Update on transverse collective effect studies for the 10 TeV collider

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Thanks to F. Batsch, J. S. Berg, F. Boattini, L. Bottura, X. Buffat, C. Carli, A. Chancé, H. Damerau, A. Grudiev, I. Karpov, T. Pieloni, D. Schulte, K. Skoufaris

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Content

- Introduction
- Effect of copper coating thickness
- Effect of initial bunch offset
- First results of beam-beam studies

Introduction

- At the Collaboration meeting in October 2022
  - Presentation on 3 TeV and 10 TeV collider options
  - First investigation on the impact of material choice on transverse beam stability
- Since the last collaboration meeting
  - Studies have been focused on 10 TeV collider
  - The magnet design (aperture, cooling options, shielding …) is being refined. See for example talks from B. Caiffi, A. Lechner or P. Borges de Sousa

Content

- Introduction
- Effect of copper coating thickness
- Effect of initial bunch offset
- First results of beam-beam studies

Goal of the study

- Find the minimum chamber aperture which ensures transverse beam stability
- Investigate **more realistic** cases for the **beam chamber materials**
  - Tungsten shield with copper coating layer, assumed to be at 300 K
  - Thicker copper coatings are more difficult to deposit → try to find the lower limit for the coating thickness

Main assumptions for the studies

- Single 5 TeV muon beam, **including the muon decay effect**
- Assume the chromaticity is corrected to zero $\mathbf{Q'_x=Q'_y=0}$, and no detuning from octupoles
- Impedance model generated with ImpedanceWake2D
  - Assume a 10 km long circular chamber → horizontal and vertical planes are equivalent
- Tracking simulations are performed with PyHEADTAIL
  - 5 tracking steps: transverse map, longitudinal map, wakefield effect, muon decay, damper
  - Tracking for 6000 turns (~2 beam lifetime)

Parameter scan for the material study

- Perform scan on different parameters:
  - Chamber radius from 10 mm to 30 mm
  - **Copper coating** thickness from **0.1 µm to 100 µm**
  - Transverse feedback damping rate from 2 turn to 1000 turn + no damper

Beam and machine parameters, common to the different studies

Beam parameters	Unit	Value
Synchrotron tune Q_s		0.00233
Synchrotron period	turns	429
Bunch length 1σ	**mm**	**1.5**
Bunch intensity	**Particles per bunch**	**1.8e12 (at start)**
ε_x / ε_y	**μm rad**	**25**
# of macropaticles		**50000**

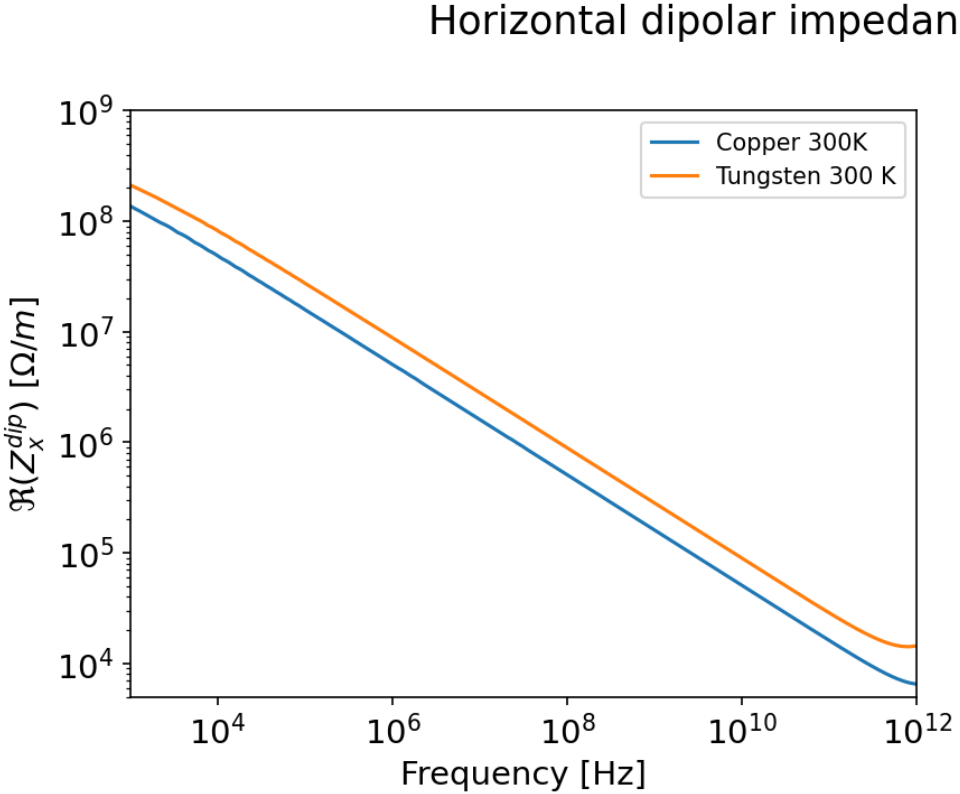
Copper at 300 K	Unit	Value
Temperature	K	300
DC resistivity	nOhm m	17.9

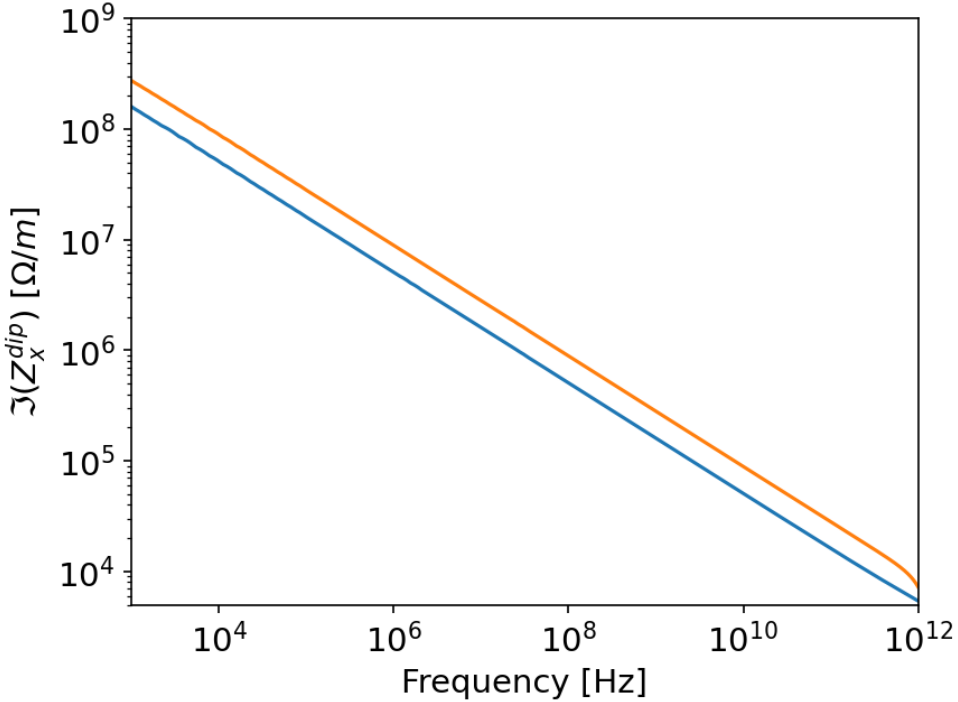
Tungsten at 300 K	Unit	Value
Temperature	K	300
DC resistivity	nOhm m	55.6

Machine parameters	Unit	Value
Circumference	m	10000
Beam momentum	GeV/c	5000
Rev. frequency	kHz	30
RF frequency	MHz	1300
Harmonic number		43478
RF voltage	MV	2e3
α_p		-2.0e-6
Avg. beta x/y	m	85 / 51
Chromaticity Q'_x/Q'_y		0/ 0
Detuning from octupoles x/y	m^{-1}	0 / 0

Scan parameters	Unit	Value
Chamber radius	mm	10 to 30
Coating thickness	μm	0.1 to 100
Transverse damper		2 to 1000 turns / No damper

