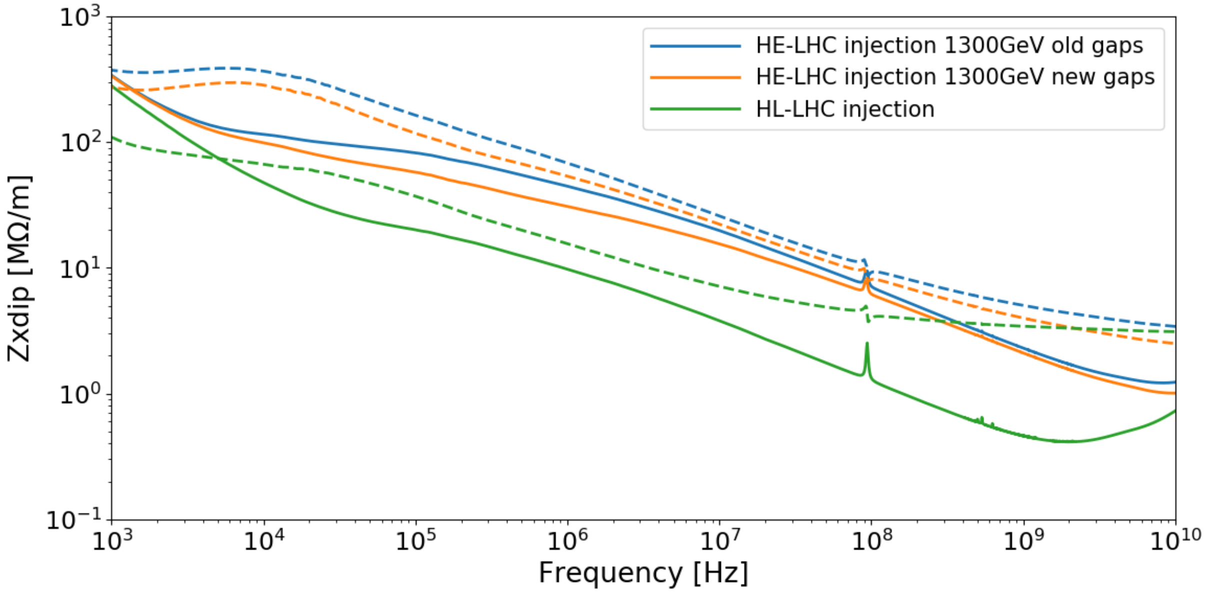
Backup

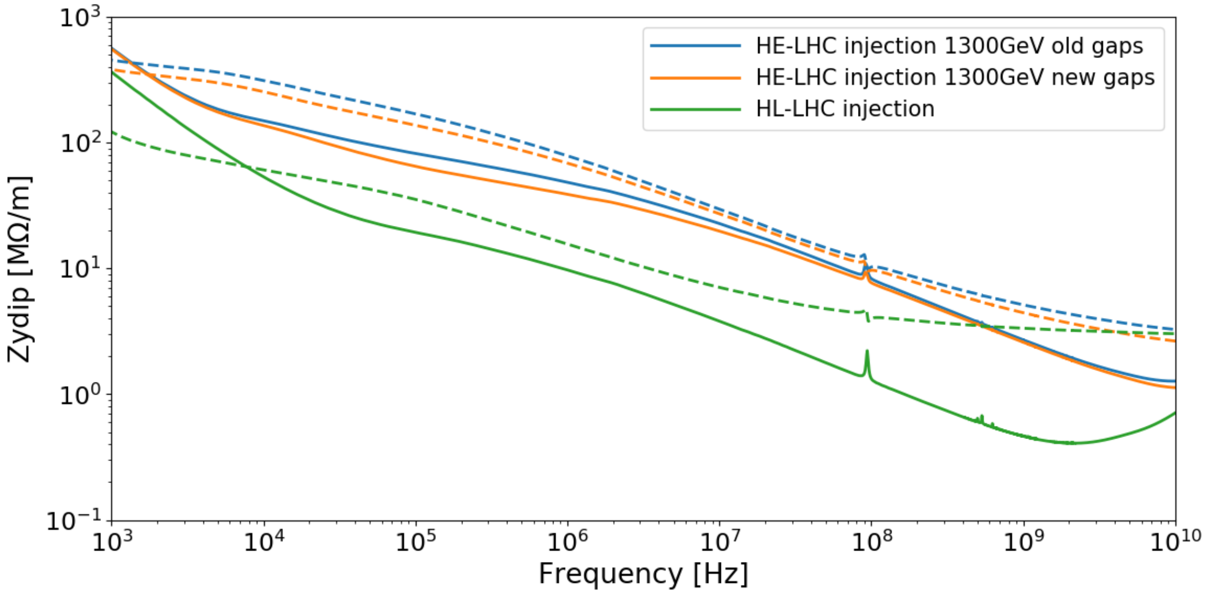
New model: impedance at 450 GeV



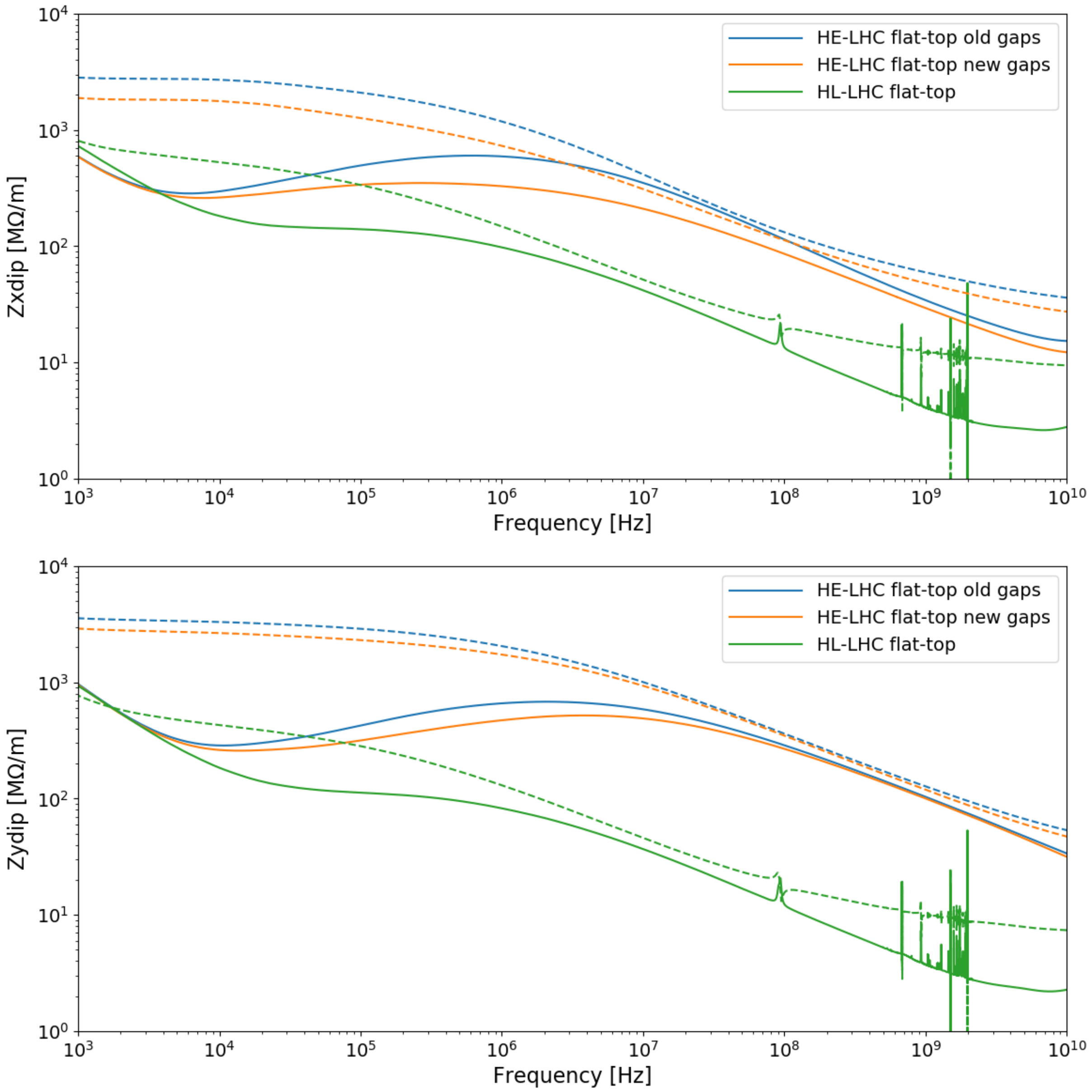


New model: impedance at 1.3 TeV

