First HE-LHC impedance model and aspects of single beam stability

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

FCC Week 2018

Amsterdam

12/04/2018

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

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Introduction

- The results presented here were showed at the HE-LHC review last December
  - https://indico.cern.ch/event/674475/

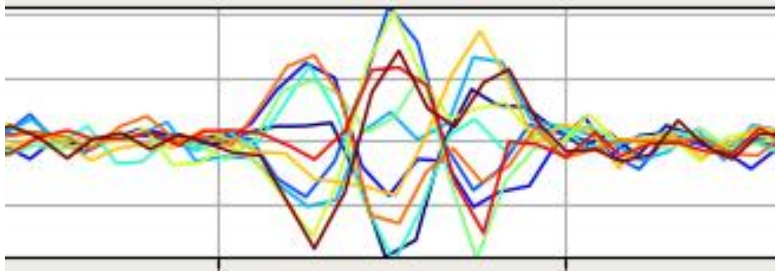
- Beam stability simulations and results were performed and presented by S.Antipov

- Only the transverse impedance and single beam stability are addressed in this talk

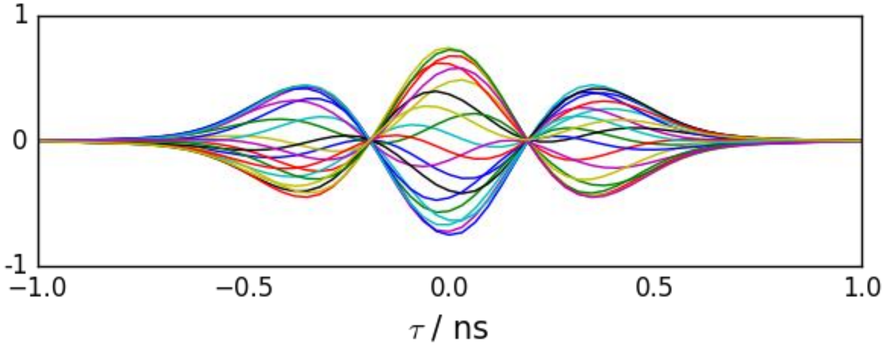
- Relevant talks presented during the week:
  - HE-LHC Beam-beam effects, T.Pieloni, 10/04
  - HE-LHC Collimation, M.Crouch, 12/04
  - FCC-hh Impedance of cold beamscreen, S.Arsenyev, 12/04
  - HE-LHC electron cloud, L.Mether, 12/04
  - FCC-hh Beam-beam effects, T.Pieloni, 12/04
  - FCC-hh Two beam stability and Landau damping, C.Tambasco, 12/04
  - FCC-hh Feedback, J. Komppula, 12/04

Introduction

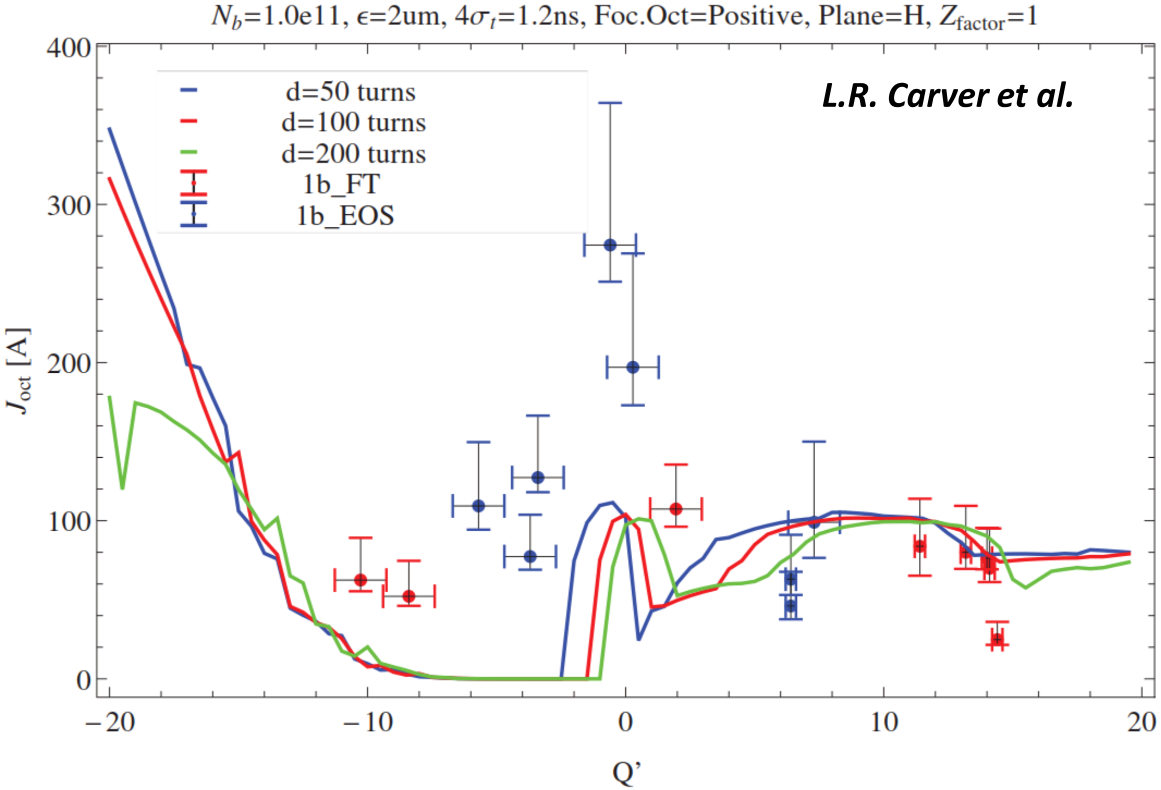
- Currently have an impedance model for LHC/HL-LHC
  - Used for transverse coherent stability studies
  - Prediction of stability thresholds
  - Reproduce machine observables



Observed head-tail mode



Simulated head-tail mode



N_b=1.0e11, ϵ=2um, $4\sigma_t$=1.2ns, Foc.Oct=Positive, Plane=H, Z_{factor}=1

L.R. Carver et al.

- Goal: elaborate an impedance model for HE-LHC

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Impedance model: assumptions

- Based on HL-LHC impedance model
- Cold beam screen
  - 2017 FCC-hh beam screen impedance, scaled to HE-LHC length (see S.Arsenyev talk)
  - No pumping holes (shielded by the beam screen)
- 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 high order 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

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Cases studied

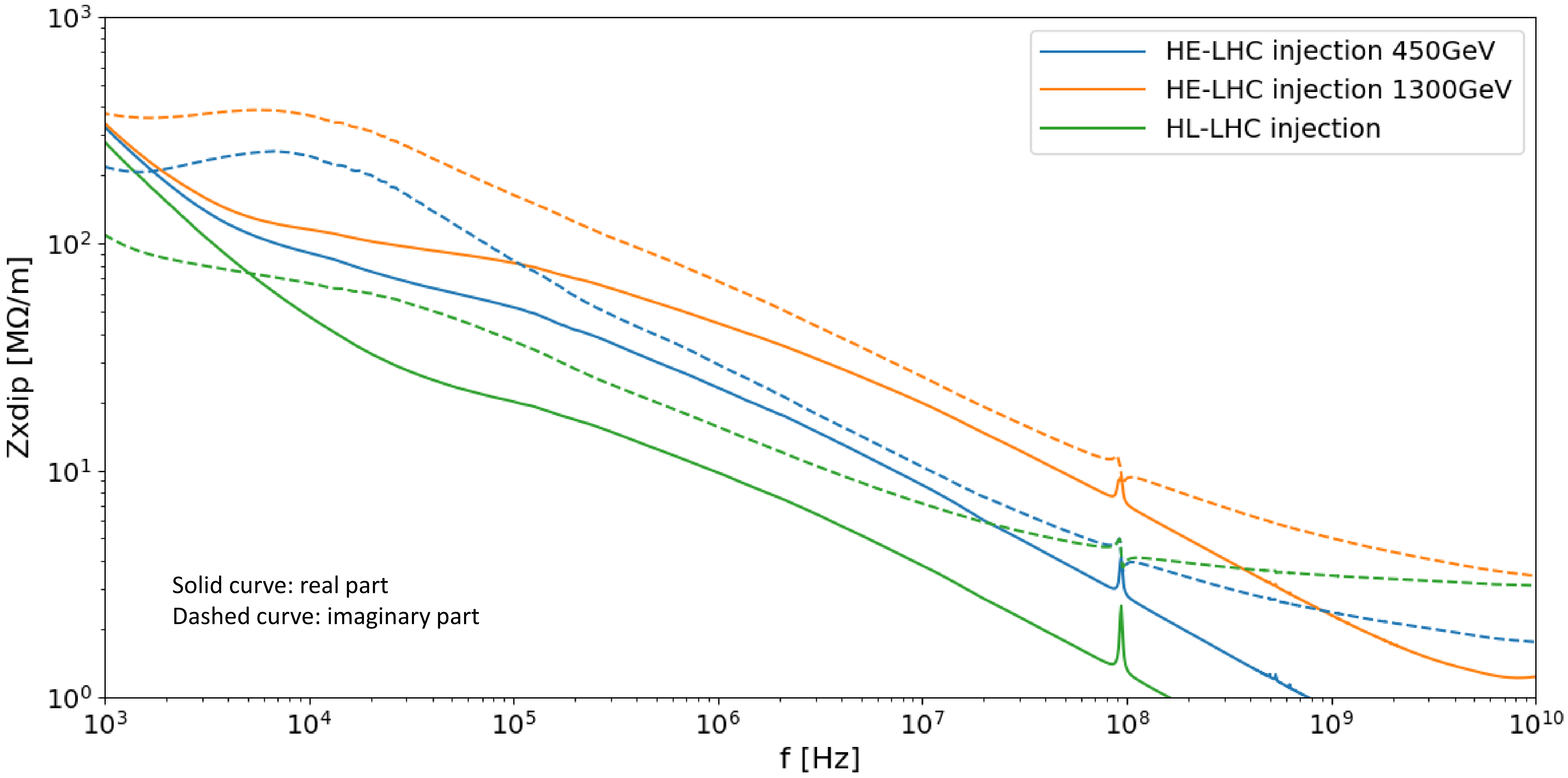
Tighter gaps than LHC/Hi-Lumi

Scaling from Hi-Lumi

	450 GeV	900 GeV	1.3 TeV	HL-LHC Inj. 450 GeV
Reference emittance	2.5 um	2.5 um	2.5 um	2.5 um
Primary colls	5 σ	5.7 σ	5.7 σ	6.7 σ
Secondary colls	6 σ	6.7 σ	6.7 σ	7.9 σ
Injection protection	5 σ	5.7 σ	5.7 σ	9.5 σ

- Gaps at could be even tighter (eg. 4.5σ in the primary collimators at 450 GeV)
  - Impact on impedance needs to be assessed
  - Risk of affecting the transverse tails