Impedance models at 300 K





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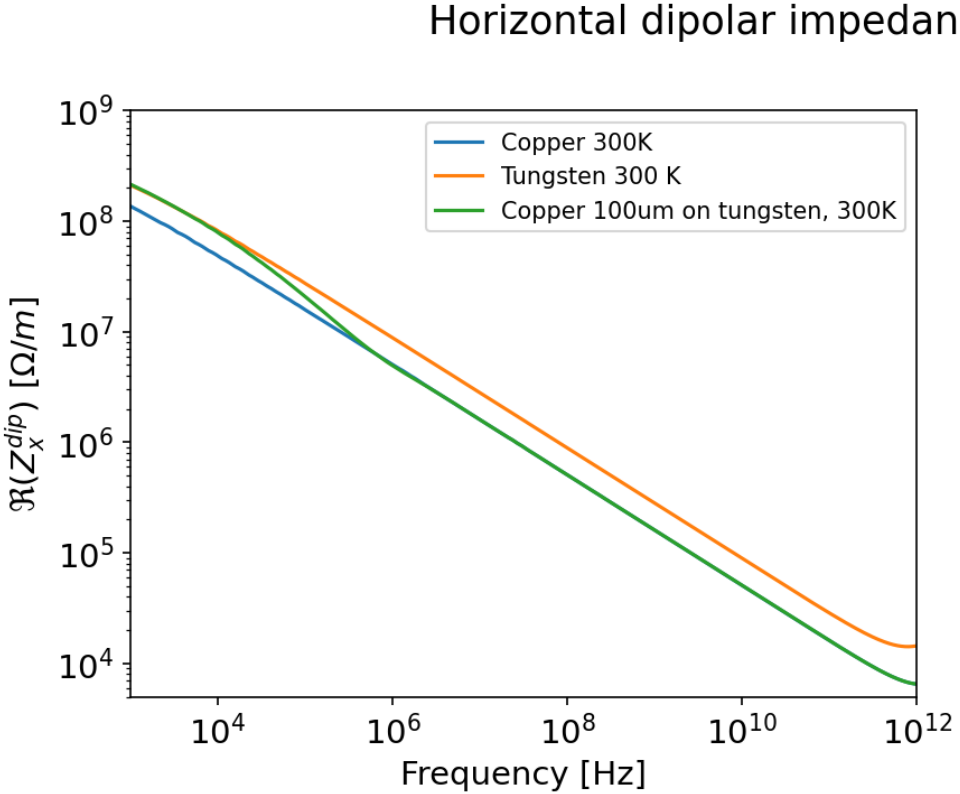

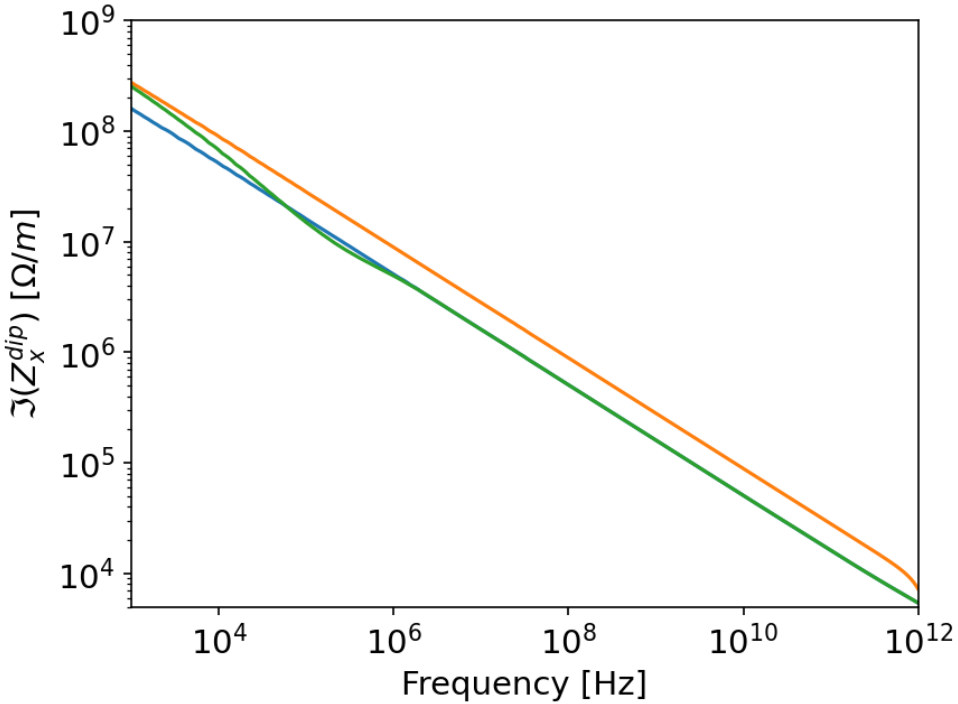

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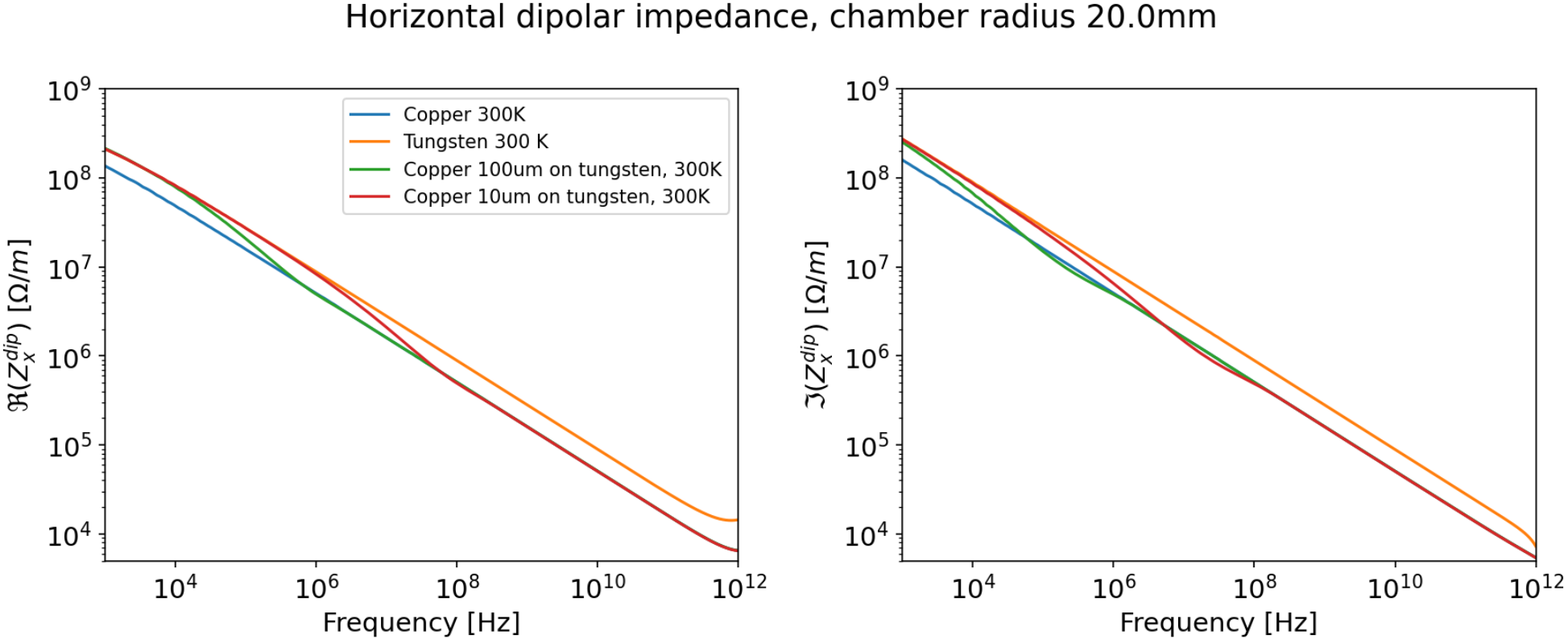