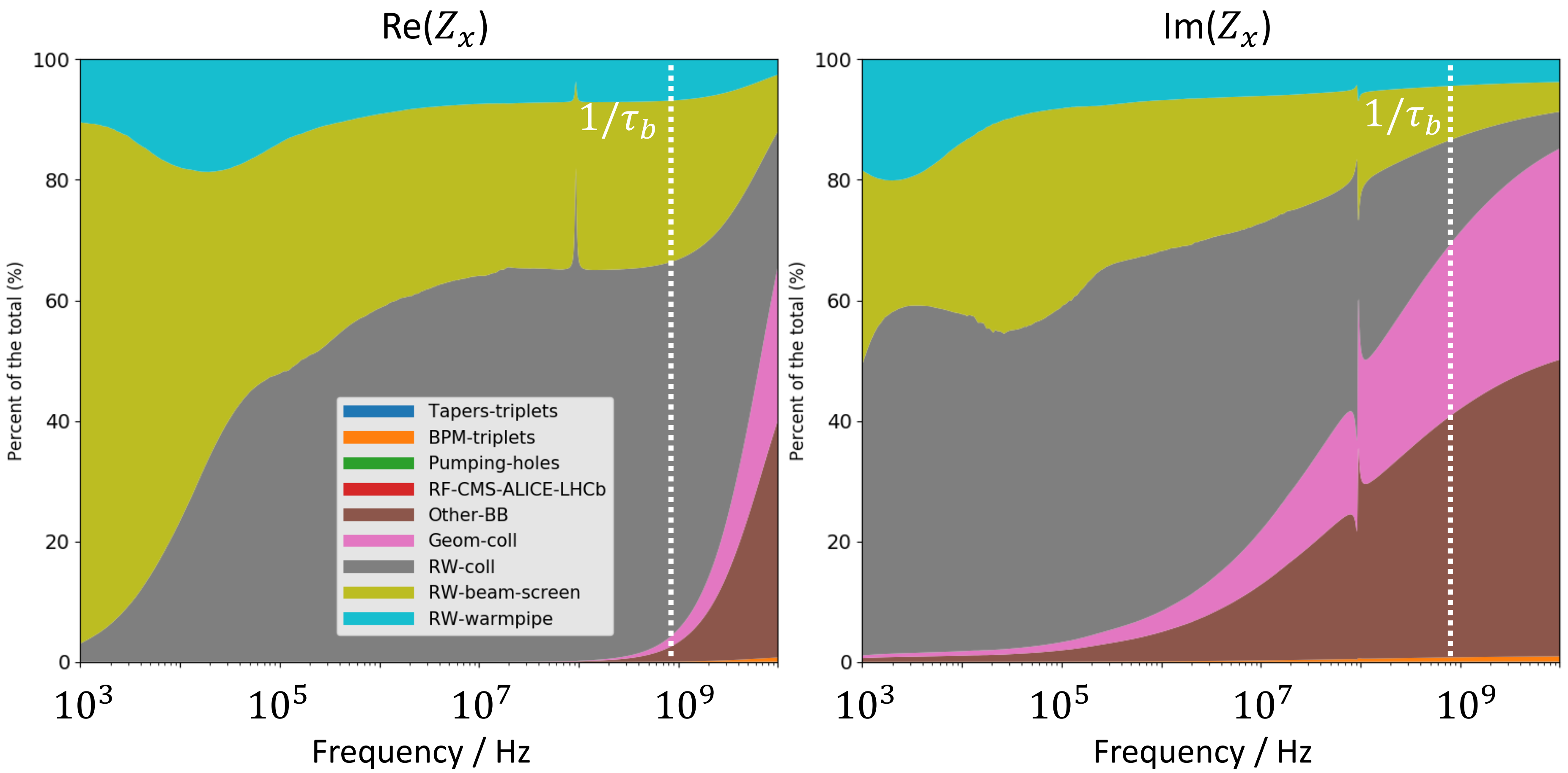




New model: impedance at top energy



Impedance at injection energy: HL-LHC



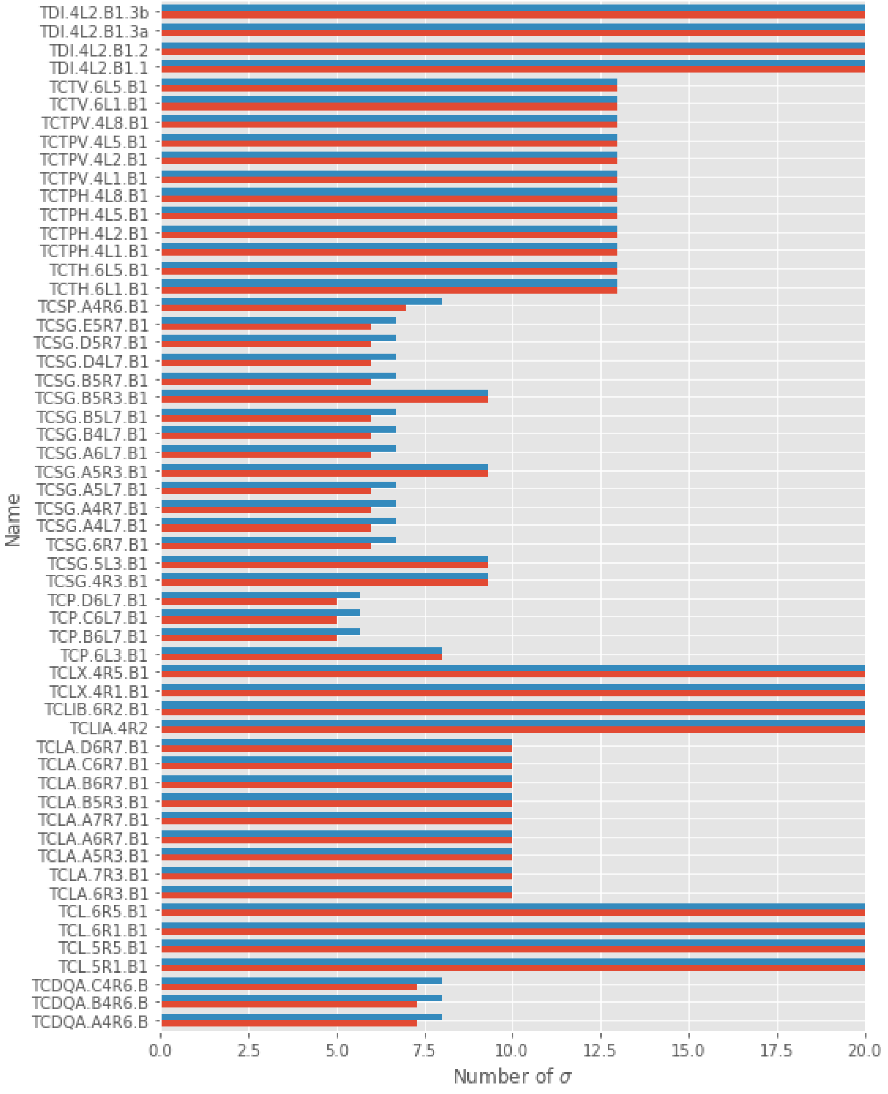
- Collimators are the main contributors to the impedance