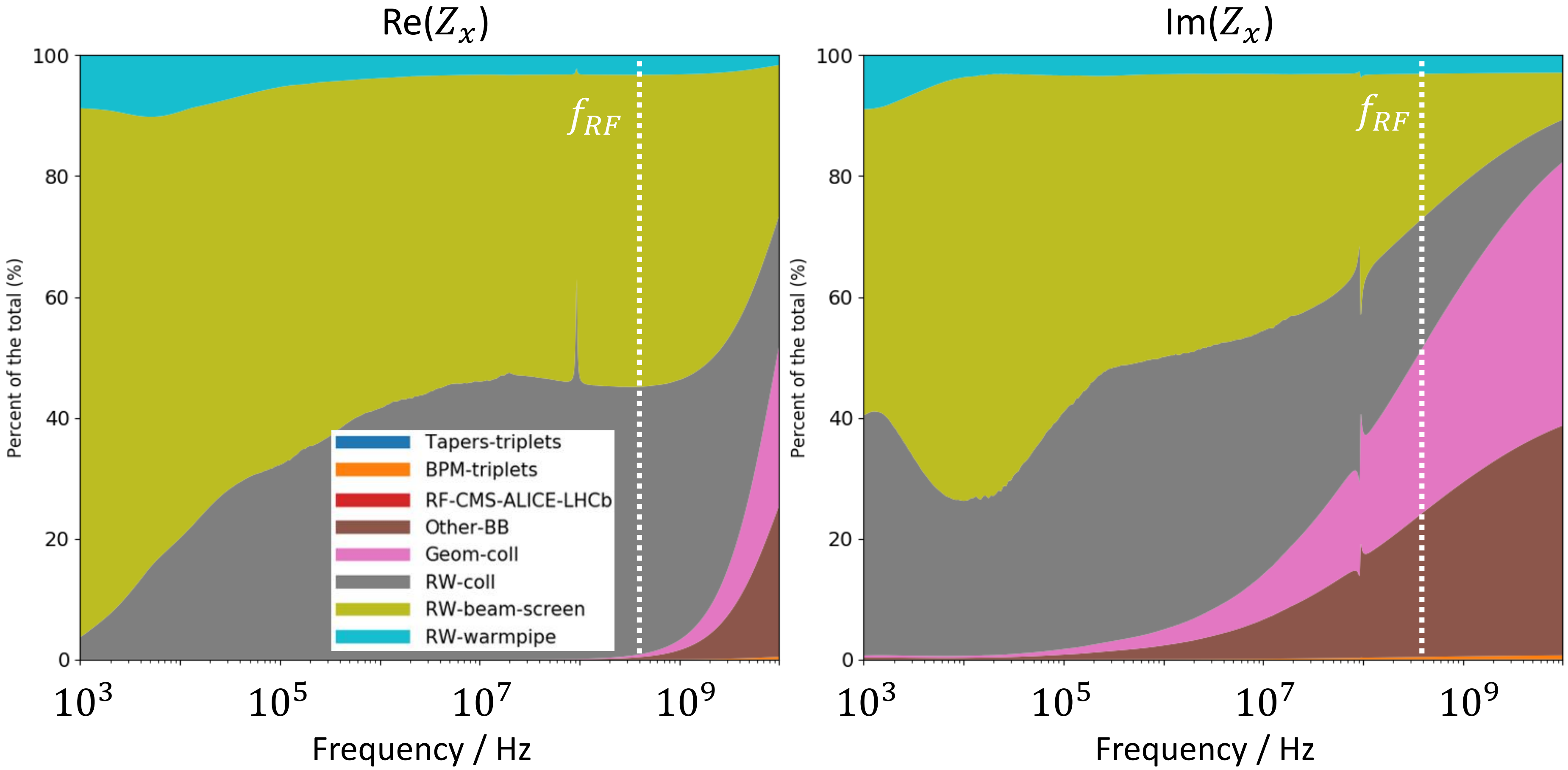
Impedance at injection energy



Solid curve: real part
Dashed curve: imaginary part

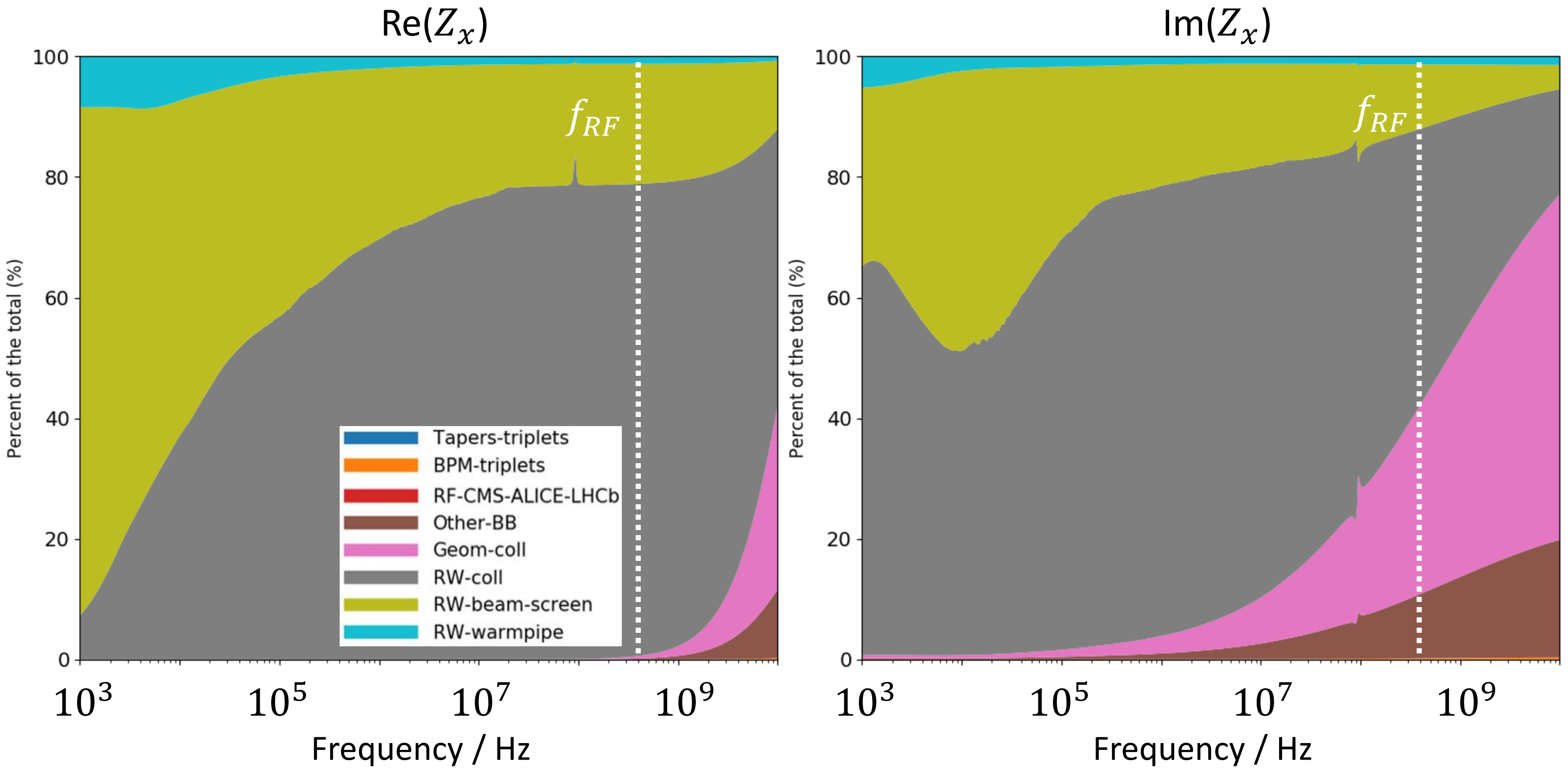
- 1.3TeV scenario has a larger impedance, because of the tighter collimator gaps

Contributors at injection energy: 450 GeV



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

Contributors at injection energy: 1.3 TeV



- Collimators become the dominant contributors to the impedance

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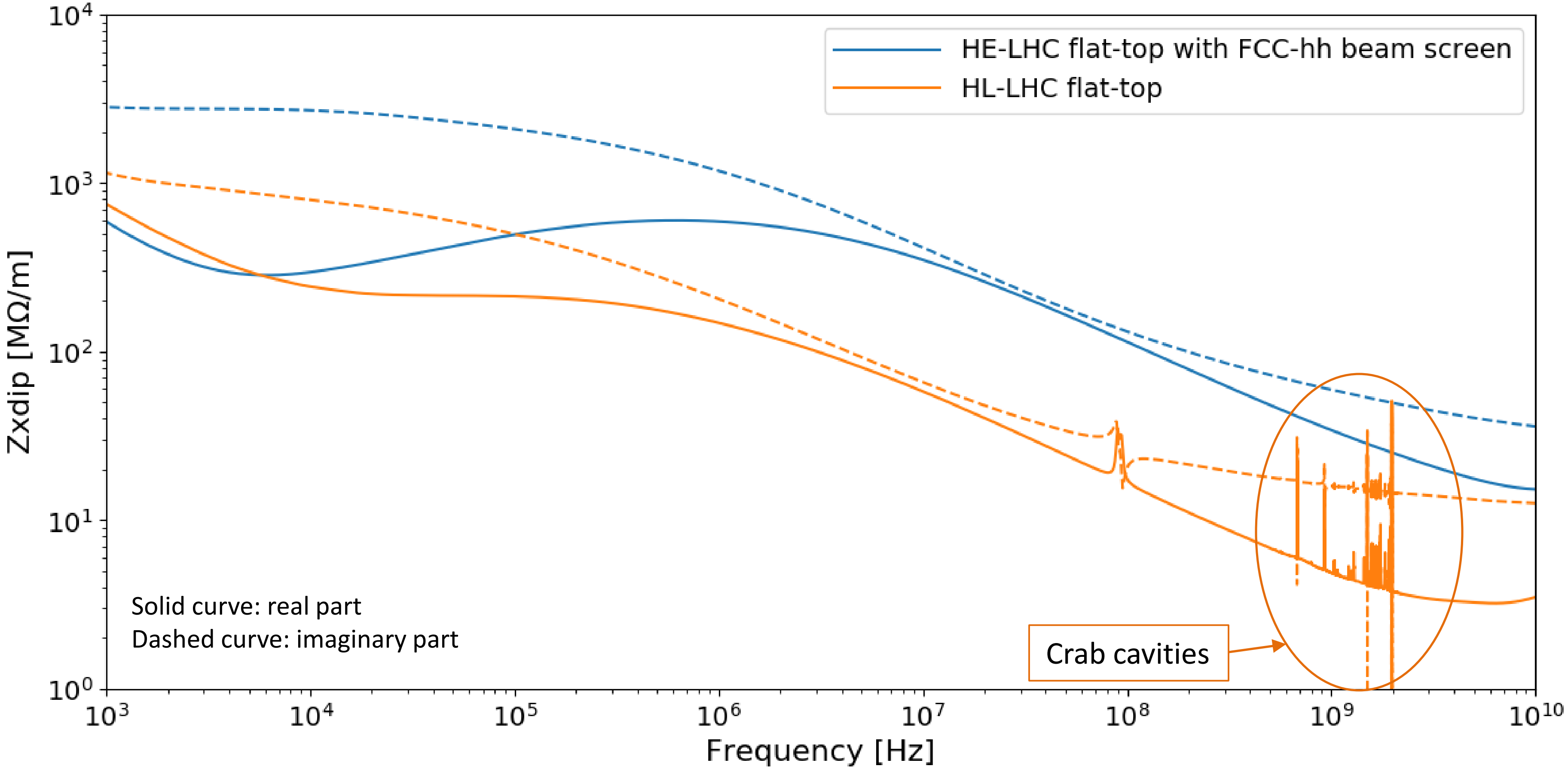
Case studied

	Simulated scenario	**HE-LHC 13.5 TeV**	**HL-LHC 7 TeV**
Reference emittance	2.5 um	2.5 um	2.5 um
Primary colls	**5 σ**	6 σ	6.7 σ
Secondary colls	**6 σ**	8.5 σ	9.1 σ
Dump protection	6.5 σ	9.8 σ	9.6 σ

- Tight collimator gaps were used (pushed LHC 2018 with 1σ retraction)
  - Tighter than the HE-LHC values
  - Showcase an ultimate scenario

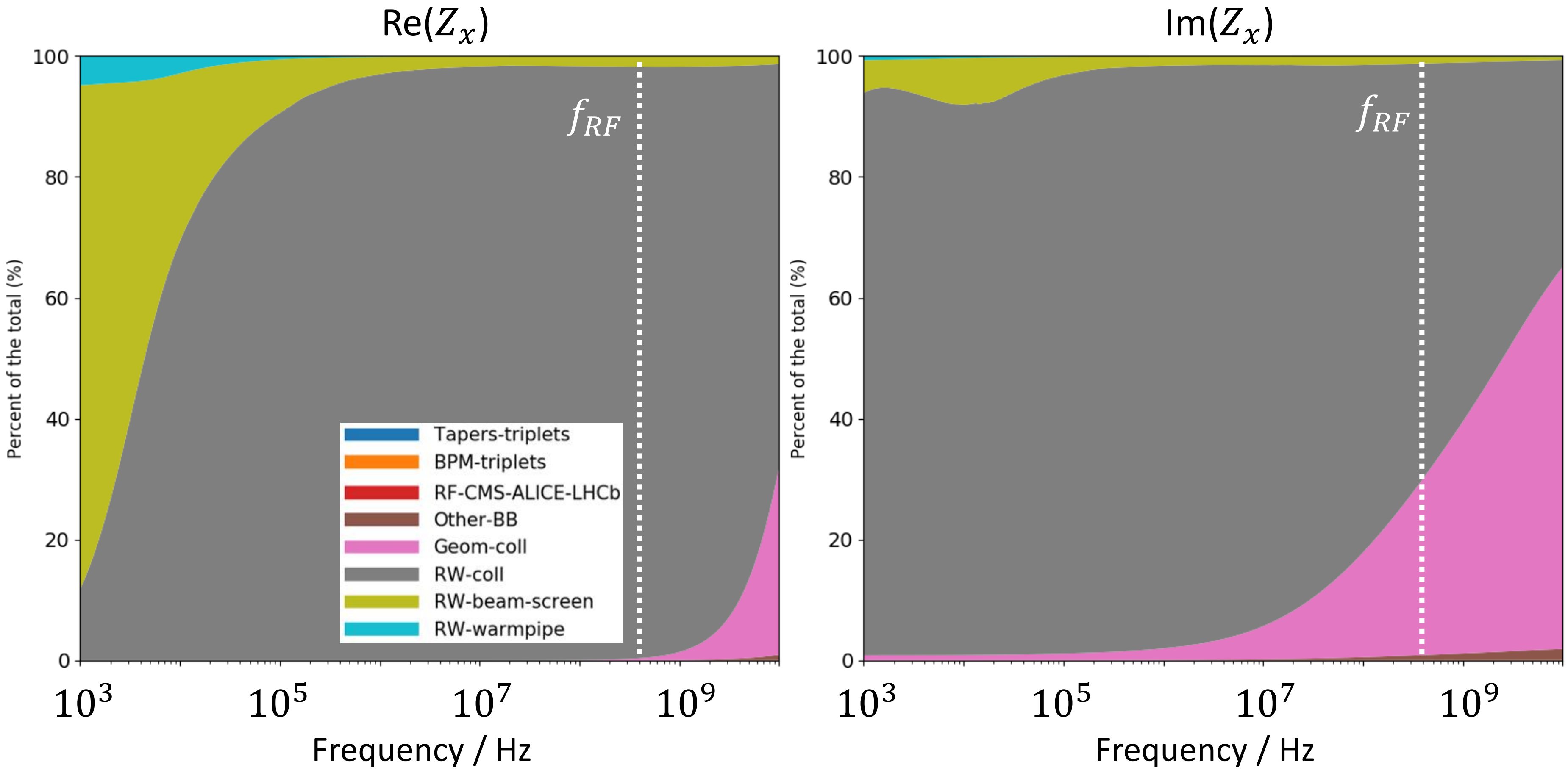
Collimators gaps from F. Zimmermann, checked with R. Bruce et al.