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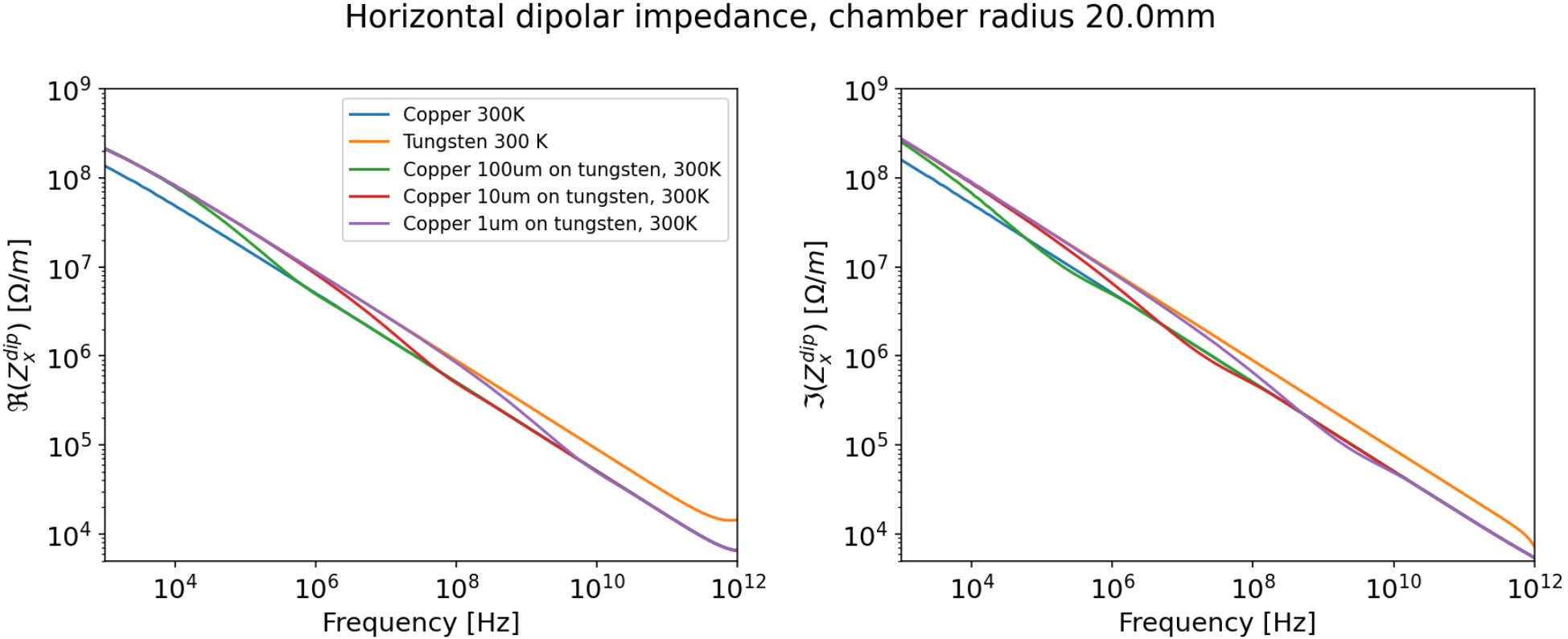

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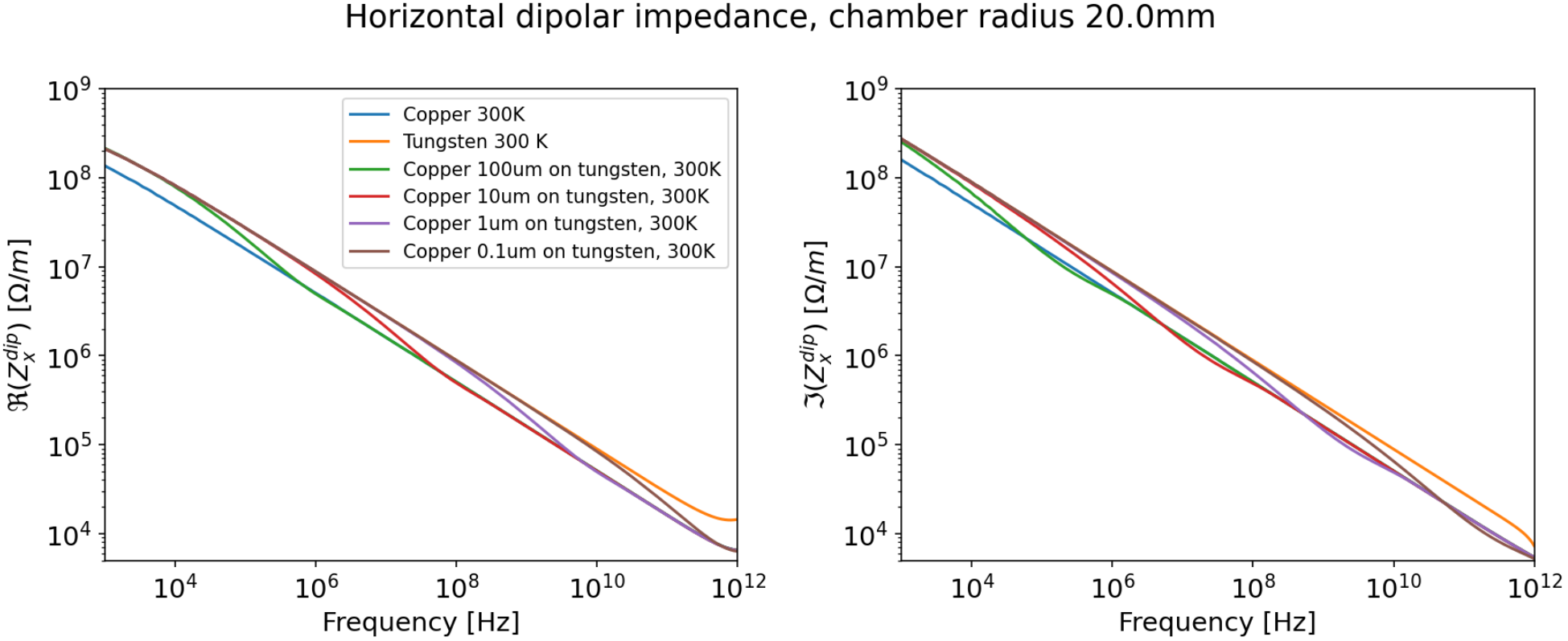
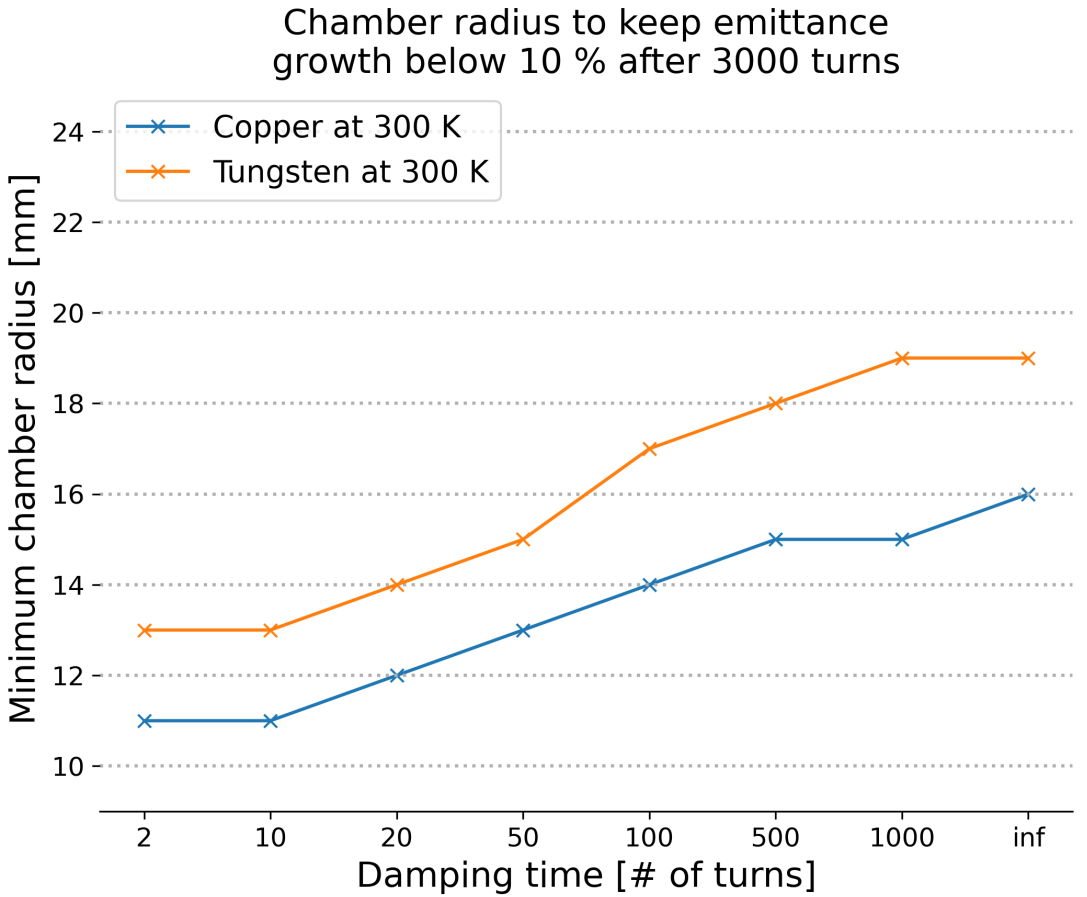