Beam and optics parameters

	HE-LHC		HL-LHC	
Machine state	**Injection**	**Flat-top**	**Injection**	**Flat-top**
Beam energy	450, 1300 GeV	13.5 TeV	450	7.0 TeV
Bunch intensity	2.2×10^{11} ppb	2.2×10^{11} ppb	2.3×10^{11} ppb	2.3×10^{11} ppb
Number of bunches	2748	2748	2760	2760
Tunes: x, y, s	0.31, 0.32, 0.006	0.31, 0.32, 0.0015	0.31, 0.32, 0.005	0.31, 0.32, 0.002
Norm. emit., rms	2 μm	2 μm	2.1 μm	2.1 μm
Bunch length, rms	9 cm	9 cm	9 cm	9 cm

Collimator gaps at 450 GeV injection

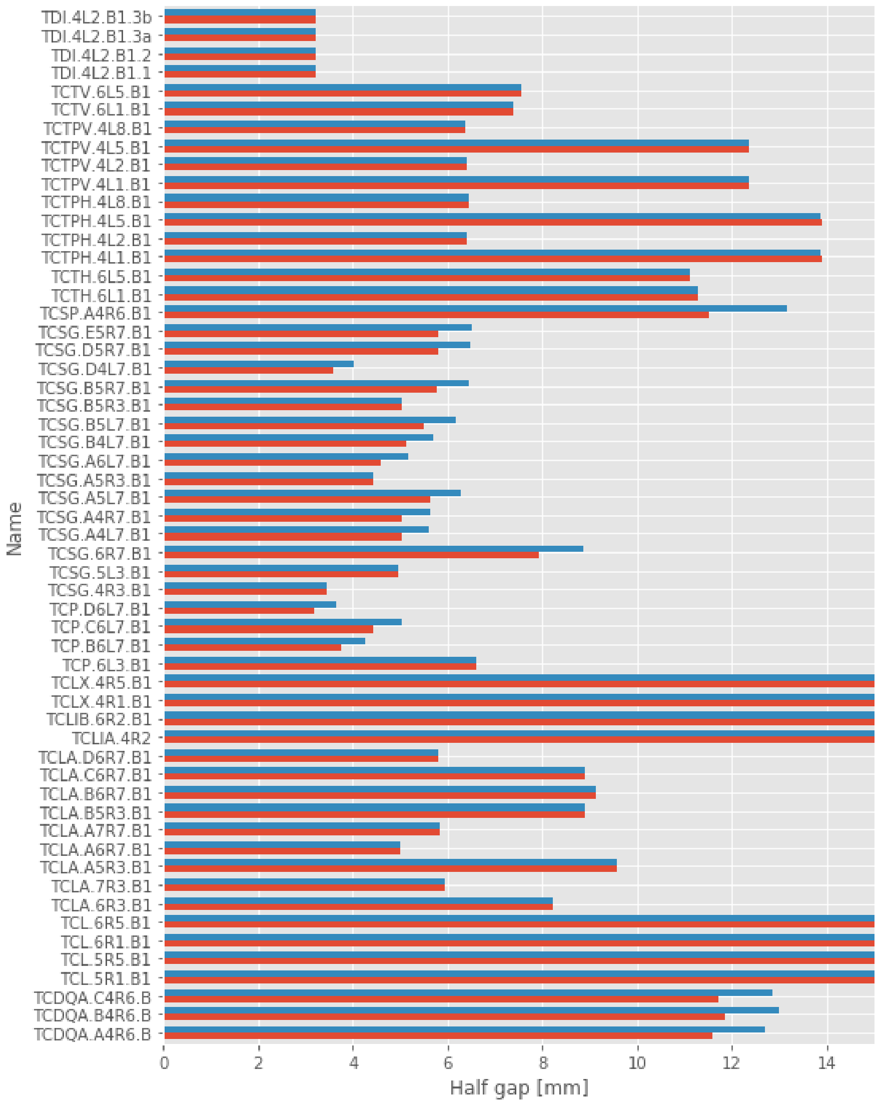
- Summary of collimator gaps, in σ_{coll} (left) and in mm (right)



Red: old gaps
Blue: new gaps

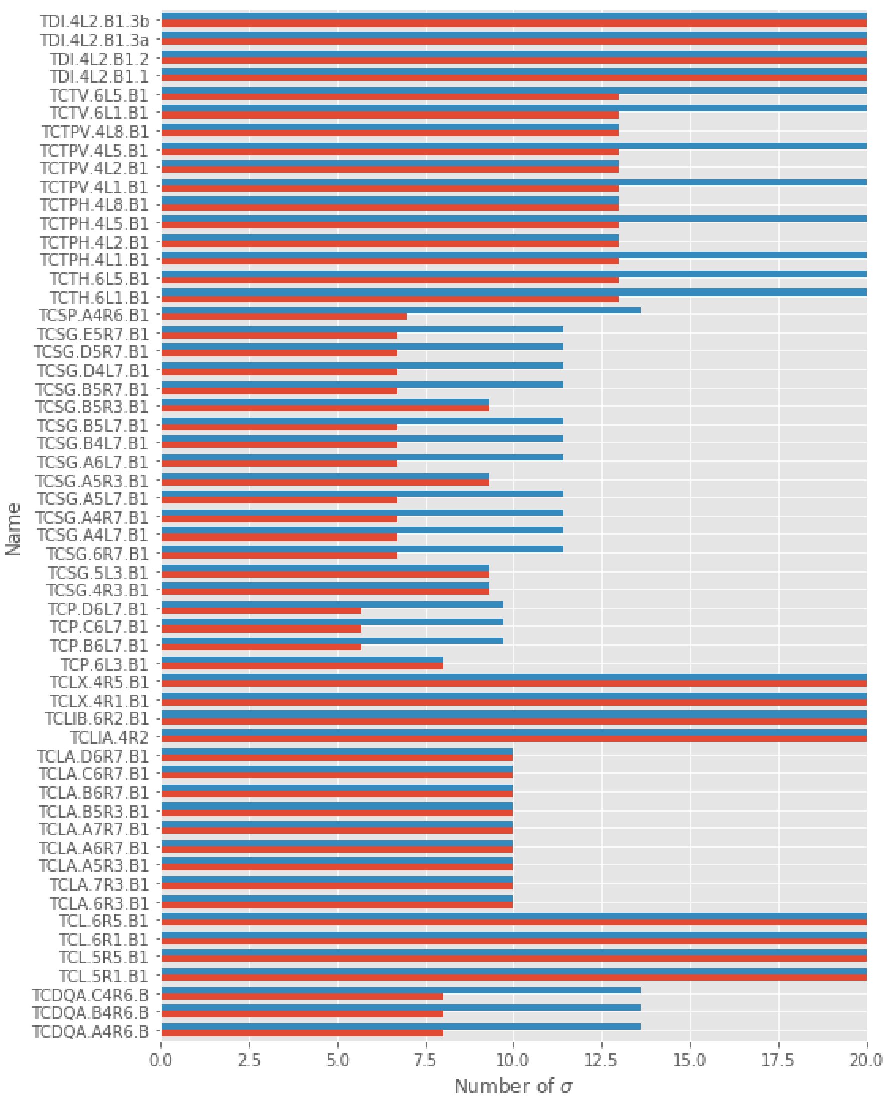
Physical gaps scale as $\sqrt{\frac{\varepsilon_n}{E}}$