Impedance at top energy



- Impedance at top energy is higher because of the tighter collimators gaps
- Tight collimator gaps were used (pushed LHC 2018 with 1σ retraction)

Contributors at top energy



- Collimators dominate the whole frequency range

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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

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

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

- Stability simulations made with NHT Vlasov Solver
  - Single-bunch and coupled-bunch simulations
- Scan over different parameters
  - Chromaticity: $Q' = -20 \dots +20$
  - Damper gain: $g = 0 \dots {}^{1}/_{25}\, turn^{-1}$
  - Intensity: $N_b = 0 \dots 10 \cdot 10^{11}\, ppb$
- Given a stability diagram and assuming the modes are uncoupled, the octupole current can be computed

- Results agree with the DELPHI code

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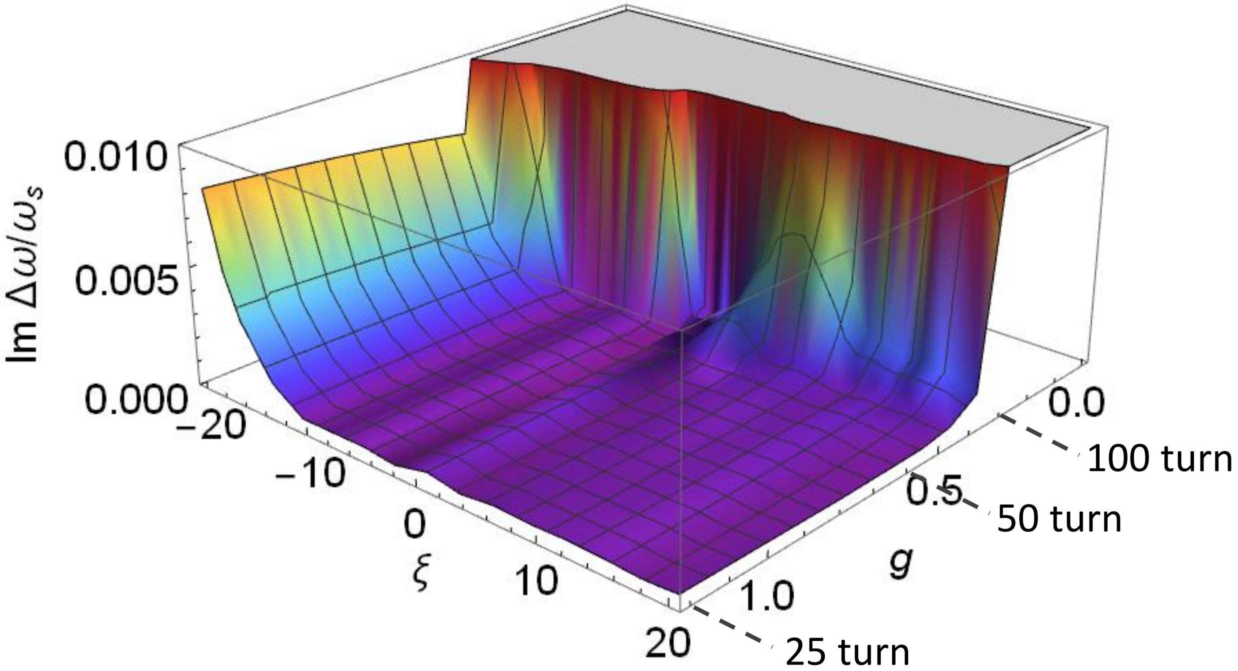
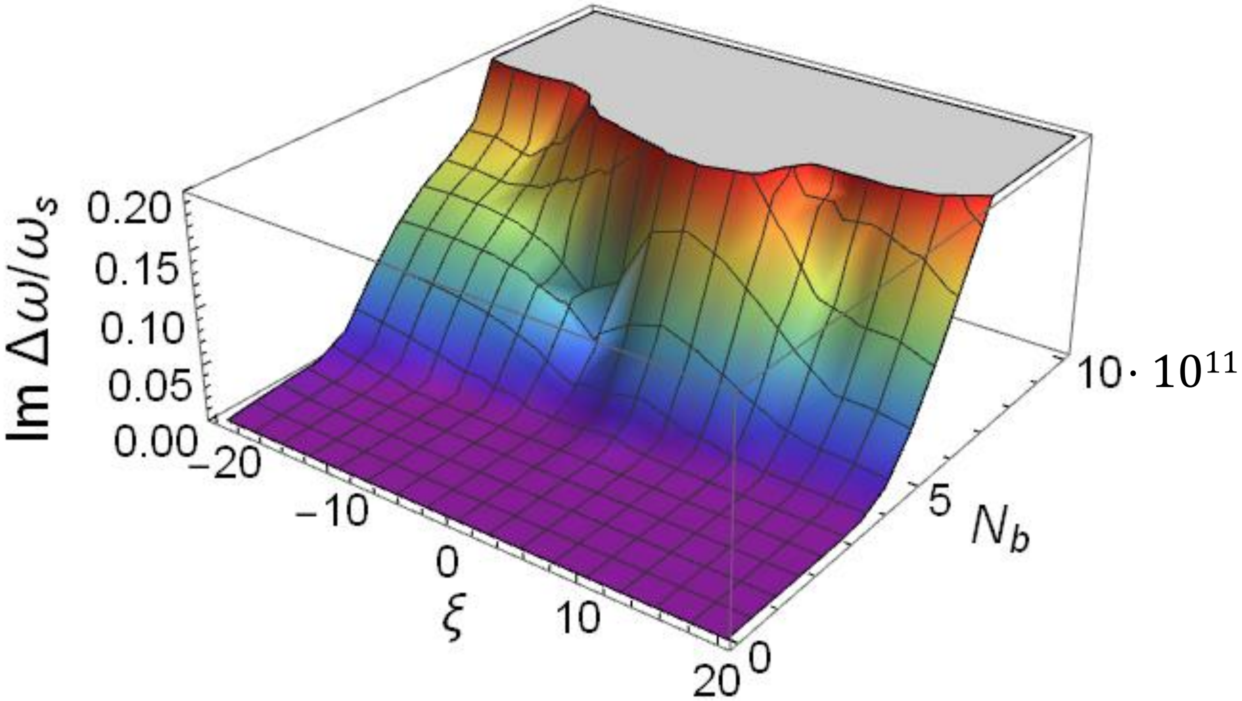
450 GeV: $2.2 \cdot 10^{11}\, ppb$, 2748b

Damper gain has to be 50 turns or higher

Less than a factor 2 margin in intensity

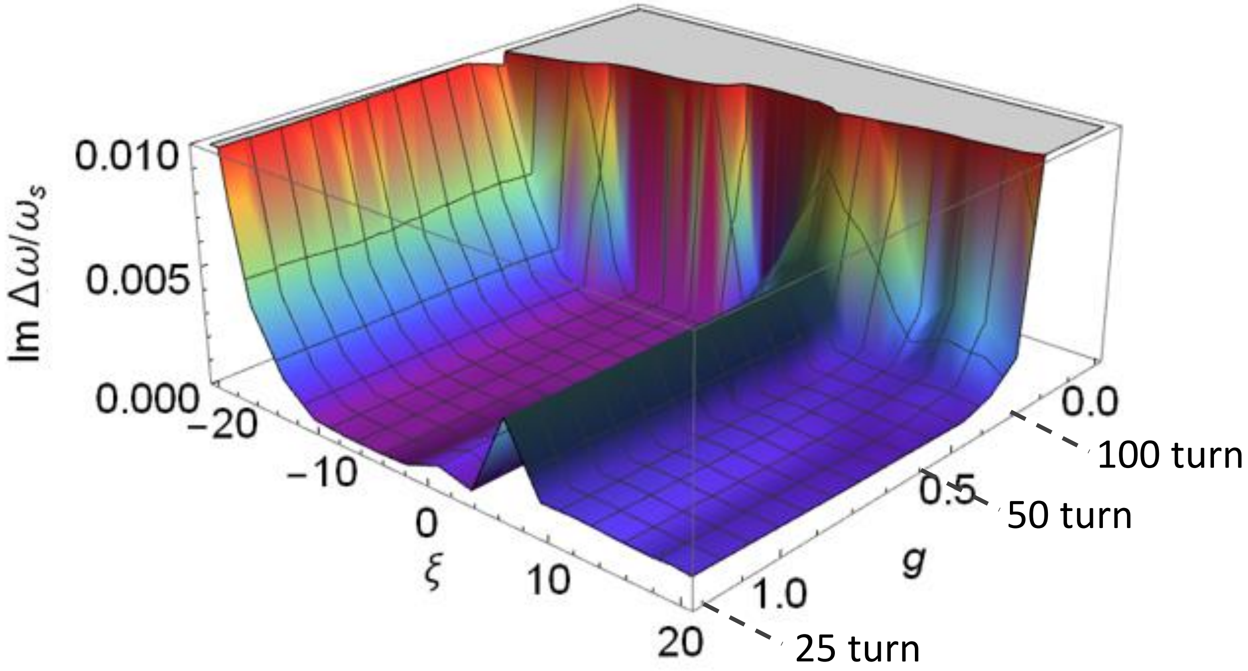




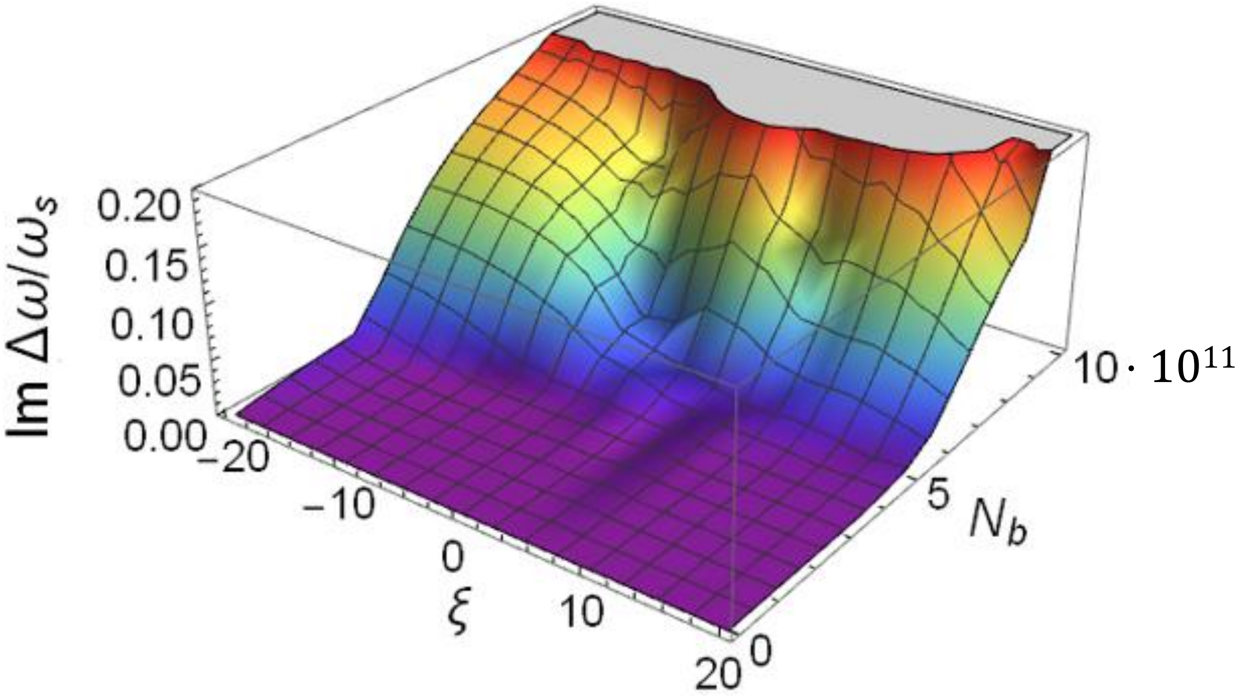
Damper gain: g = damping rate / ω_s

1300 GeV: $2.2 \cdot 10^{11}\,ppb$, 2748b

Damper gain has to be 75 turns or higher



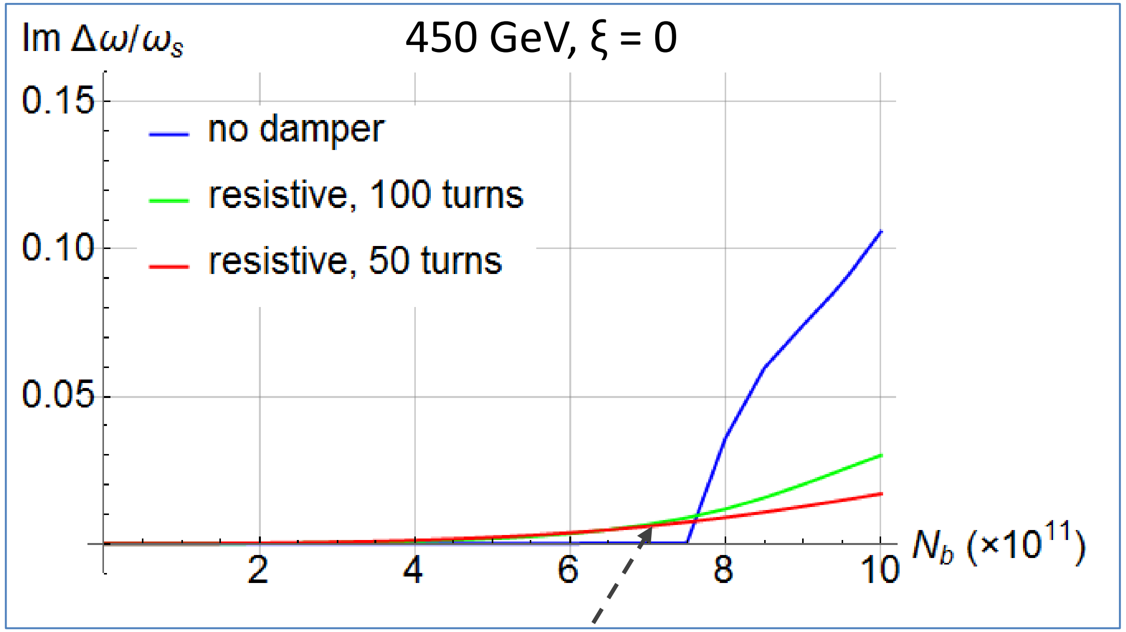
Less than a factor 2 margin in intensity