- Visible effect of coating thickness on transverse dipolar impedance → with thicker copper coating (green) the impedance approaches pure copper for a larger frequency range

Minimum chamber radius achievable with different materials

- Simulations with **muon decay included**
  - Lifetime at 5 TeV: 104 ms → 3100 turns in the 10 km ring



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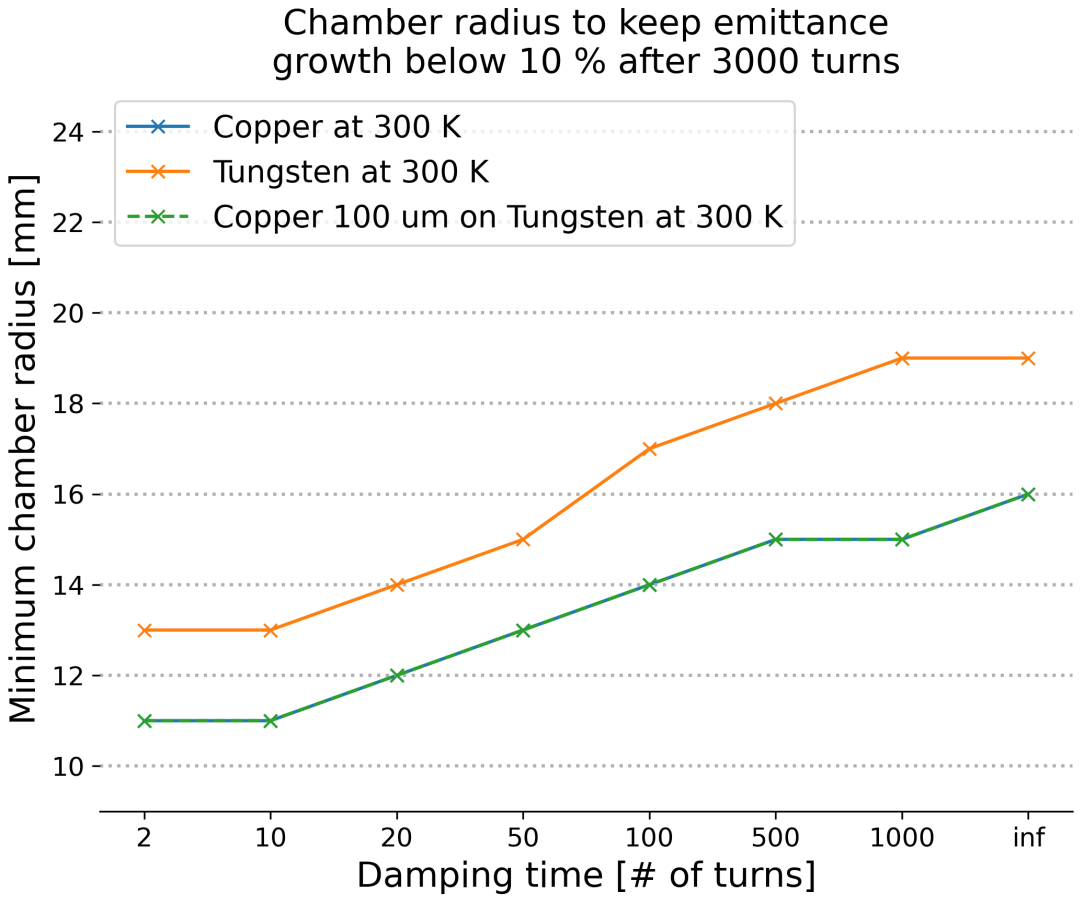

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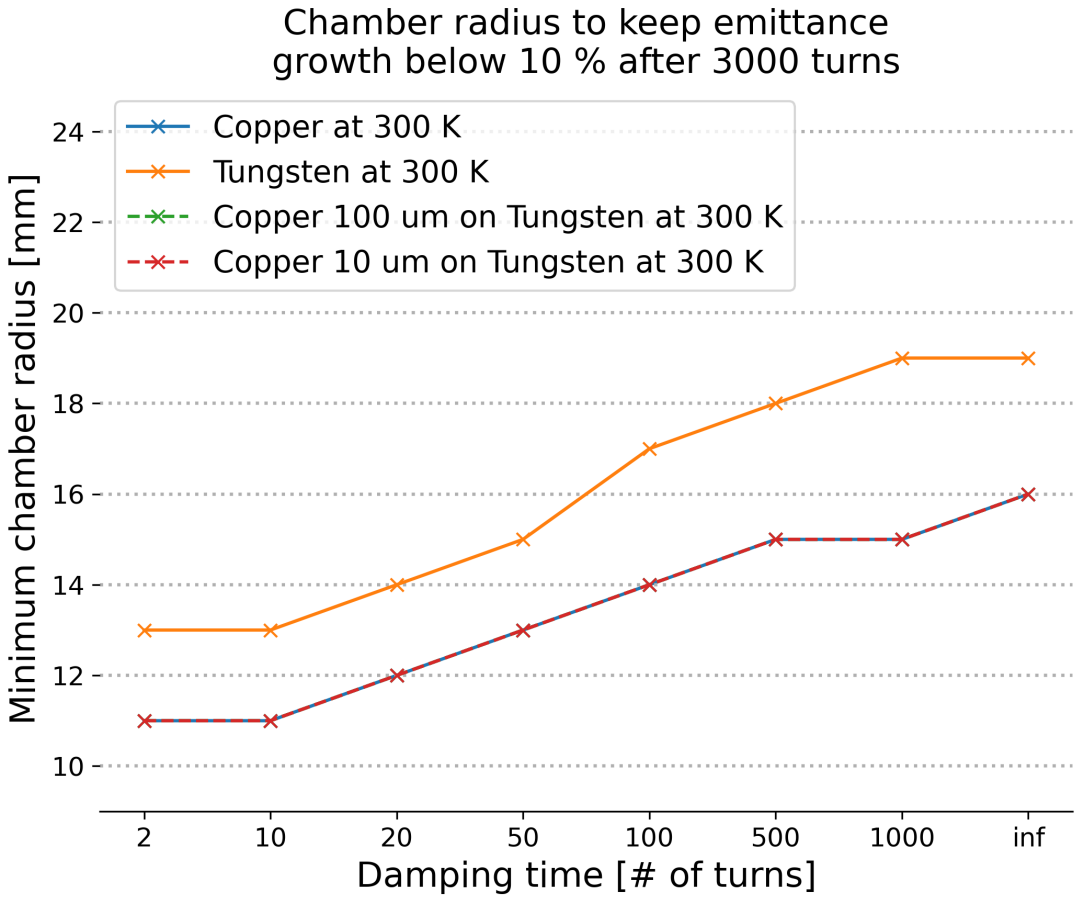