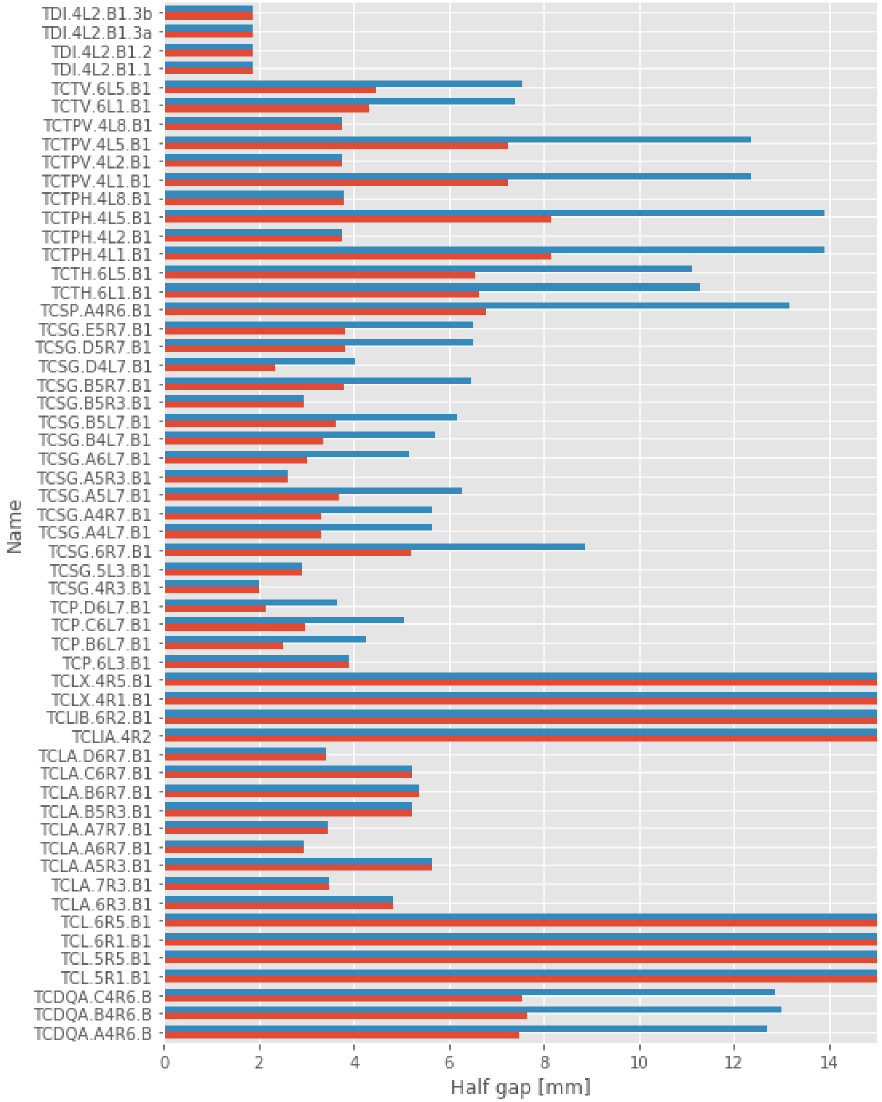
For HL-LHC, $\varepsilon_n = 2.5\mu m$
For HE-LHC, $\varepsilon_n = 2.5\mu m$



Collimator gaps at 1.3 TeV injection

- Summary of collimator gaps, in σ_{coll} (left) and in mm (right)