Damper gain: g = damping rate / ω_s

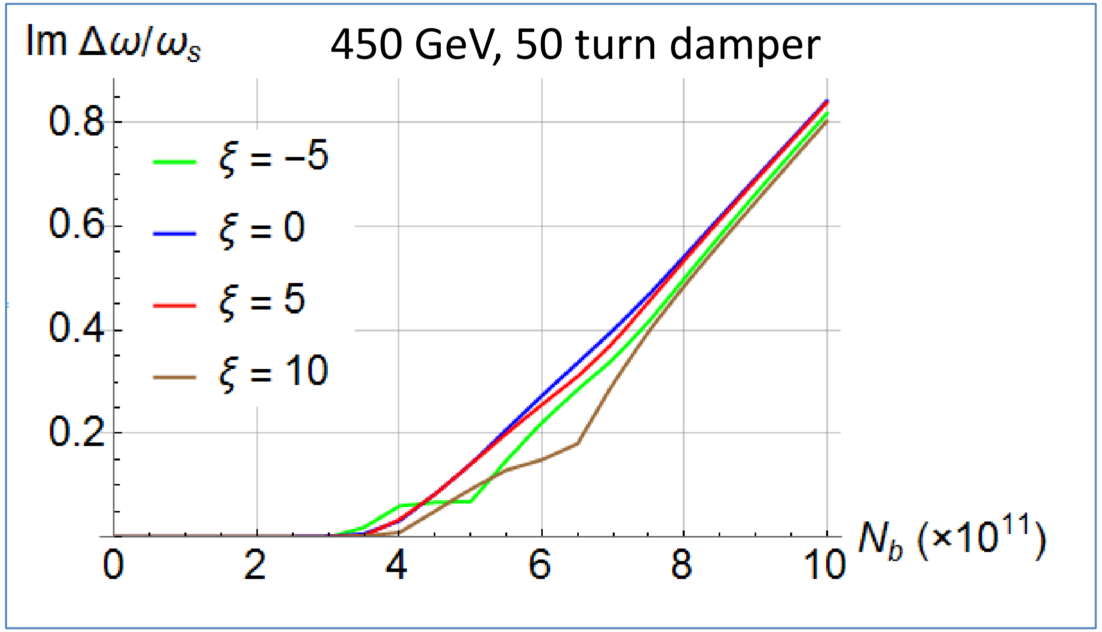
Single bunch vs. Coupled bunch instability threshold

Single bunch case: TMCI around 7×10^{11} p



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

Coupled-bunch: the intensity threshold is two times lower



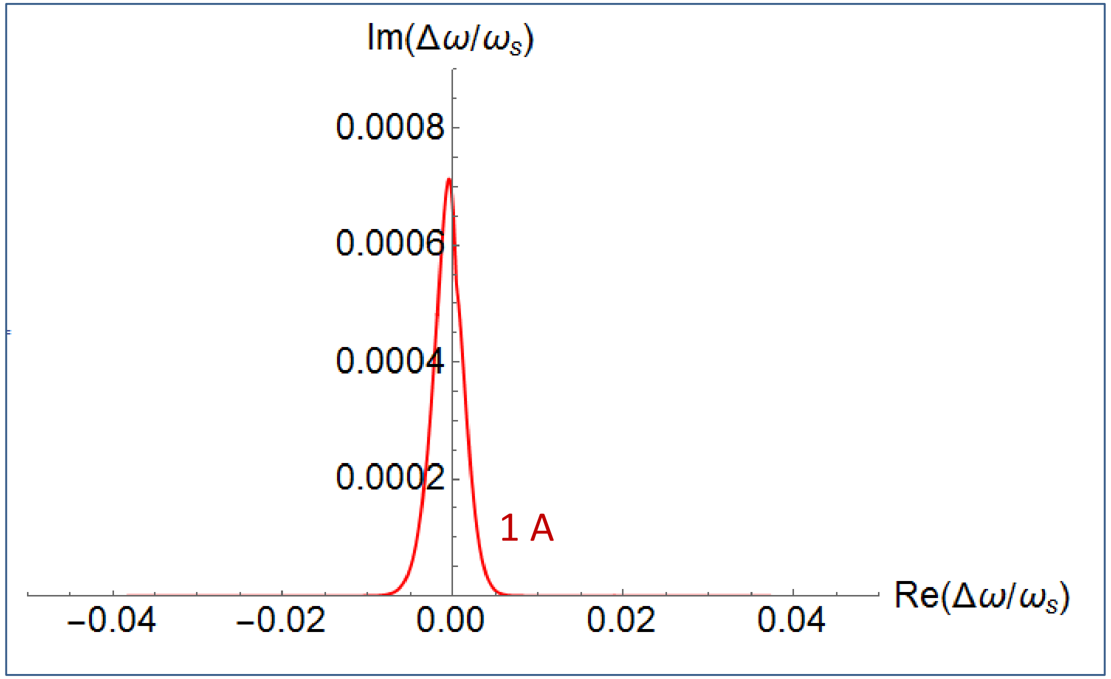
- Instability threshold is much lower in coupled bunch regime

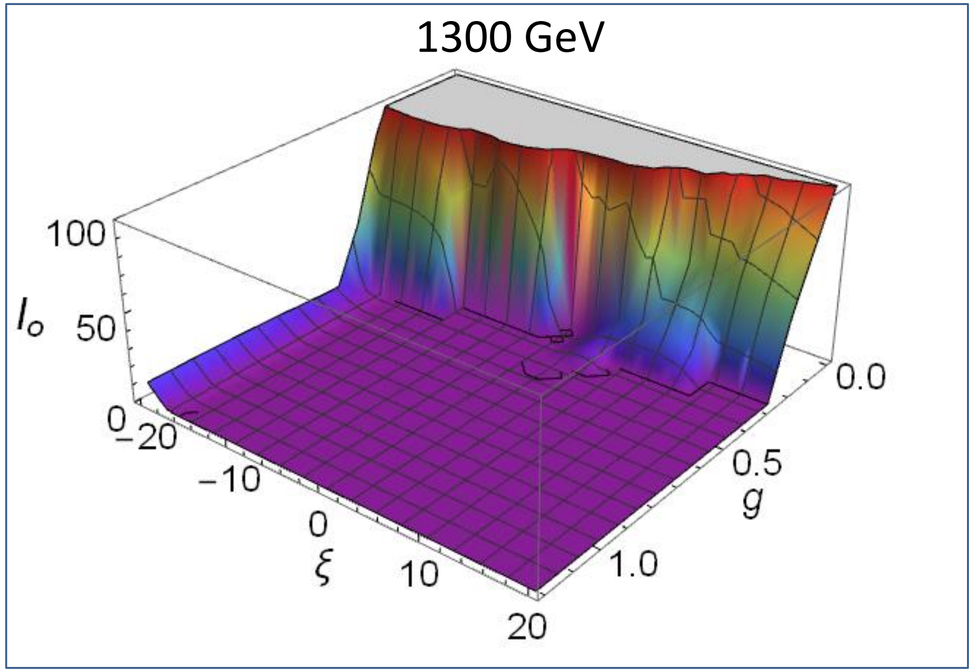
Octupole current

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

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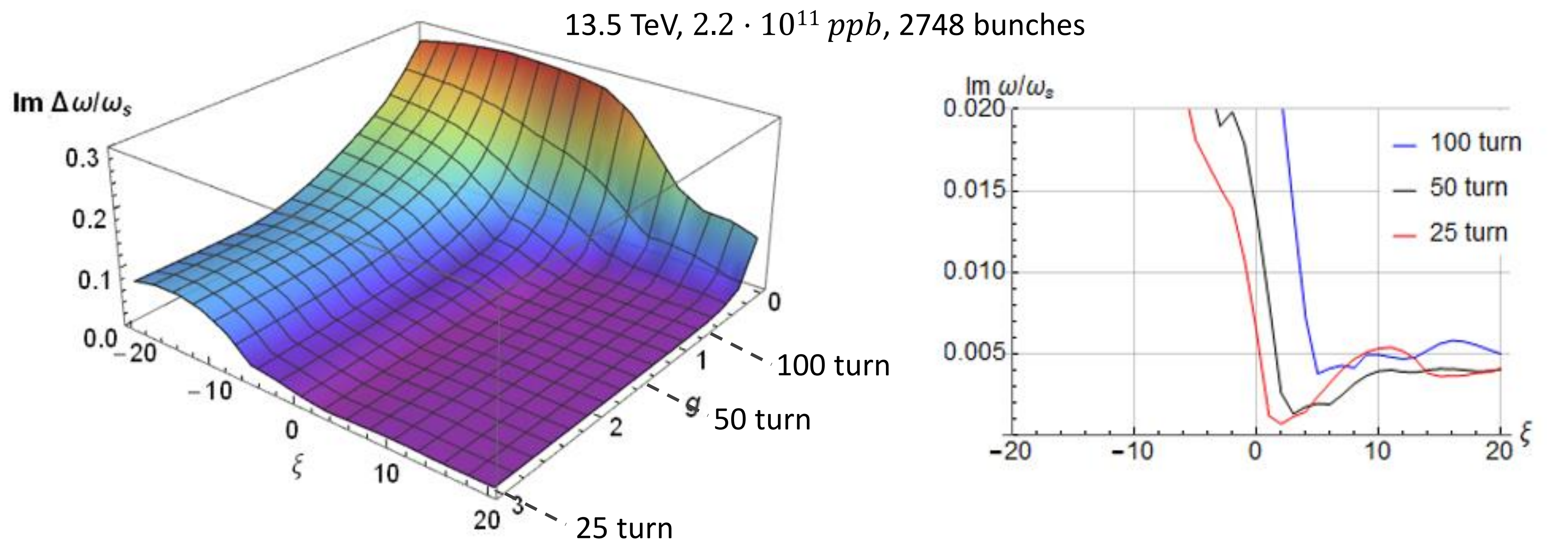
Top energy

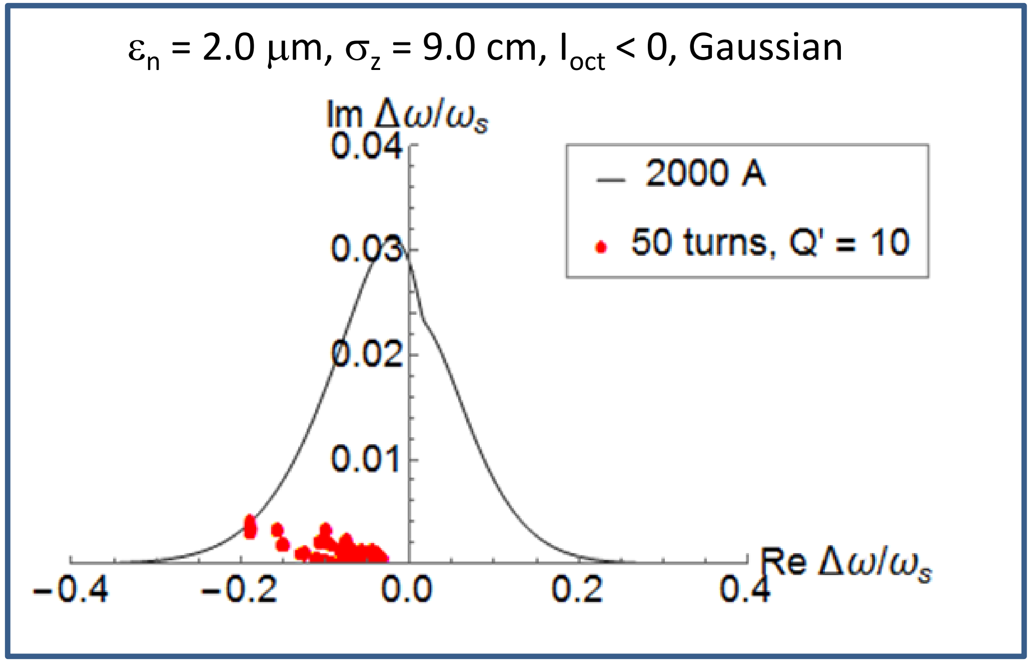

13.5 TeV, $2.2 \cdot 10^{11}\ ppb$, 2748 bunches

HL-LHC OP scenario: E. Metral, 7th HL-LHC Meeting, Madrid, 2017

- The impedance model is dominated by collimators. The beam screen does not have a significant impact