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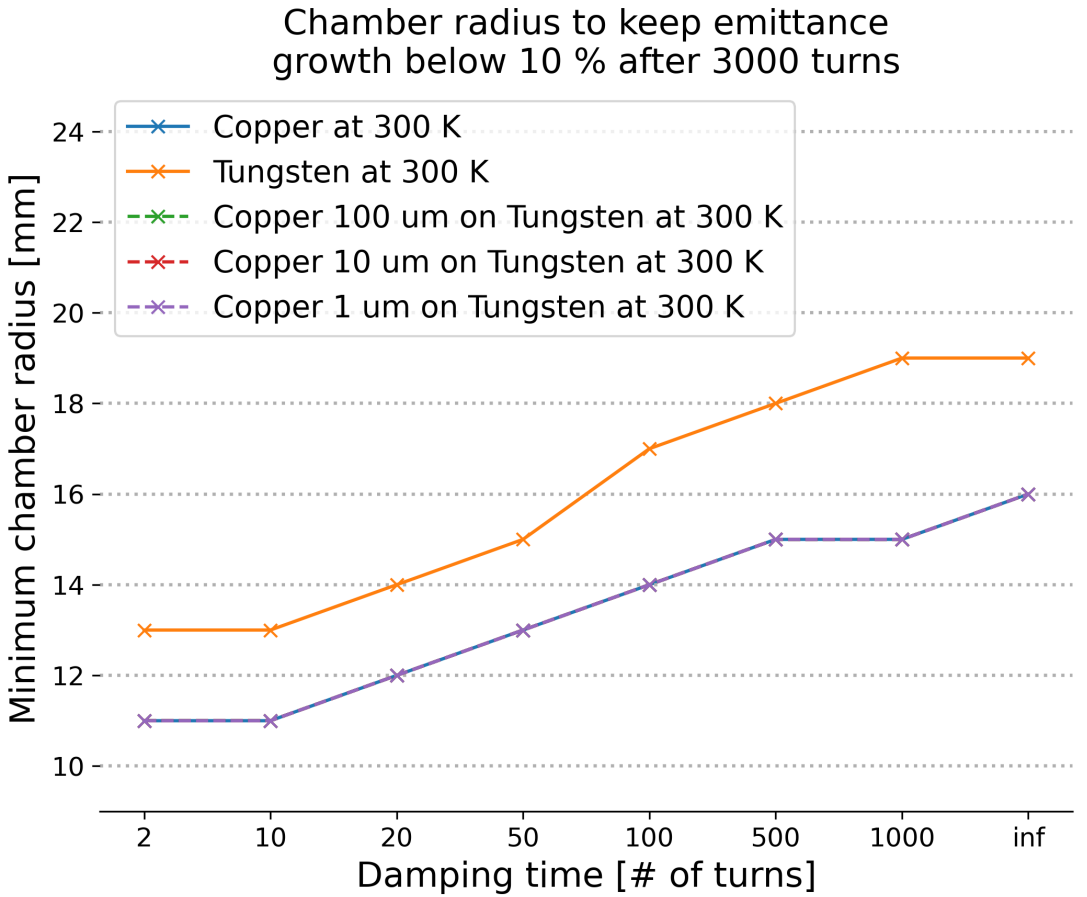
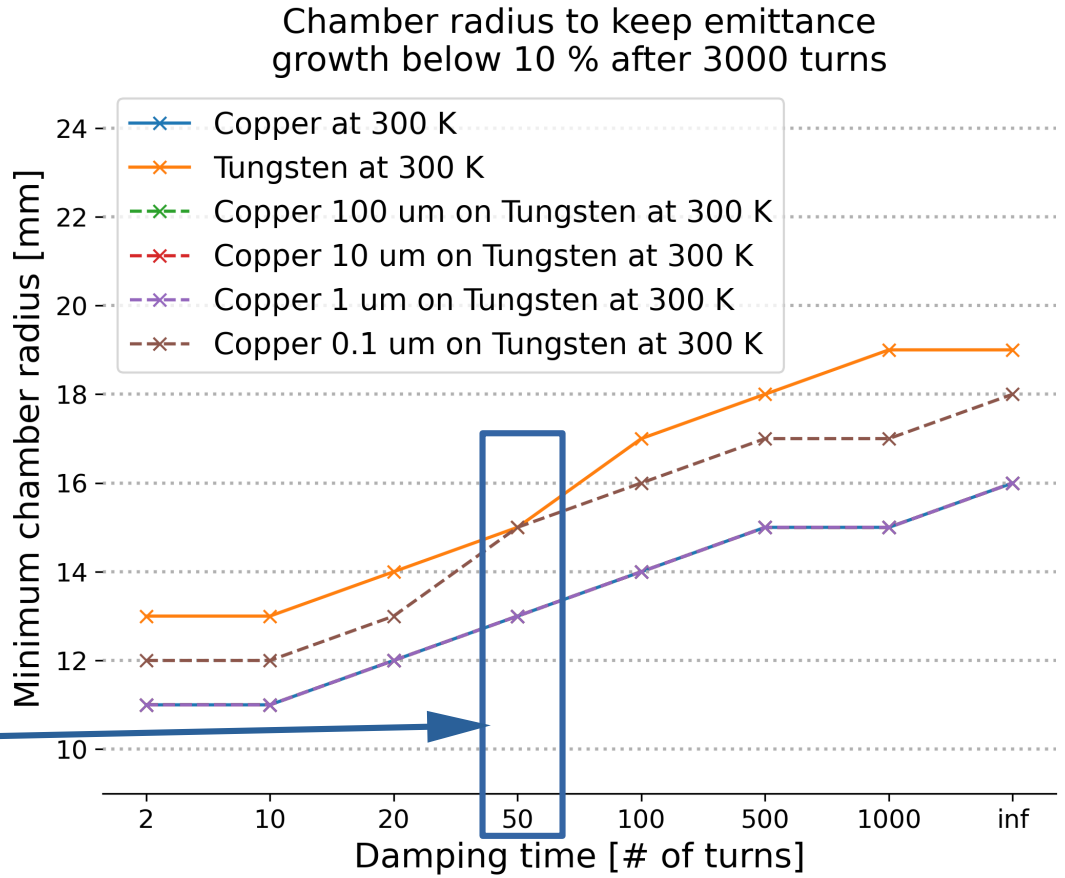


Take-home: few µm copper coating performs as well as a pure copper chamber

- Simulations with **muon decay included**
  - Lifetime at 5 TeV: 104 ms → 3100 turns in the 10 km ring
- **Copper coatings > 1µm perform as well as pure copper**
  - Minimum chamber radius below 20 mm for all damper settings

With copper coated tungsten and 50-turn damper: 13 mm radius



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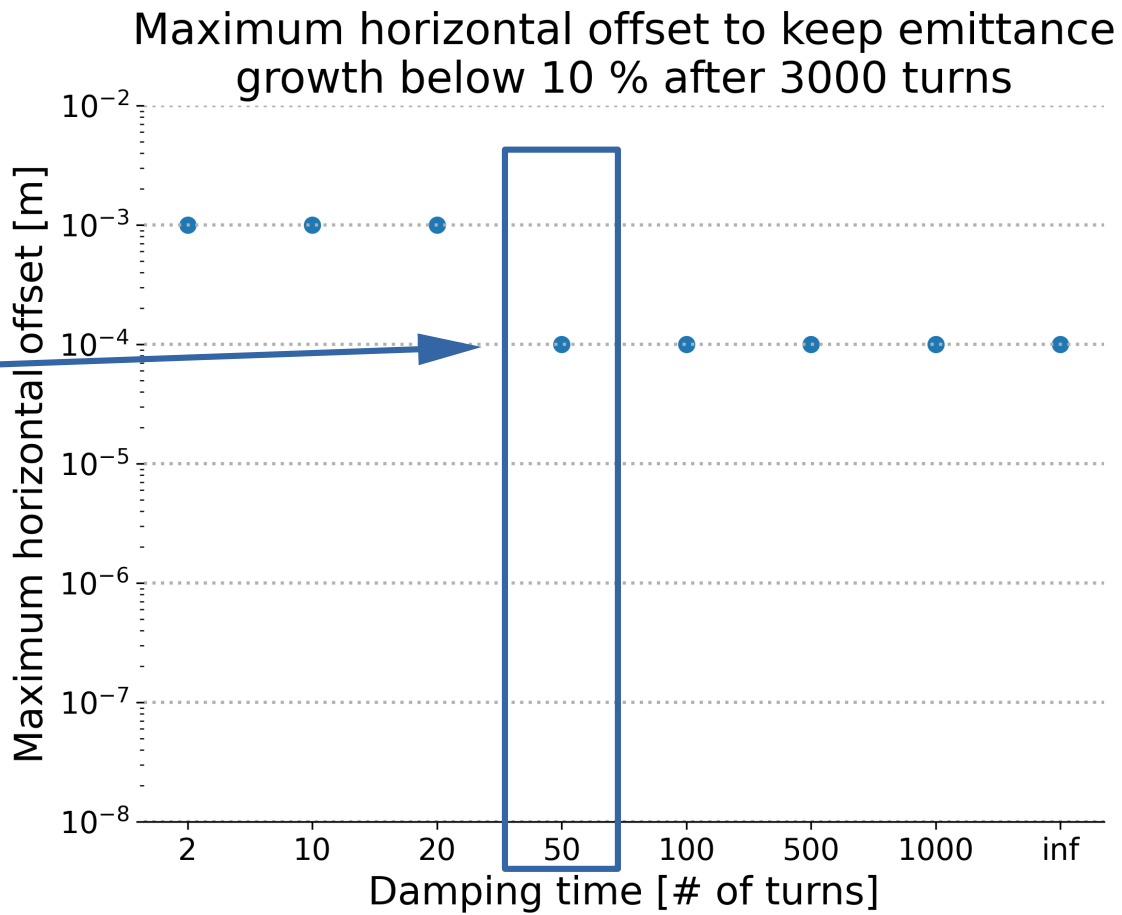
Goal of the study