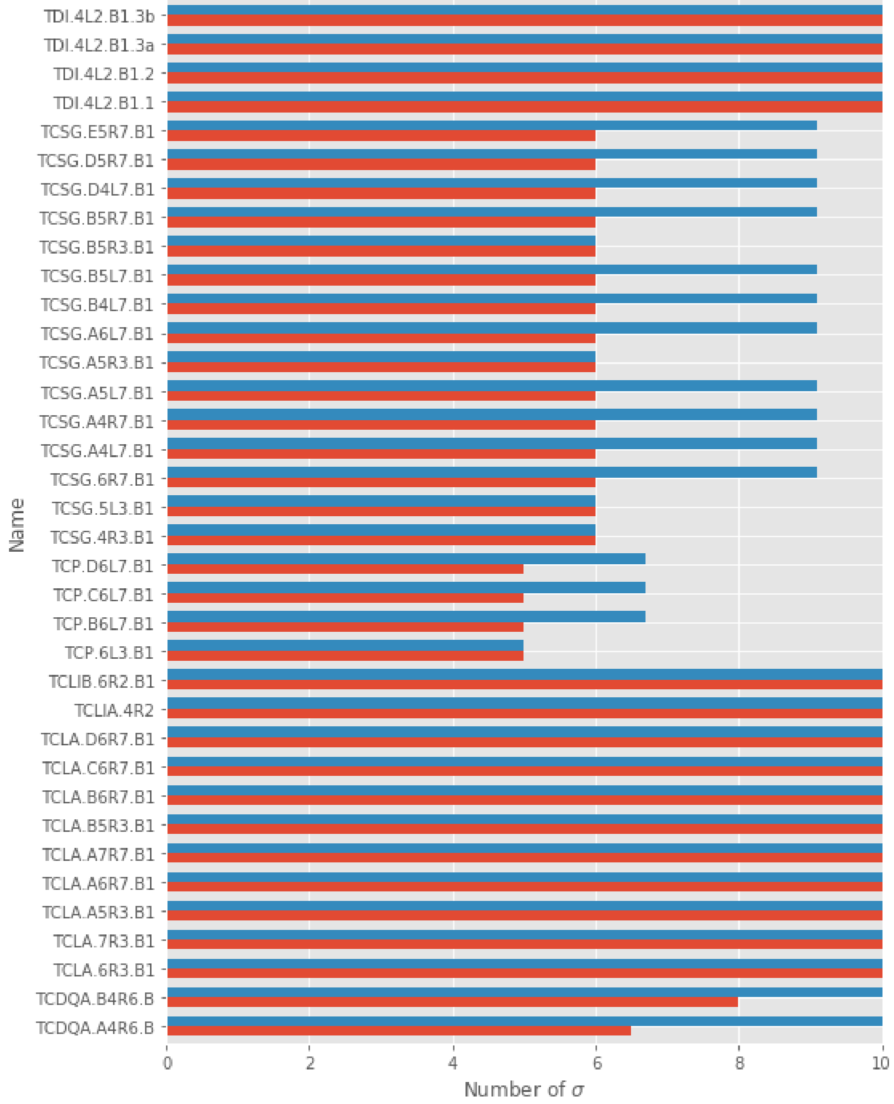
Red: old gaps
Blue: new gaps

Physical gaps scale as $\sqrt{\frac{\varepsilon_n}{E}}$

For HL-LHC, $\varepsilon_n = 2.5\mu m$
For HE-LHC, $\varepsilon_n = 2.5\mu m$

Collimator gaps at top energy

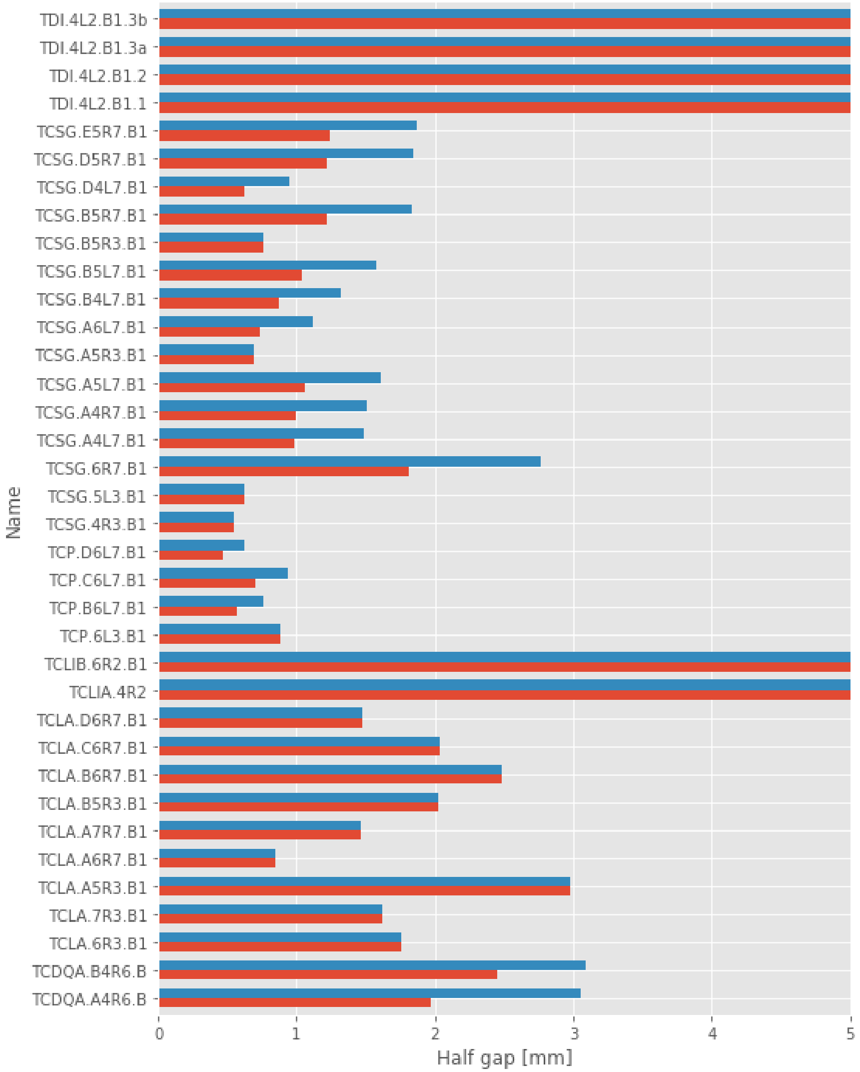
- Summary of collimator gaps, in σ_{coll} (left) and in mm (right)



Red: old gaps
Blue: new gaps

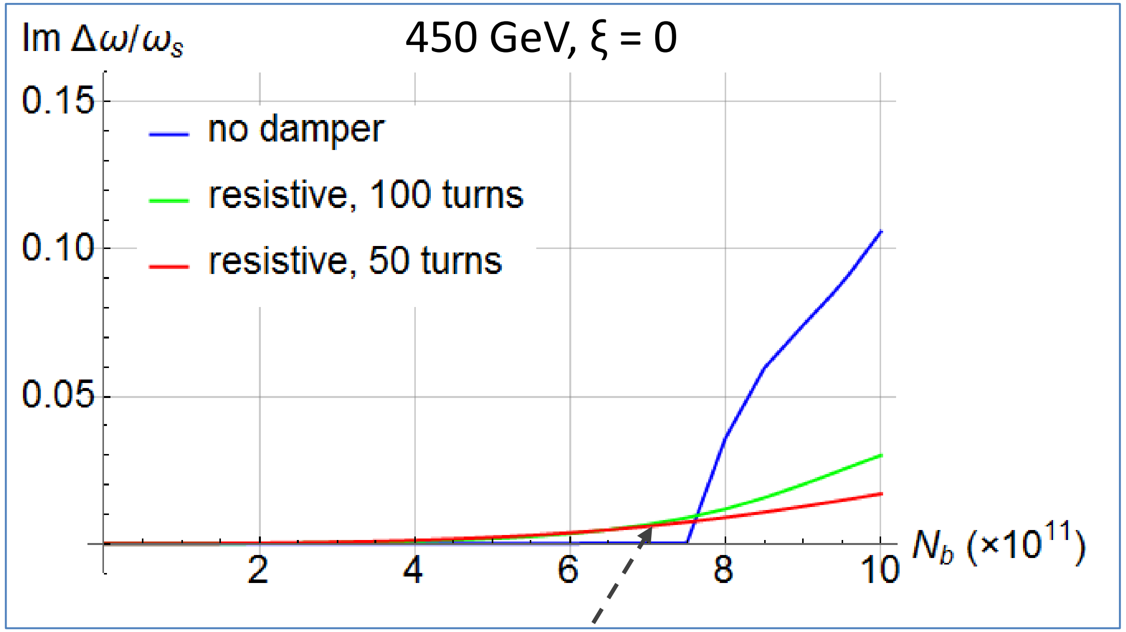
Physical gaps scale as $\sqrt{\frac{\varepsilon_n}{E}}$

For HL-LHC, $\varepsilon_n = 2.5\mu m$
For HE-LHC, $\varepsilon_n = 2.5\mu m$



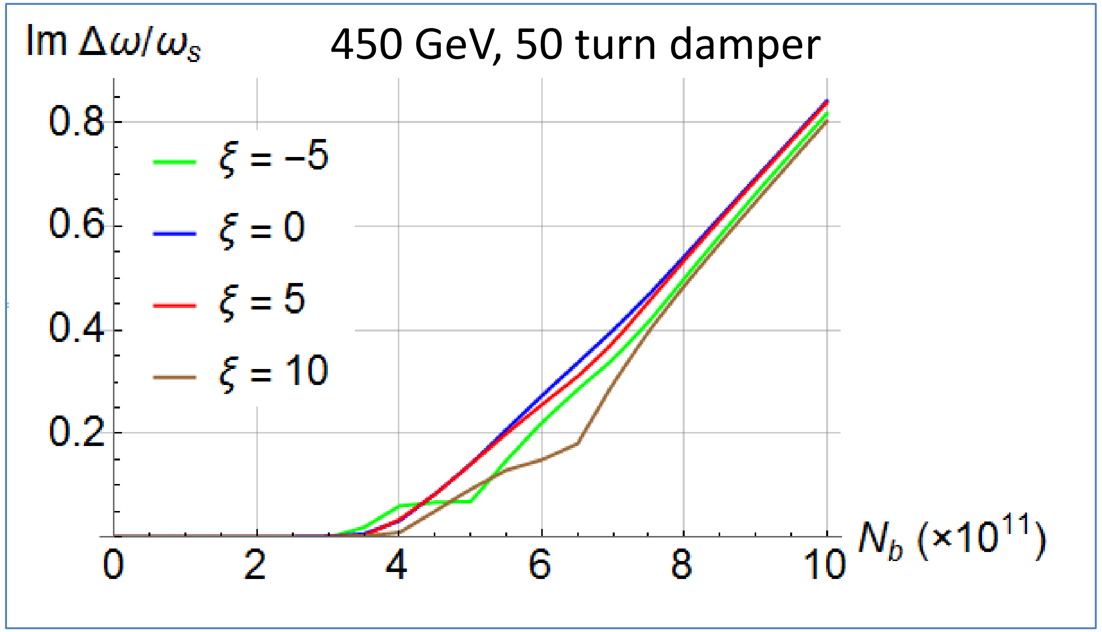
Old gaps: single bunch vs. Coupled bunch instability threshold