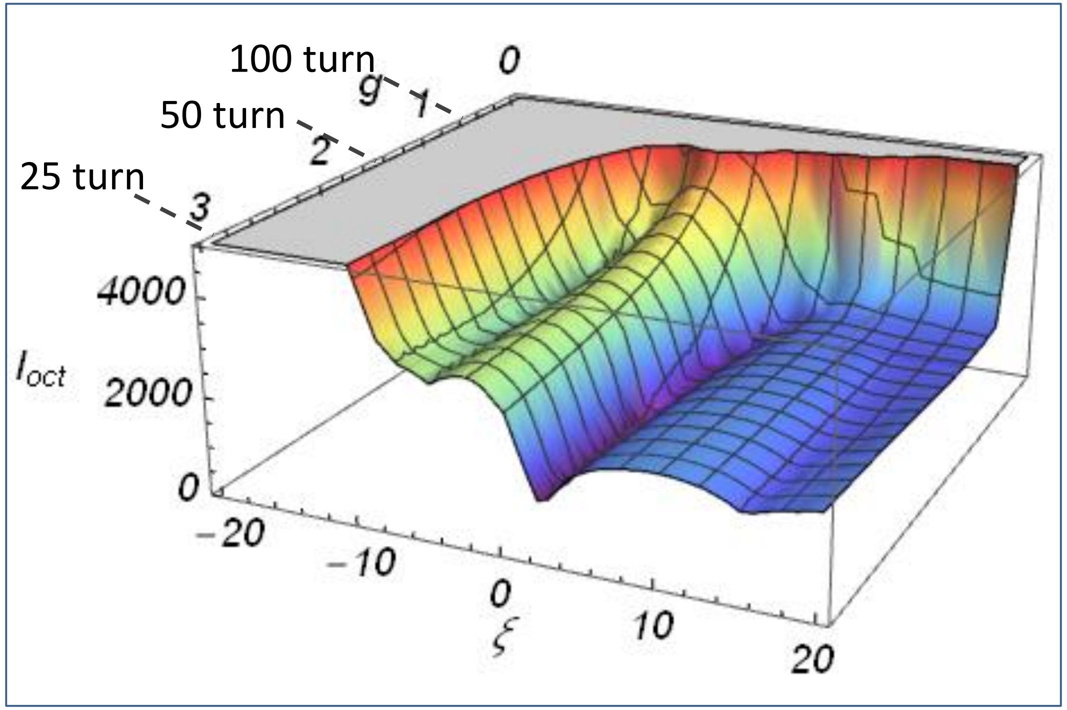
Landau damping

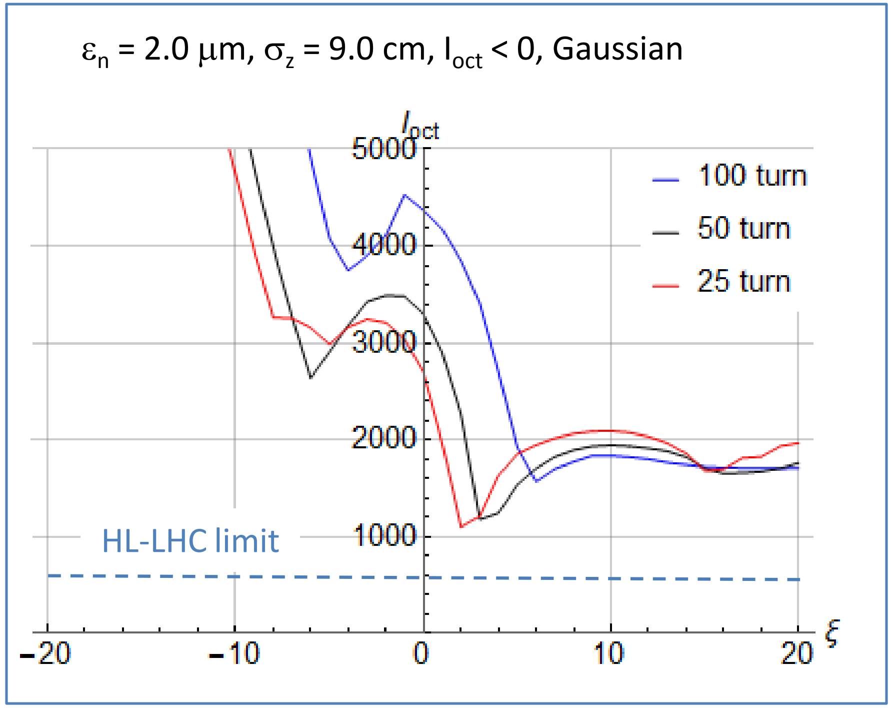
- Octupoles become inefficient for Landau damping at high energies
  - Octupole tune spread $\propto 1/\gamma^2$
  - Long range beam-beam might have a detrimental effect on SD
    - Effect is considerable for some Hi-Lumi operational scenarios: see for example X.Buffat, 7th HL-LHC Meeting, Madrid, 2017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


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

Octupole current

- About 2000 A of octupole current needed to stabilize at the top energy



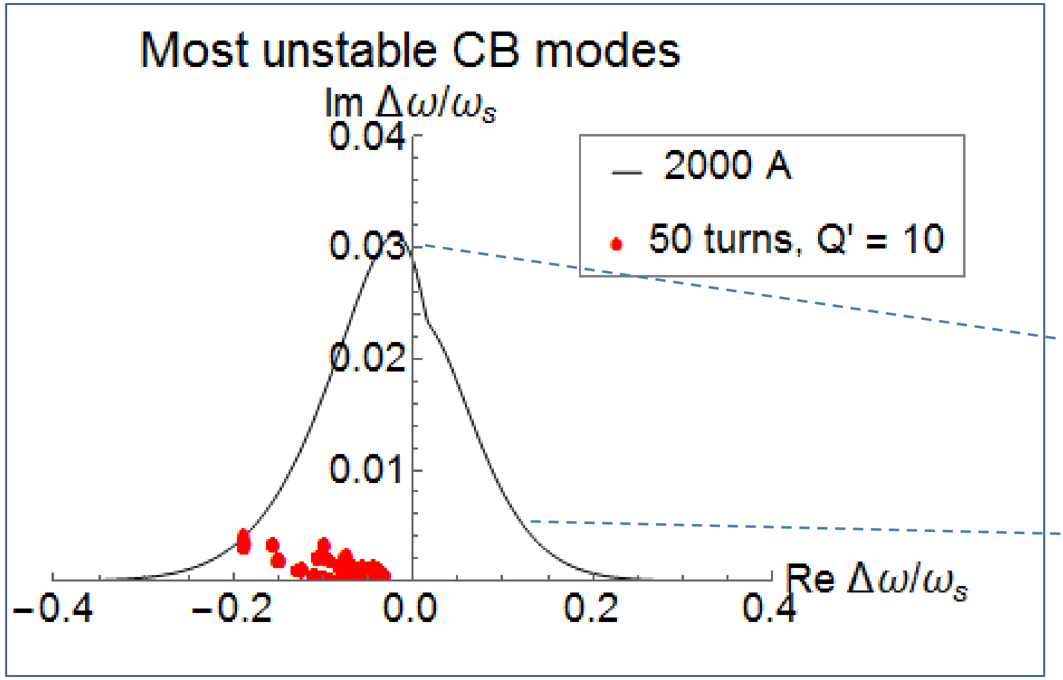


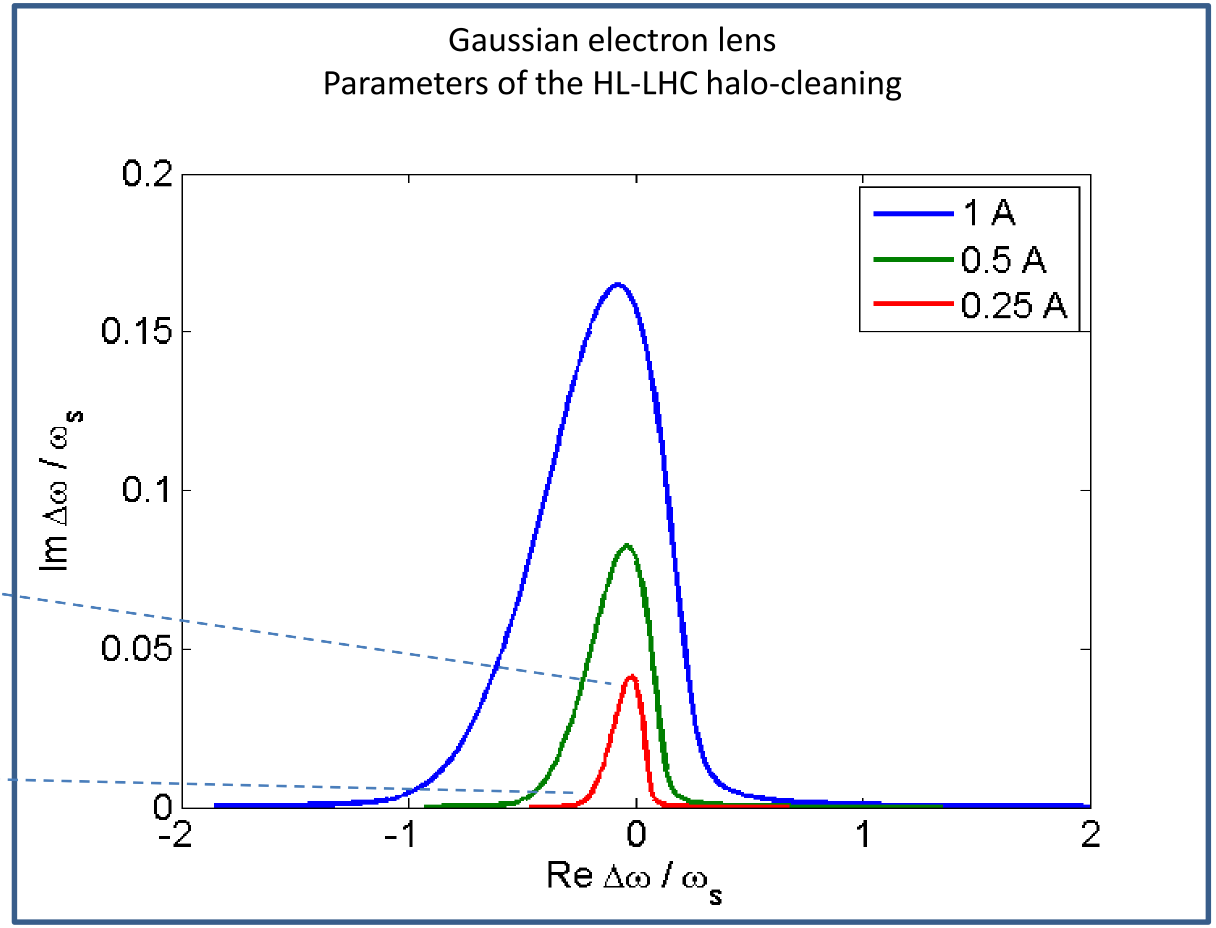
Alternative methods may be required:

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

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




Gaussian electron lens
Parameters of the HL-LHC halo-cleaning

Impact on DA has to be carefully studied

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

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Conclusions

- The HE-LHC impedance model was created on the HL-LHC basis
  - All contributors included, except for the crab cavities
  - The 2017 FCC-hh beam screen was used
- At 450 GeV, the beam screen and the collimators are the major contributors
  - A change of the beam screen design could have a non-negligible impact on impedance
- At higher energy, the impedance is dominated by the collimators and is significantly higher than at injection