- Injections errors could degrade the transverse emittance in the first turns, leading to luminosity loss
  - Injections errors can come from field errors in kicker magnets, transfer line steering…
  - Check the tolerance we have on the injected bunch offset w.r.t collective effects
- For a given impedance model, **scan the initial horizontal offset of the bunch** and the transverse feedback damping time
  - Impedance model: 20 mm radius chamber, 100 um copper coated tungsten at 300 K
  - Offset scan from 0.1 µm to 1mm

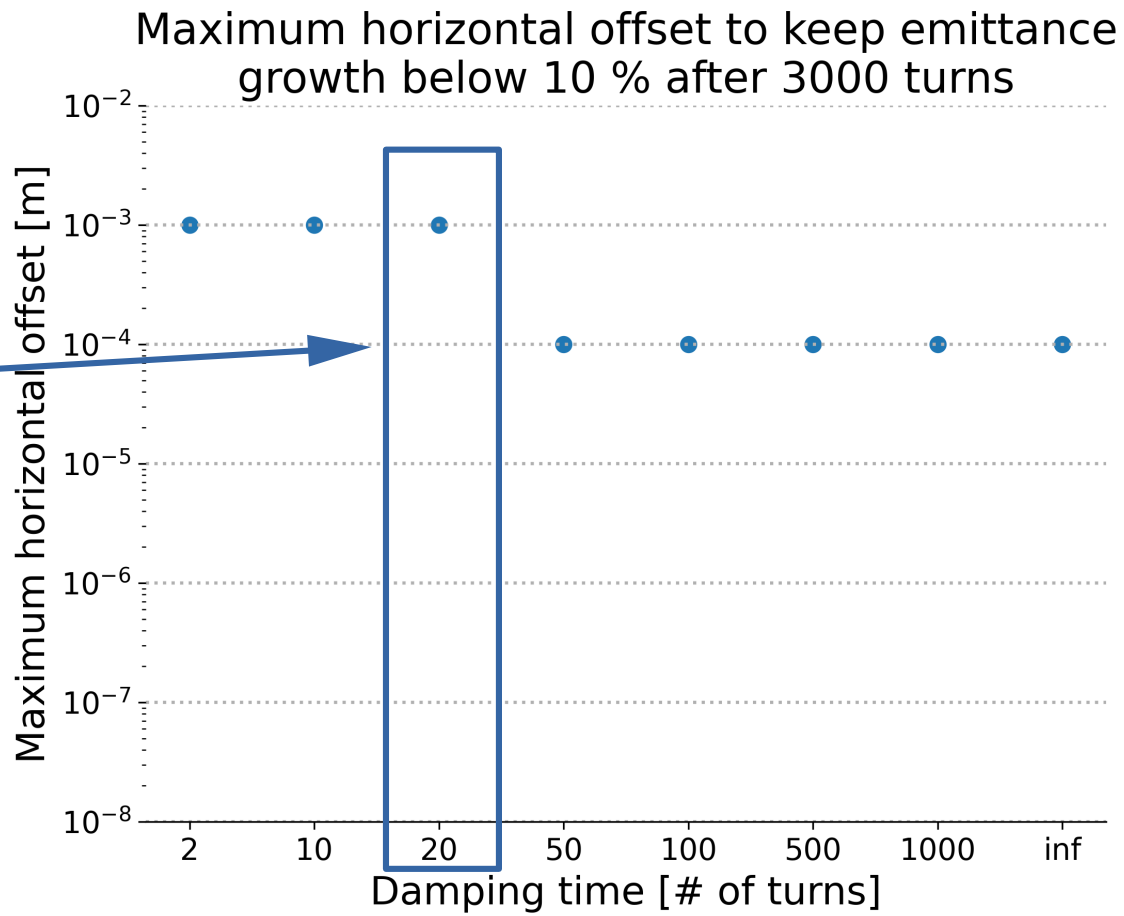
Maximum tolerable initial bunch offset

- **Initial bunch offset** should be **smaller than 100 μm** to preserve transverse emittance with a 50-turn damper



Maximum tolerable initial bunch offset

- Tolerance **can be increased to 1 mm** with a stronger, **20-turn damper**



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Goal of the study

- Collider and RCS will have two counter-rotating bunches
  - The beams will cross at two points
  - Need to **estimate the effect of beam-beam on transverse stability**

- Start the study with the 10 TeV collider
  - **Two low-beta regions** needed for the experiments
  - Longer storage times compared to the RCS

Goal of the study

- With round beams, the linear beam-beam parameter is $\xi = \frac{N_b r_0}{4\pi\varepsilon_n}$
- For the 10 TeV collider ξ is similar to LEP horizontal plane

Parameter	RCS 1	COLL10	LEP	HL-LHC
Beam total energy [GeV]	63	5000	100	7000
Single bunch intensity [10^{11}]	25.4	18.0	4.0	2.2
β_x^* / β_y^* [m]	50/50[1]	1.5×10^{-3}	1.25 / 0.05	0.64[2]
Normalised transverse emittance $\varepsilon_{n,x}$ / $\varepsilon_{n,y}$ [µm rad]	25/25	25/25	3910/63[3]	2.5/2.5
Beam size at IP σ_x^* / σ_y^* [µm]	1450/1450	0.89 / 0.89	160 / 4	13.6/13.6
Beam-beam parameter ξ	0.11/0.11	0.078/0.078	0.072/0.045	0.011/0.011

[1] We assume that the bunches cross head-on in the RCS as well, though without strong focusing.
[2] Value for IP1 and IP5 at the start of stable beams.
[3] Value computed from the transverse beam sizes reported in [1].

Classical radius r_0	Value [m]
Electron	$2.82 \cdot 10^{-15}$
Muon	$1.36 \cdot 10^{-17}$
Proton	$1.53 \cdot 10^{-18}$

Main hypothesis for the study

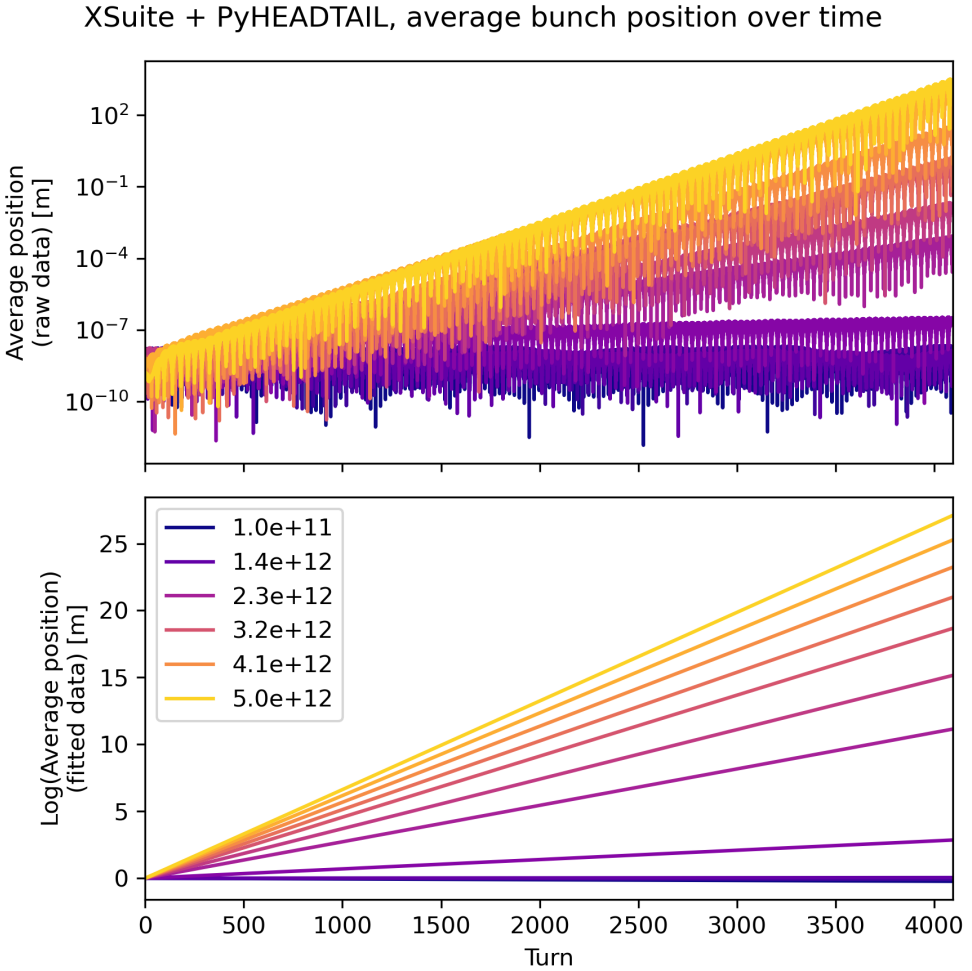
- **Muon decay**, and subsequent intensity loss, **not included**
- **Chromaticity** corrected to **Q'_x=Q'_y=0, no transverse damper**
- **Single beam impedance** considered (equivalent to bunches traveling in separate chambers)
  - 20mm radius, copper coated (100 μm) tungsten at 300 K
- Perform a **scan in bunch intensity**, from $1 \cdot 10^{11}$ to $5 \cdot 10^{12}$
  - Allows to check the transverse mode coupling instability threshold for the chosen impedance model
  - Compare different simulations techniques (particle tracking, analytic estimates, Vlasov solver)