Single bunch case: TMCI around 7x10^11 p



Destabilizing effect of the resistive damper
See E. Métral, IPAC18, Vancouver, 04/2018

Coupled-bunch: the intensity threshold is two times lower

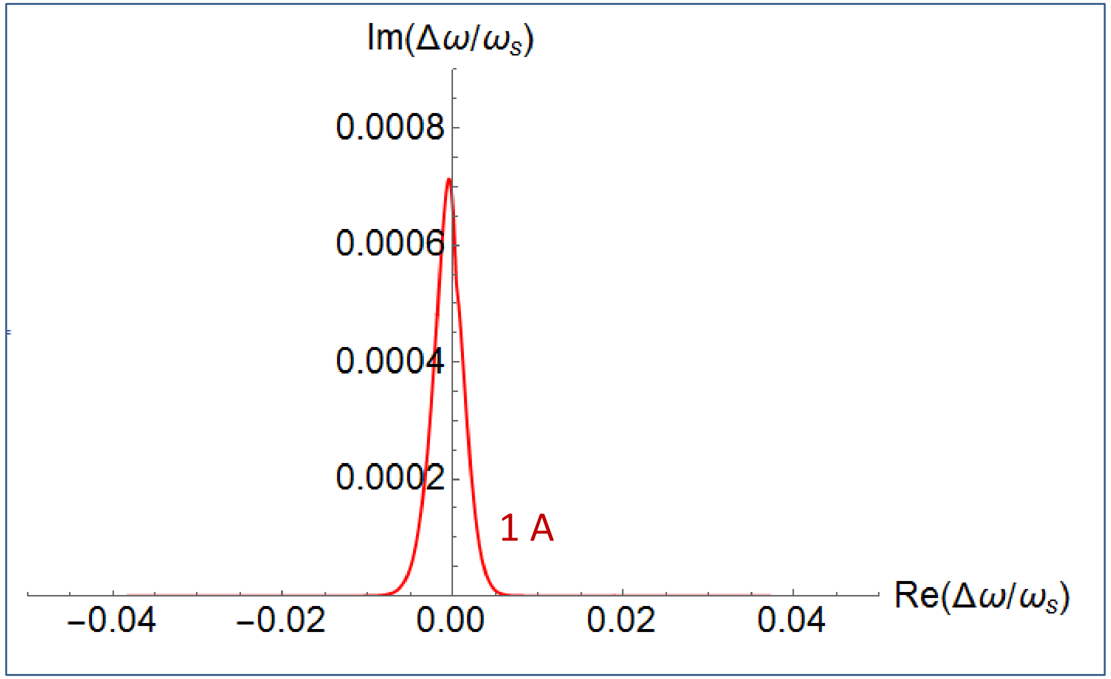


- Instability threshold is much lower in coupled bunch regime

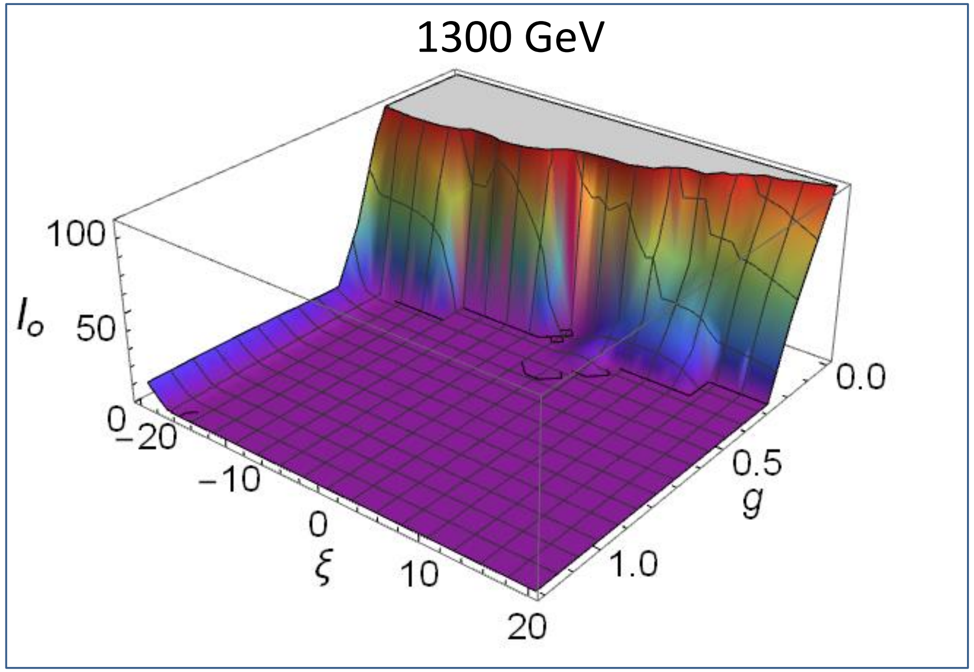
Old gaps: octupole current at injection

Octupole stability diagram for 1300 GeV:

ε_n = 2.0 μm, σ_z = 9.0 cm, I_{oct} < 0, Gaussian



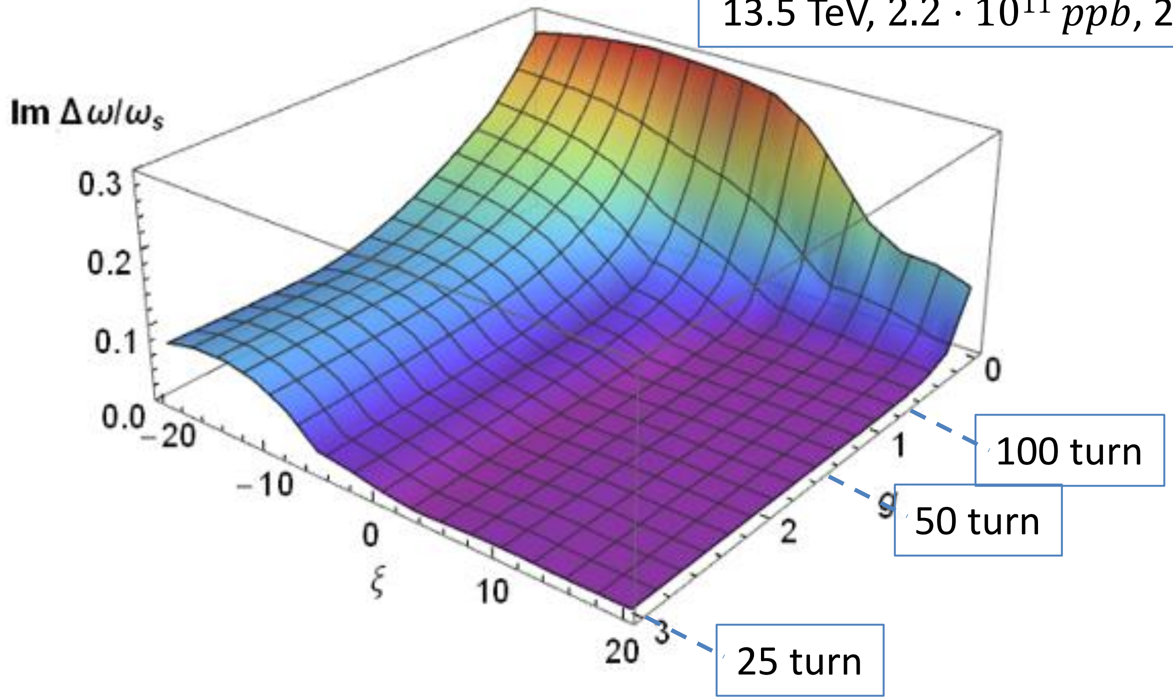
Octupole threshold is lower than 10 A, provided sufficient damper gain

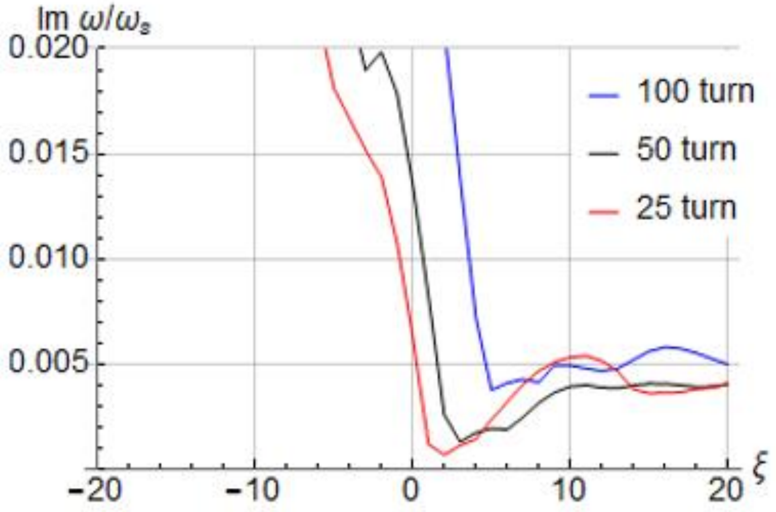


- The octupole current needed to stabilize the beam at injection is small
- However the impact on DA can be important