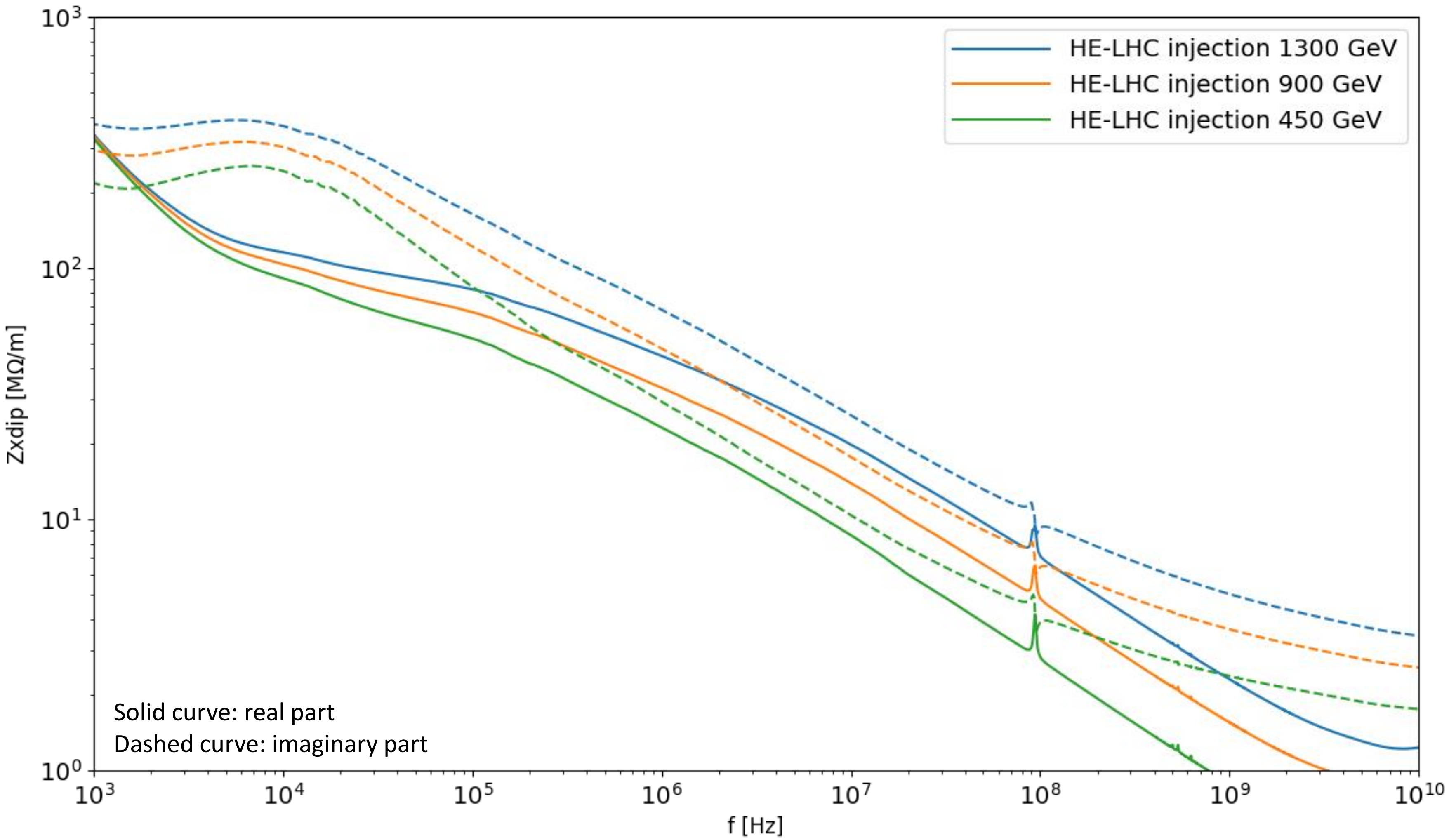
- The stability estimates include impedance effects only
- For all injection energy options the beam is stable for a damper gain of 50-100 turns
  - Small octupole currents needed to stabilize (~10 A or below)
  - Impact on DA needs to be assessed
  - The 450 GeV option has less margin in intensity threshold and damper gain
- The top energy is expected to be more challenging for beam stability
  - 2000 A is required assuming the current Hi-Lumi optics

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

Thank you for your attention!

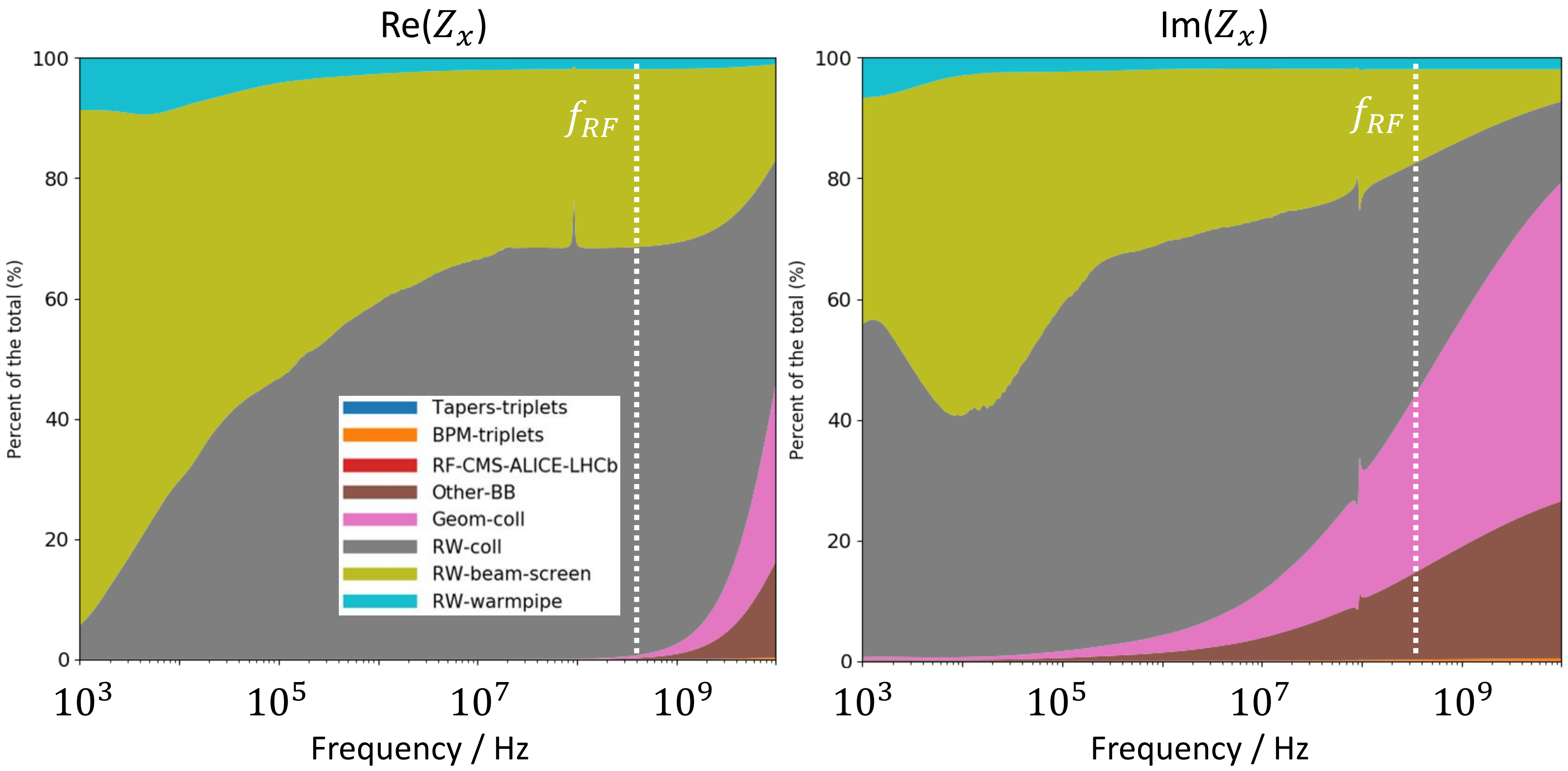
Backup

Impedance at injection energy



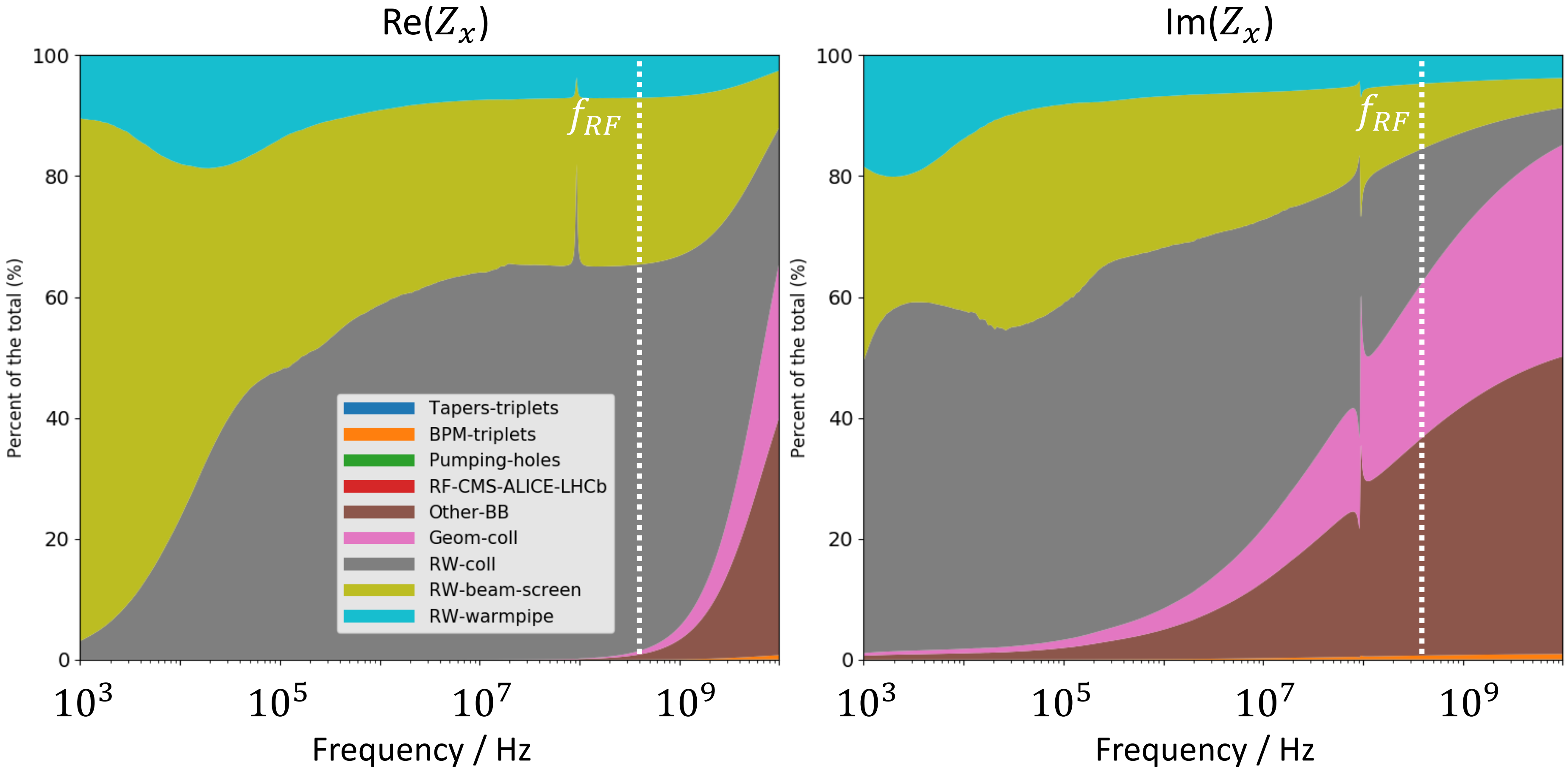
Solid curve: real part
Dashed curve: imaginary part

Contributors at injection energy: 900 GeV



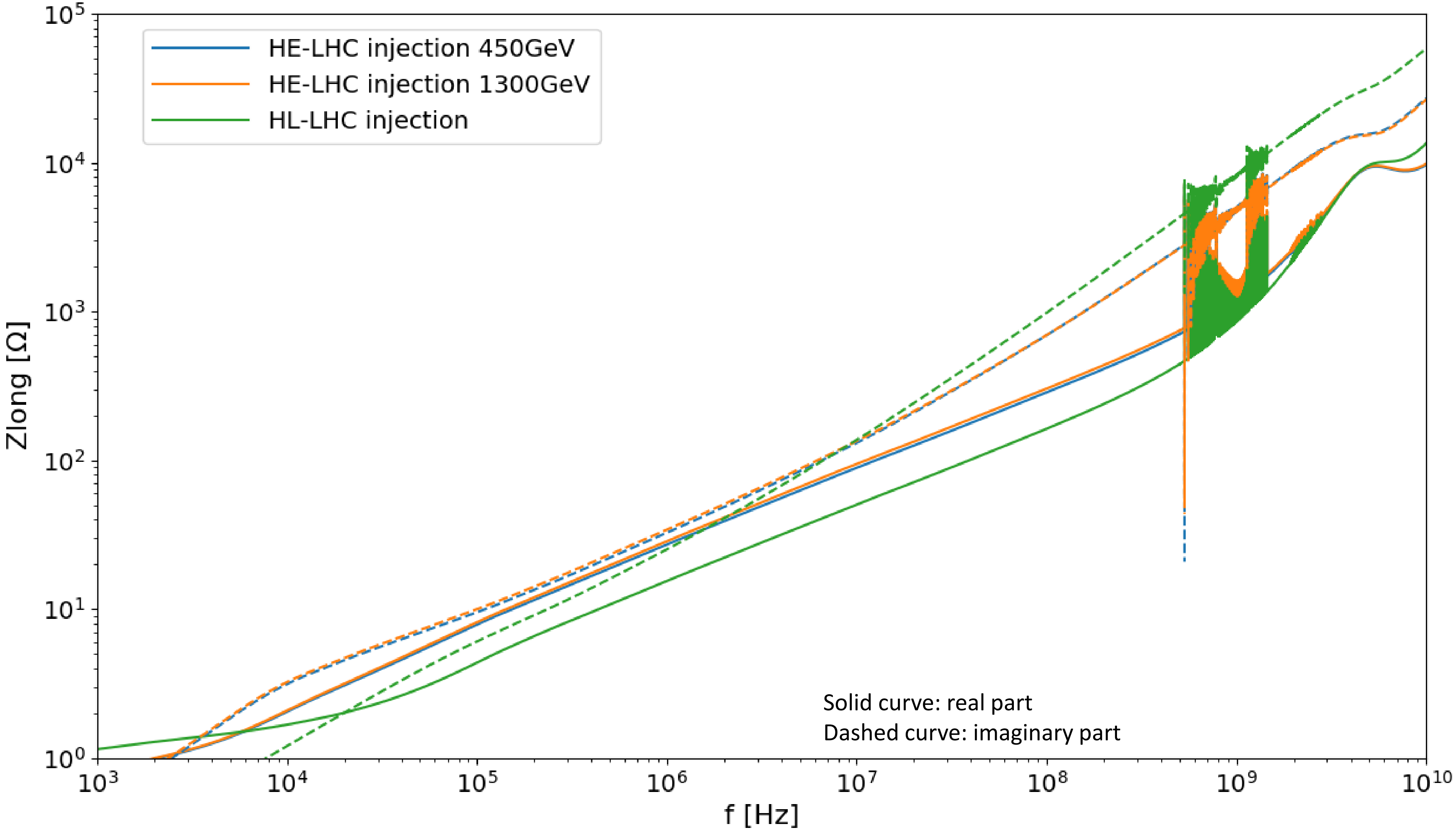
- Collimators start to dominate the impedance budget