Simulation tools used: tracking, analytic estimate, Vlasov solver

- Tracking simulations are performed with XSuite+PyHEADTAIL
  - **XSuite** for the **transverse** and **longitudinal tracking** and **beam-beam** effects. Only 4D (transverse planes) effects simulated for beam-beam for now
  - **PyHEADTAIL** interface for **collective effects** (impedance/wakefield, dampers)
- Analytic formulas from Sacherer derivations
  - Tune-shift versus intensity can be estimated, but effects such as mode coupling, quadrupolar impedance are not covered
- Vlasov formalism using DELPHI
  - Covers effects such as mode coupling and transverse damper

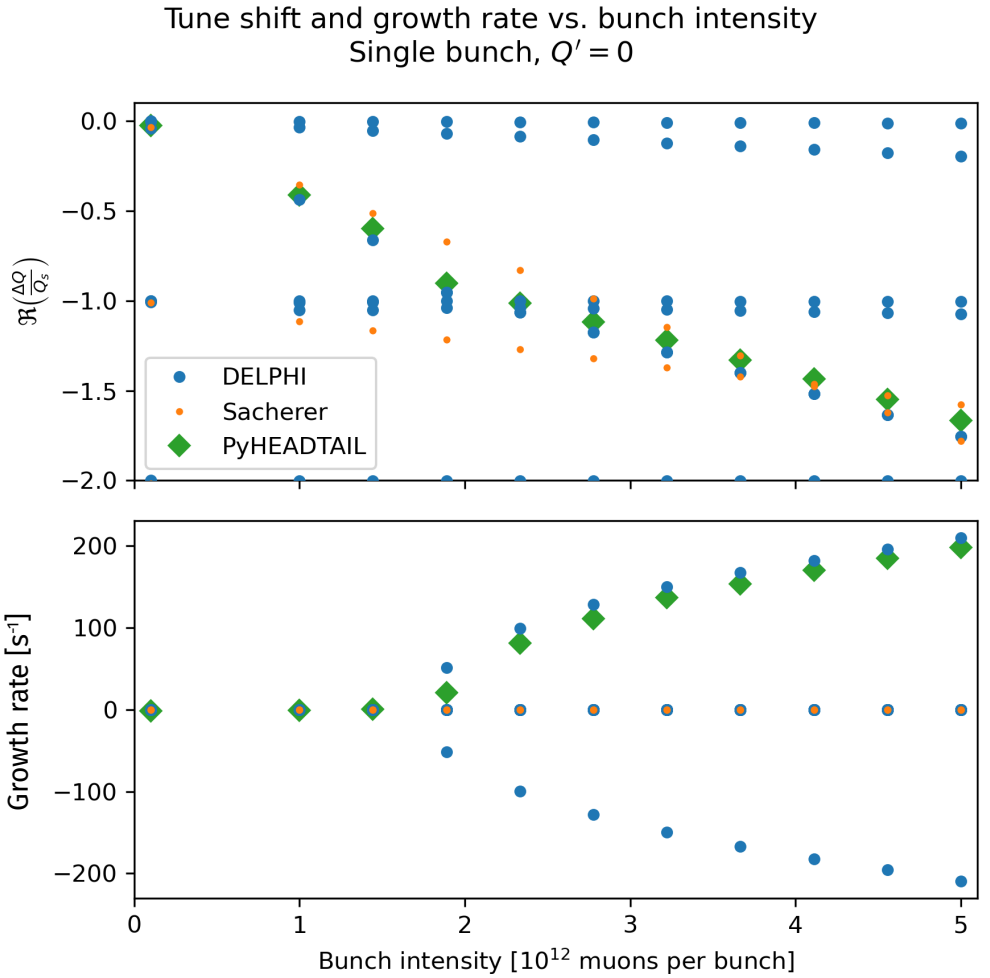
Beam tracking results, without beam-beam

- Clear instability signal in tracking for bunch intensities > 2e12
- Perform FFT or Harmonic analysis with PyNAFF of the position signal provide the bunch tune



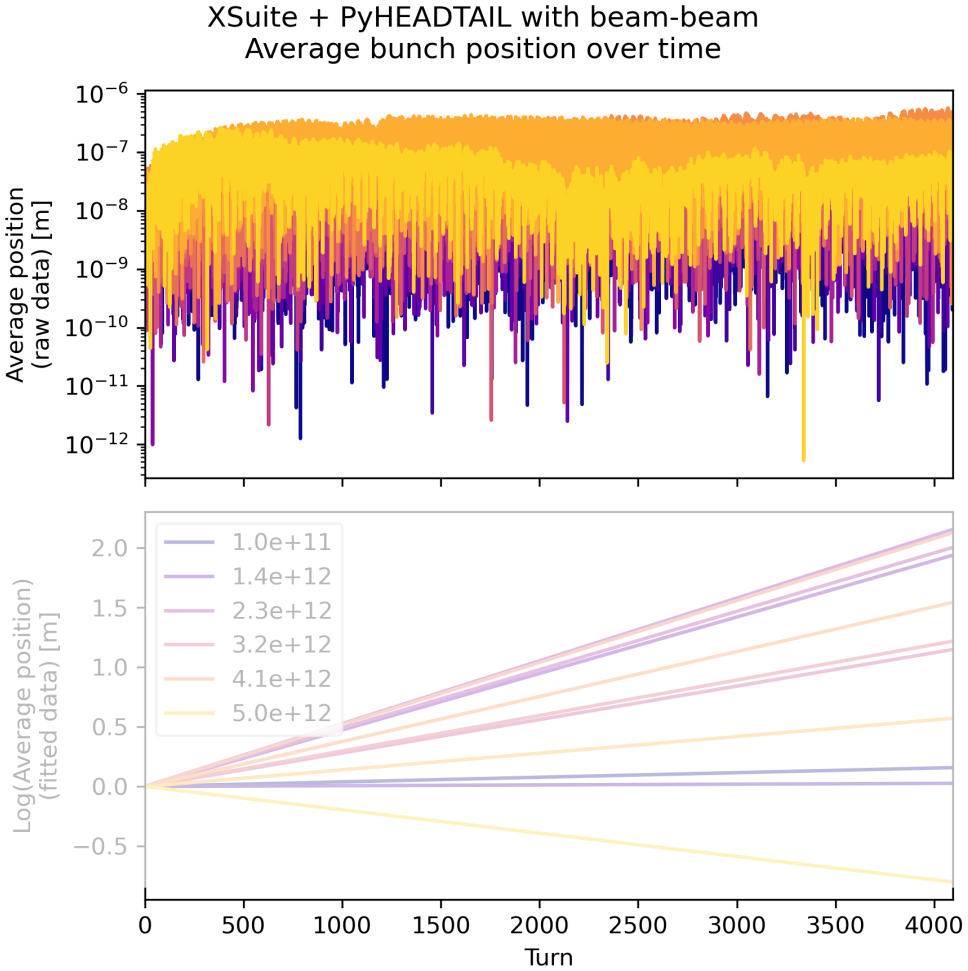
Tune shift versus intensity result, without beam-beam effect