Old gaps: growth-rates at top energy

13.5 TeV, $2.2 \cdot 10^{11}\ ppb$, 2748 bunches

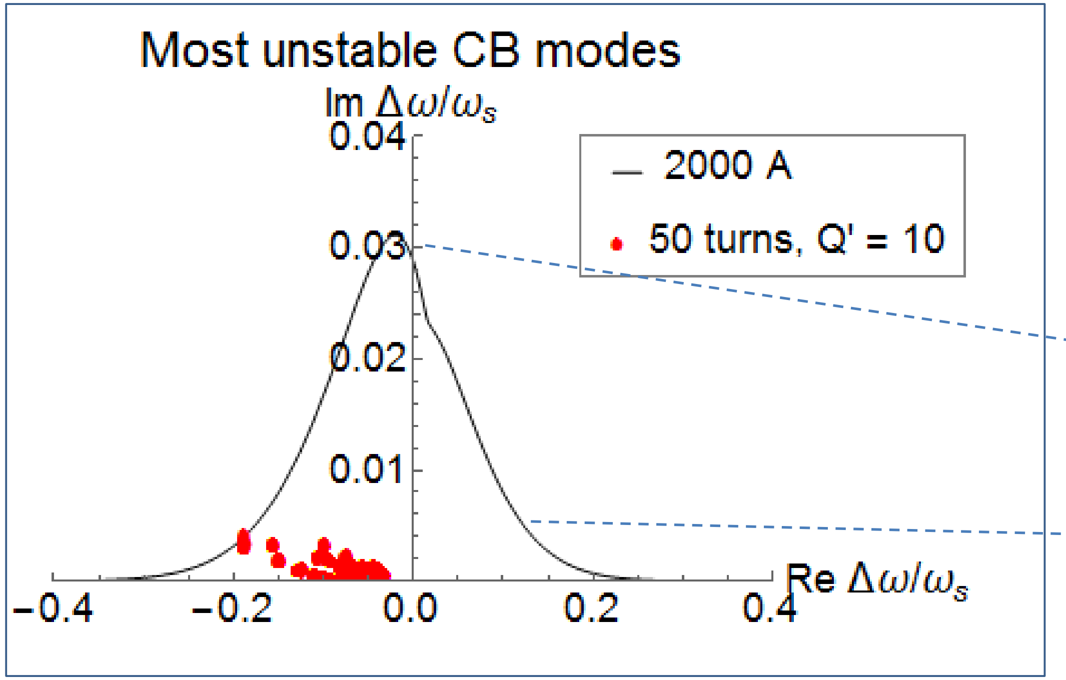


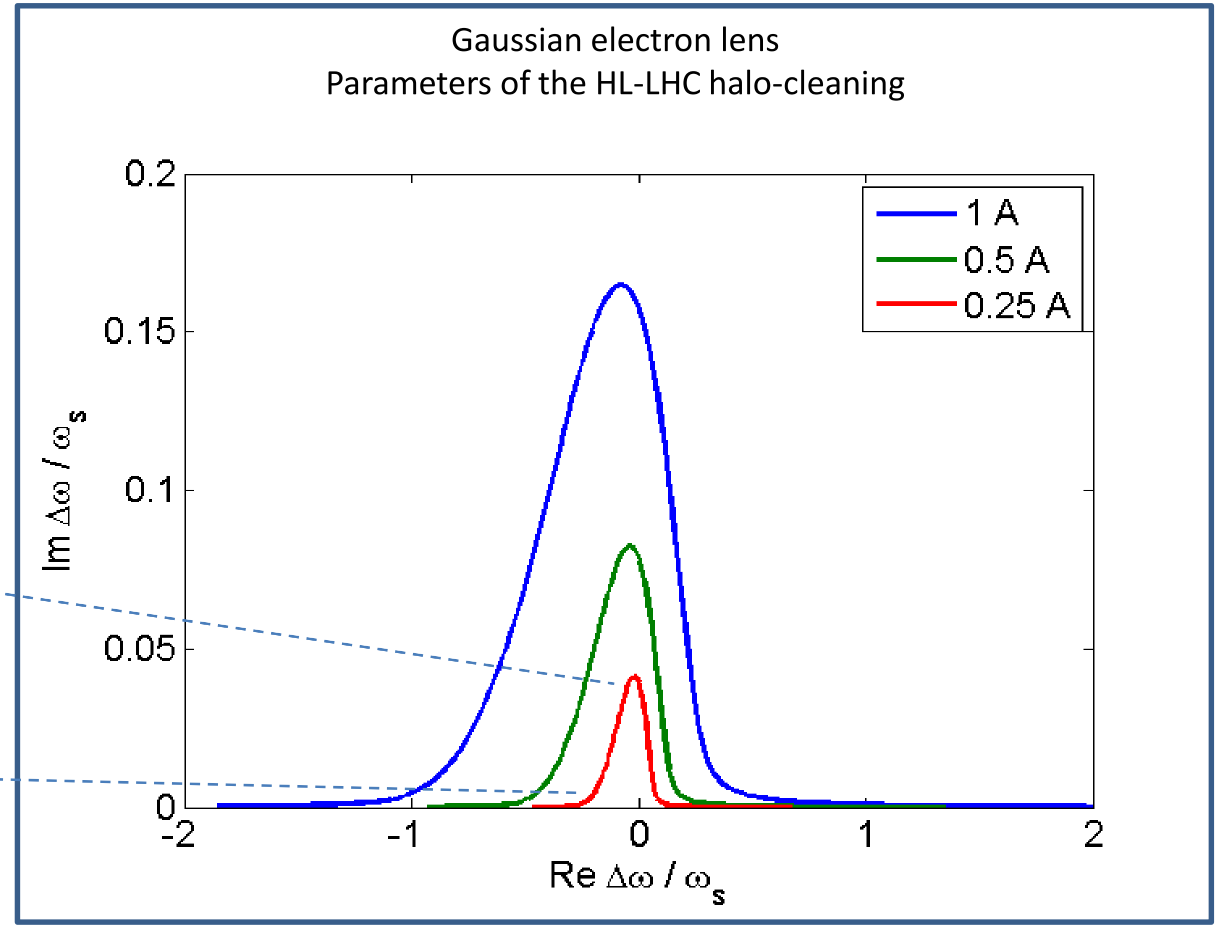


- Growth-rates are slightly reduced compared to previous model
- Will help with instability damping

Electron lens

- An electron lens might help stabilizing the beam at the top energy
- Gaussian electron lens is efficient Landau damping
    - E-lens tune shift scales as $1/\gamma$ vs for $1/\gamma^2$ octupoles





Impact on DA has to be carefully studied

C. Tambasco, *et al.*, EuroCirCol, CERN, 2017

Electron lens parameters

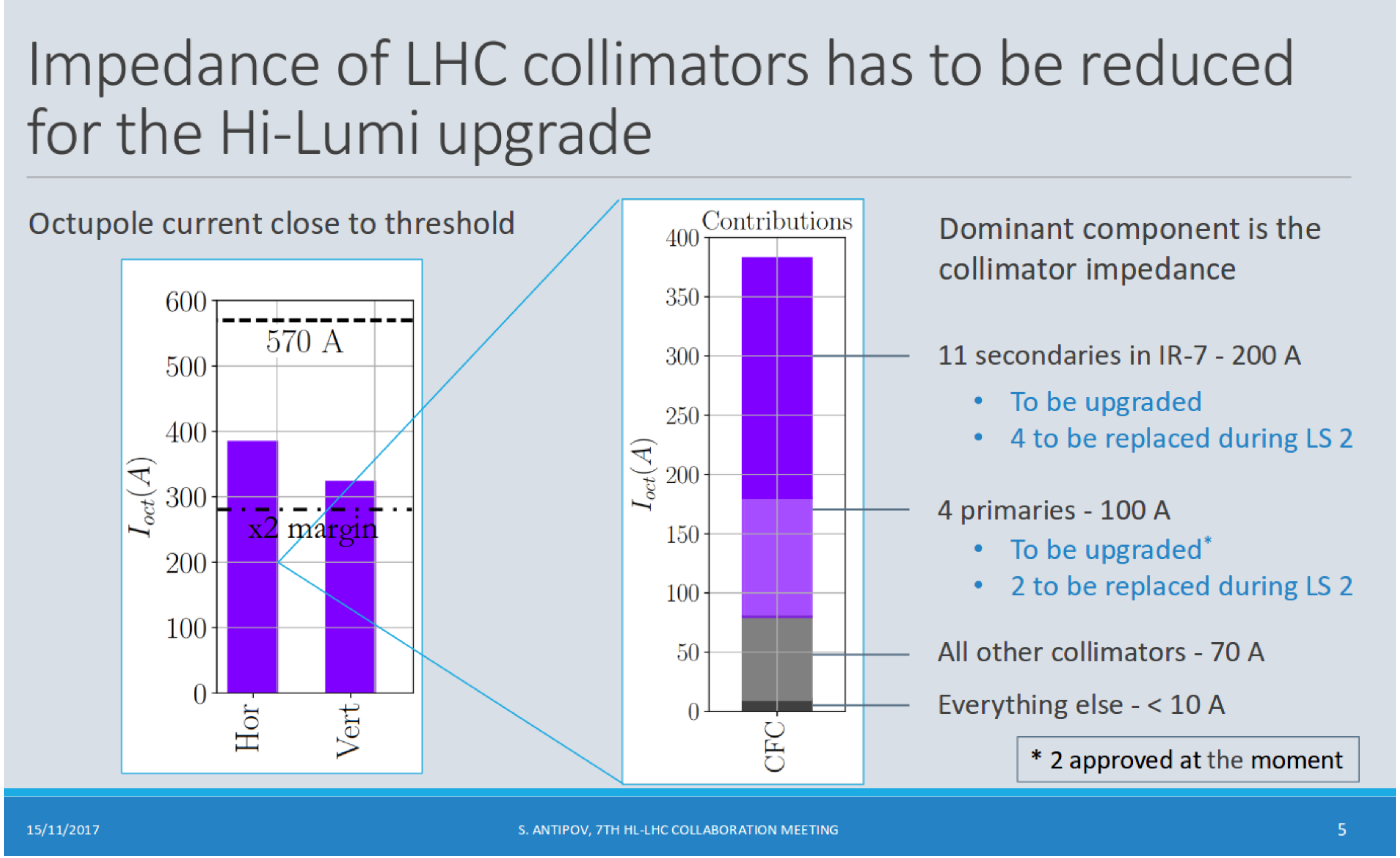
Table 1: Parameters of a Gaussian electron lens for Landau damping in the HE-LHC at the top energy

Parameter (Constraint)	Value	Comment
Current density	< 2-10 A/cm^2	Present technology limit
Electron current	< 1 A	HL-LHC E-Lens: up to 5
Electron beam length	3 m	
Electron energy	10 kV	
Max field ratio	B_m/B_g < 4.0 T/0.2 T = 20	HL-LHC E-Lens design
Electron beam size	0.4 – 2.0 mm	
Beta-function	240 m	40 m downstream IP-4
Proton beam energy	13.5 TeV	
Norm. emittance	2.0 μm	
Proton beam size	0.18 mm	
Transverse distribution	Gaussian	

Impedance model: assumptions

- In LHC, IR7 collimators are the main contributors to the impedance budget
- Primary (TCP) and secondary (TCSG) collimators in IR7
  - MoGr bulk, 25mm thickness, resistivity $\rho = 1 \cdot 10^{-6}\ \Omega \cdot m$
  - Mo coating, 5µm thickness, resistivity $\rho = 5.3 \cdot 10^{-8}\ \Omega \cdot m$
- Current LHC: CFC (carbon fiber reinforced carbon), 25mm thickness, resistivity $\rho = 5 \cdot 10^{-6}\ \Omega \cdot m$
- The gaps are scaled with energy and normalized emittance

IR7 collimators are the main contributors to the LHC impedance



***S.Antipov**, 7th HL-LHC collaboration meeting, Madrid, 2017*