Impedance at injection energy: HL-LHC

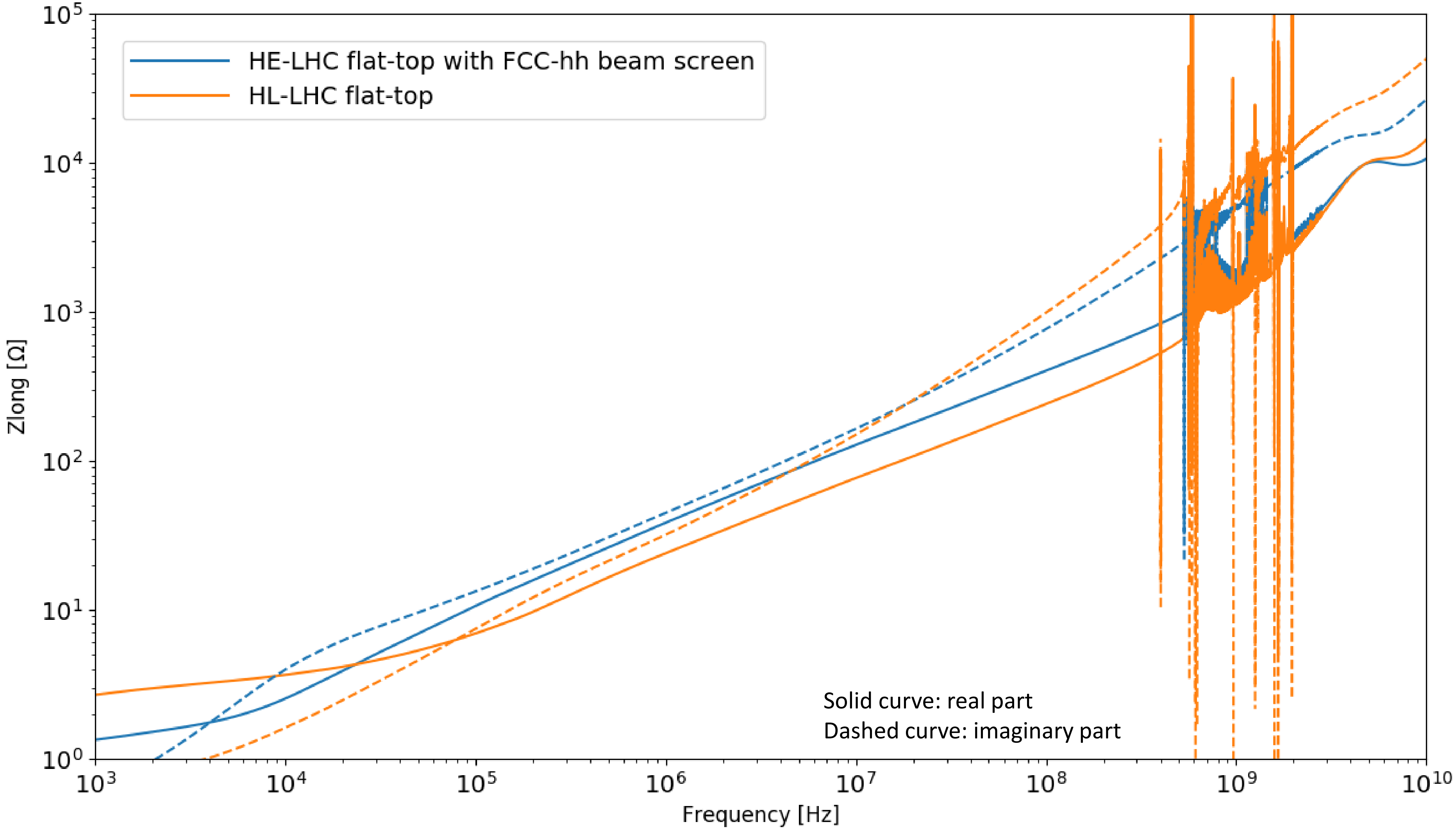


- Collimators are the main contributors to the impedance

Longitudinal impedance at injection energy



Longitudinal impedance at top energy



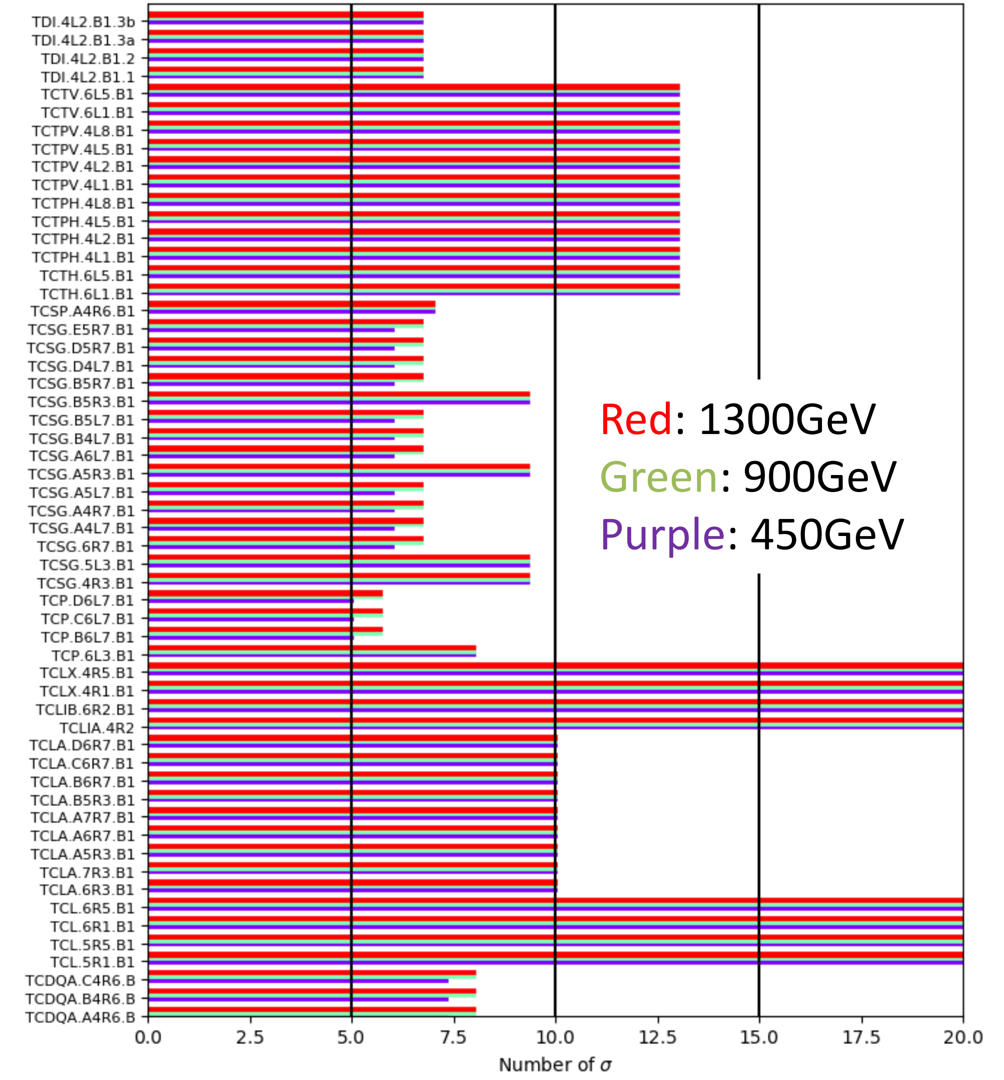
Solid curve: real part
Dashed curve: imaginary part

Beam and optics parameters

	HE-LHC		HL-LHC	
Machine state	**Injection**	**Flat-top**	**Injection**	**Flat-top**
Beam energy	450, 900, 1300 GeV	13.5 TeV	450	7.0 TeV
Bunch intensity	2.2x10^{11} ppb	2.2x10^{11} ppb	2.3x10^{11} ppb	2.3x10^{11} ppb
Number of bunches	2748	2748	2760	2760
Tunes: x, y, s	0.31, 0.32, 0.005	0.31, 0.32, 0.002	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 injection

- Summary of collimator gaps (in σ_{coll})

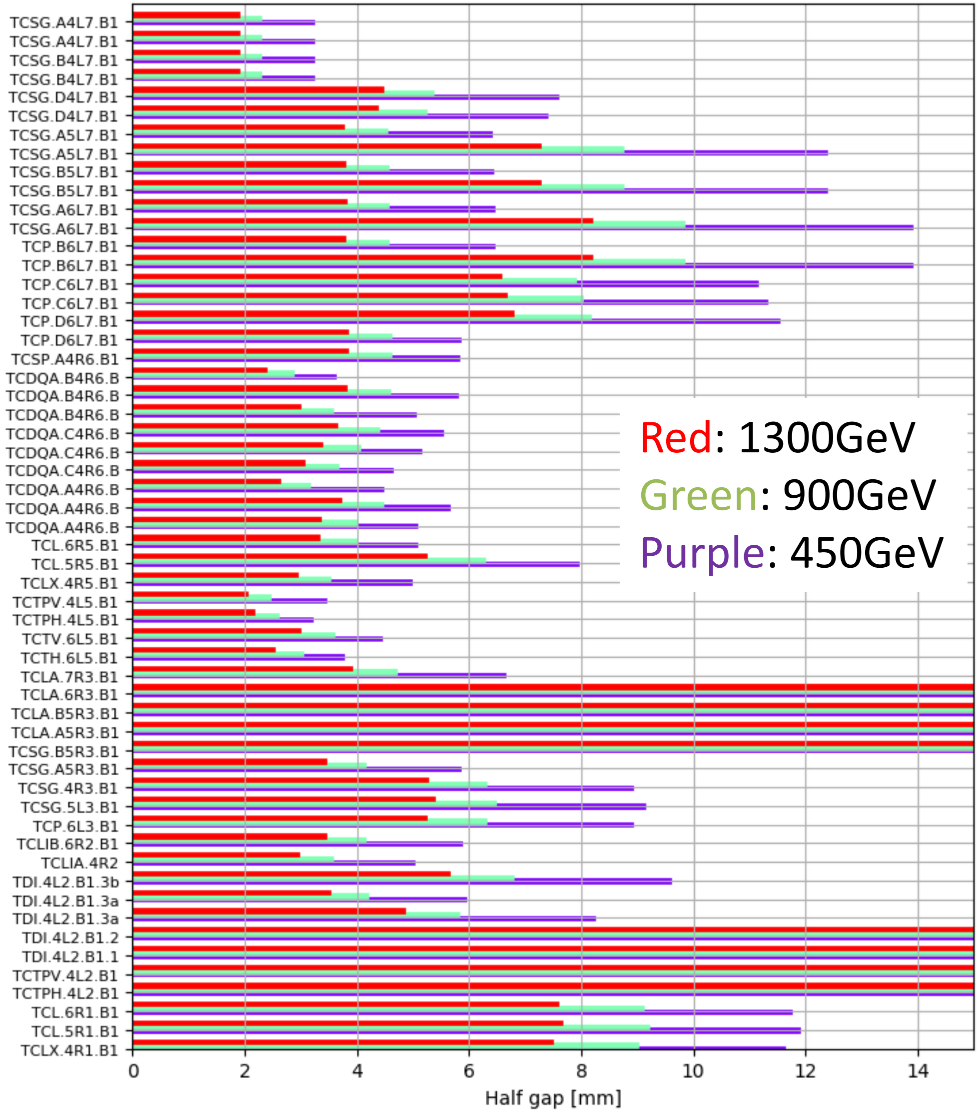


Energy	**TCP7**	**TCSG7**	**TCDQ**
450GeV	5	6	7.3
900GeV	5.7	6.7	8
1300GeV	5.7	6.7	8

Gaps in σ_{coll} assumed for the scenarios

Collimator gaps at injection

- Summary of collimator gaps (in mm)

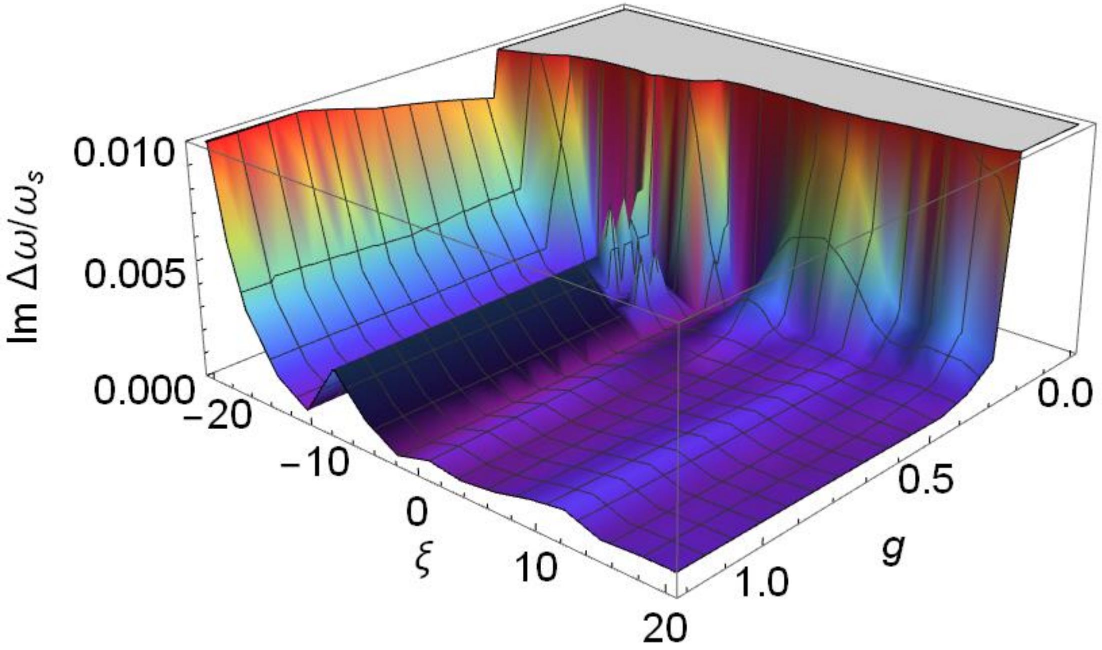


Physical gaps scale as $\sqrt{\frac{\varepsilon_n}{E}}$

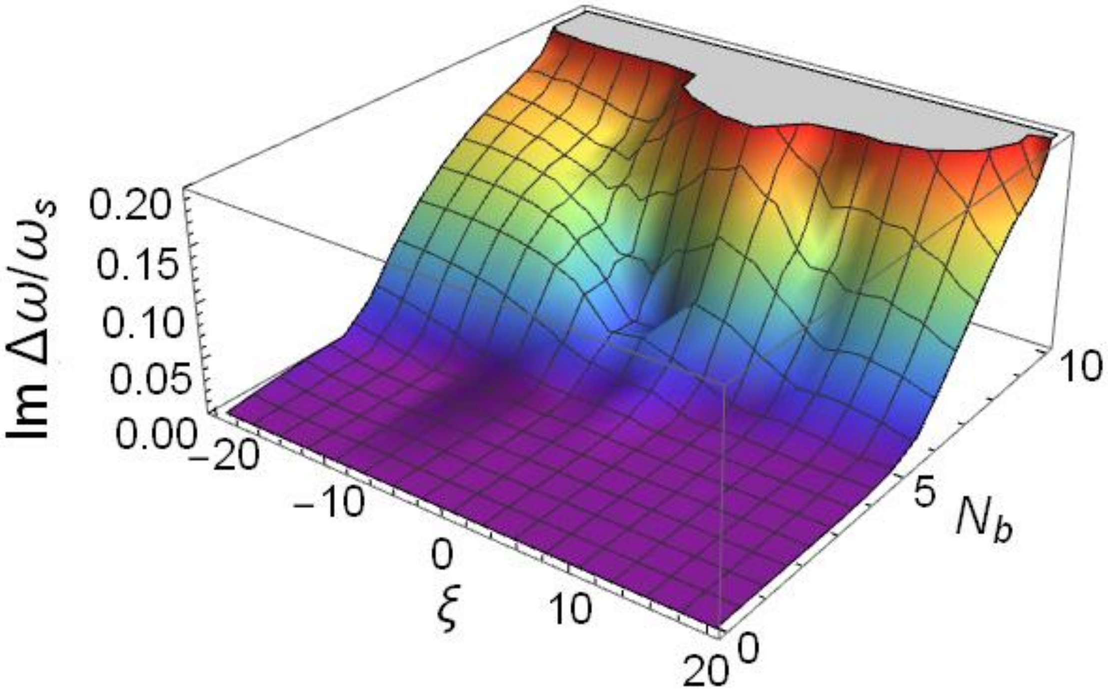
For HL-LHC, $\varepsilon_n = 2.5\mu m$
For HE-LHC, $\varepsilon_n = 2.5\mu m$

900 GeV: 2.2x10^{11} ppb, 2748b

Damper gain has to be 75 turns or higher



A factor 2 margin in intensity



Damper gain: g = damping rate / ω_s

Electron lens parameters

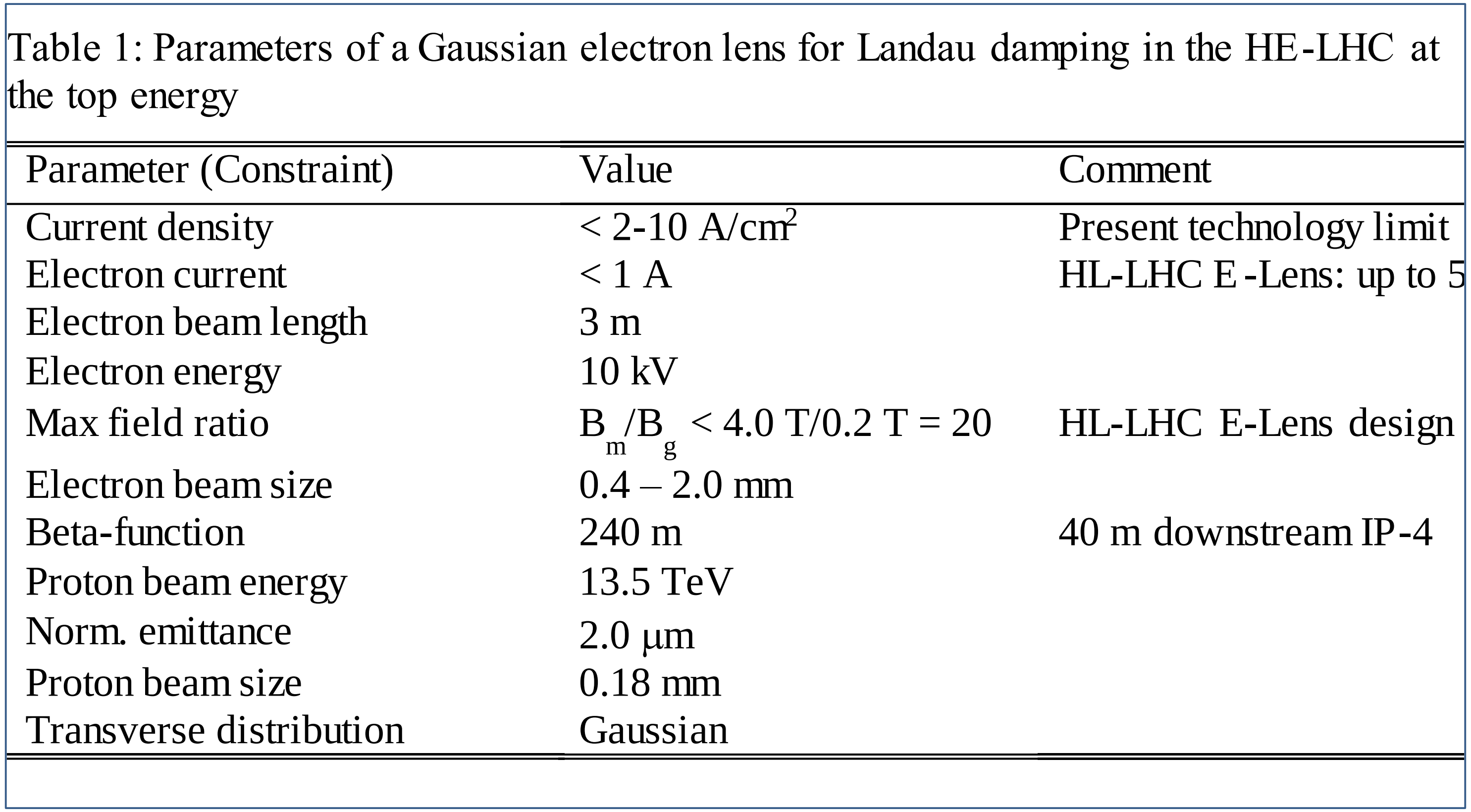


Table 1: Parameters of a Gaussian electron lens for Landau damping in the HE-LHC at the top energy

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

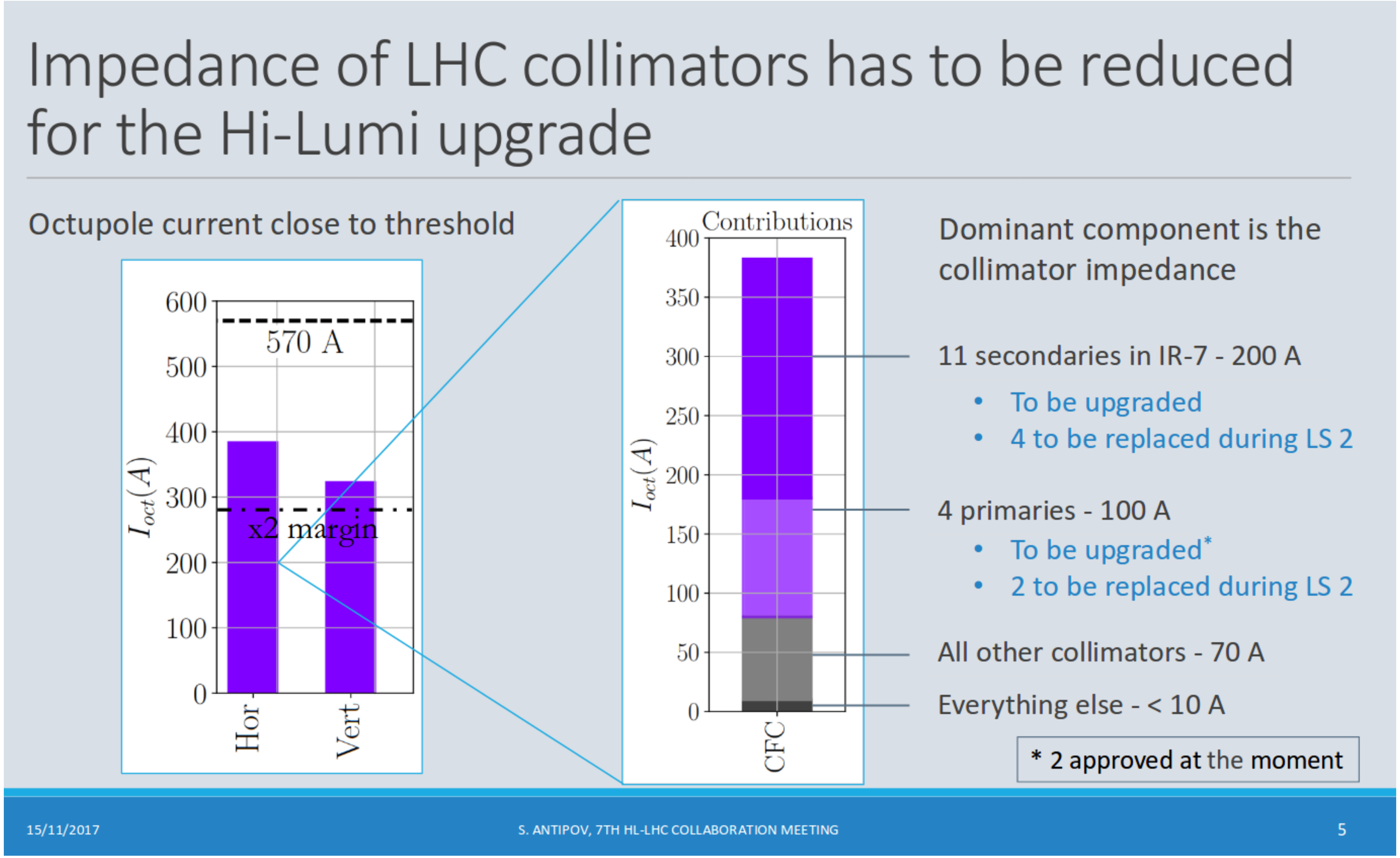
- In LHC, IR7 collimators are the main contributors to the impedance budget

- 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



Impedance of LHC collimators has to be reduced for the Hi-Lumi upgrade

Octupole current close to threshold

Dominant component is the collimator impedance

11 secondaries in IR-7 - 200 A

- To be upgraded
- 4 to be replaced during LS 2

4 primaries - 100 A

- To be upgraded*
- 2 to be replaced during LS 2

All other collimators - 70 A

Everything else - < 10 A

* 2 approved at the moment

15/11/2017 S. ANTIPOV, 7TH HL-LHC COLLABORATION MEETING 5

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