- Similar results between DELPHI (blue dots) and Tracking (green diamonds)
  - Mode coupling **instability** at **~1.8e12** muons per bunch
  - Similar to the nominal bunch intensity of 1.8e12 at injection
  - But **effect of muon decay is not included →** over time, the beam would becomes **less sensitive to collective effects**
  - **No damper and Q'_x=Q'_y=0**



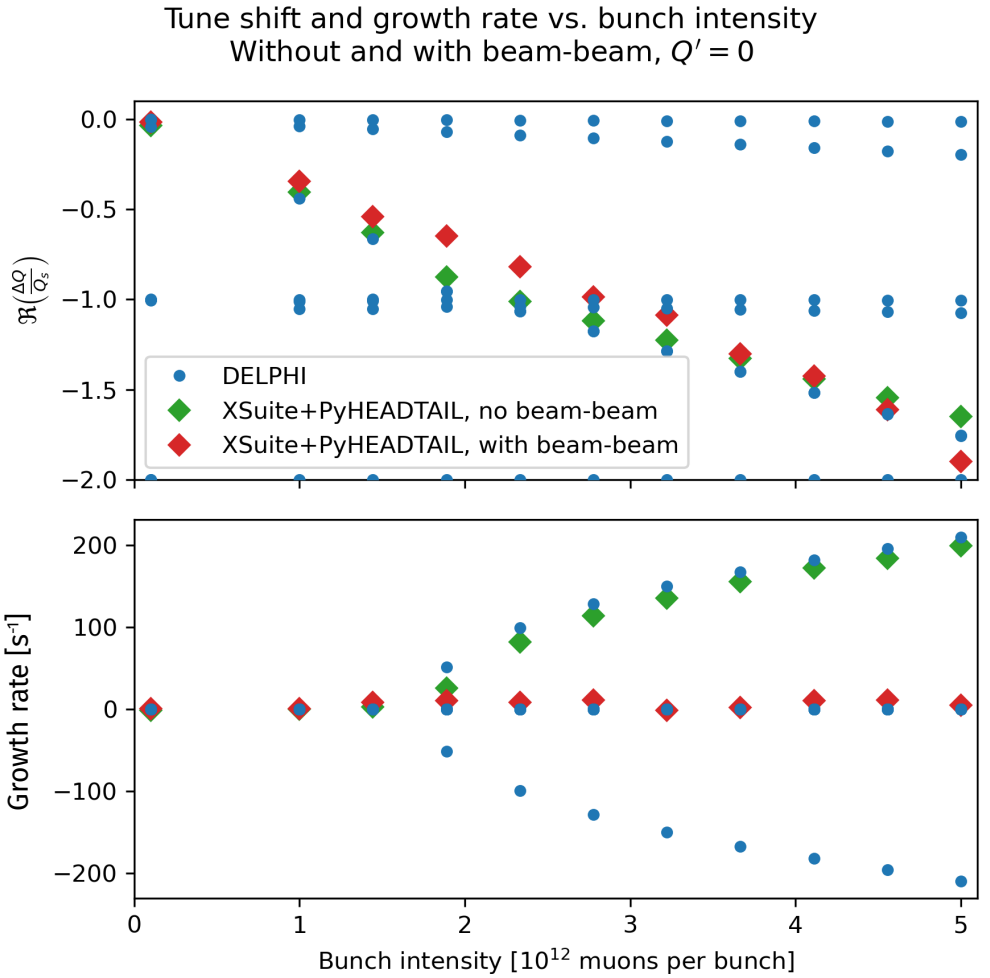
Beam tracking results, including beam-beam

- No large transverse position excursions, compared to the case without beam-beam
- Growth-rate fit (bottom plot) are not a good indicator



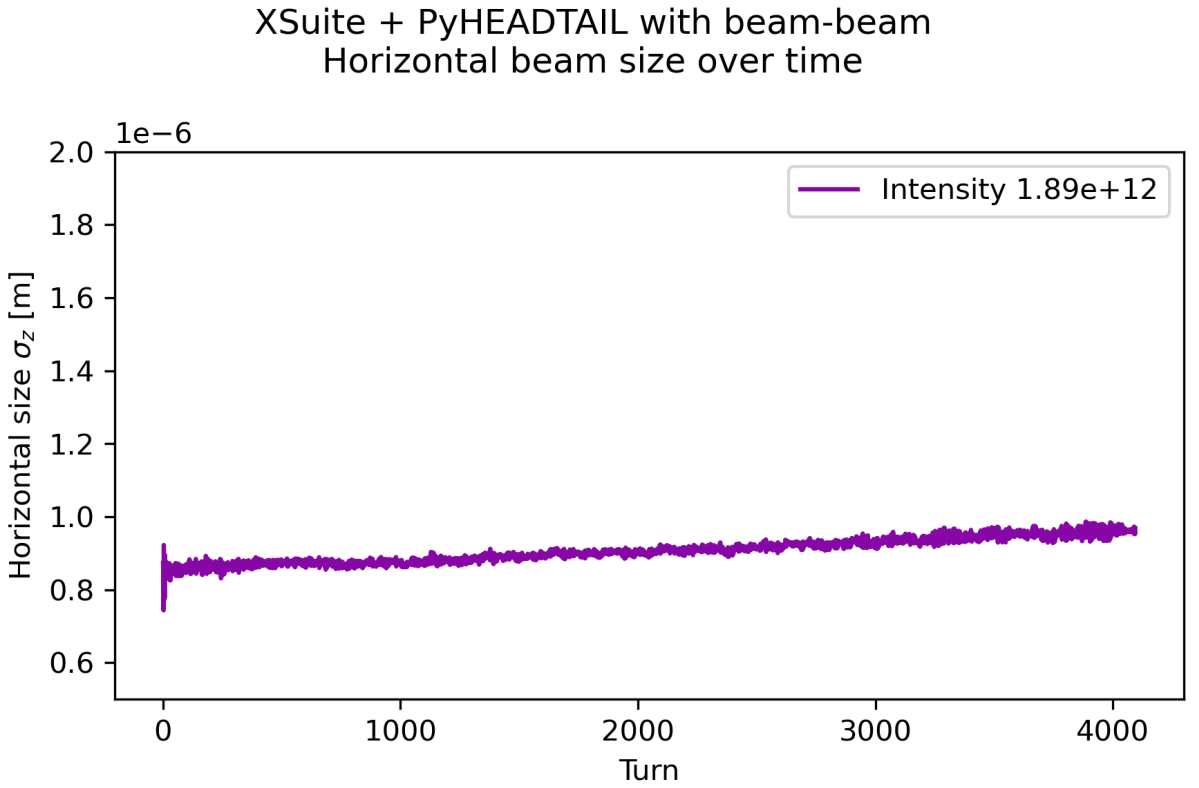
Tune shift versus intensity result, including beam-beam effect

- DELPHI simulations are single bunch only (kept for comparison)
- Compare tracking simulations **without (green diamonds)** and **with (red diamonds) beam-beam effect**
- Simulations assume that the **two bunches collide head-on at the IPs**
- Mode coupling instability appears suppressed in simulations
  - This should be checked with Circulant Matrix Model (CMM)



Transverse beam size evolution with beam-beam effect

- With a bunch intensity of 1.9e12 muons, the horizontal size growth is ~10%
- Reminder: the muon decay effect is not included



Conclusions and next steps

- **Impedance effects do not** appear to **limit the chamber aperture**
  - Current magnet build has a beam **aperture of 23.5 mm, above the limit of 13 mm** for a copper coated tungsten chamber, **without bunch offset**
  - Initial bunch offset should be below 100 um with a 50-turn damper, and can increase to 1 mm with a 20-turn damper
- **Two beam effects start to be investigated**
  - Beam-beam effects at two interaction points investigated
  - Mode coupling instability appears to be suppressed by beam-beam in tracking simulation

Conclusions and next steps

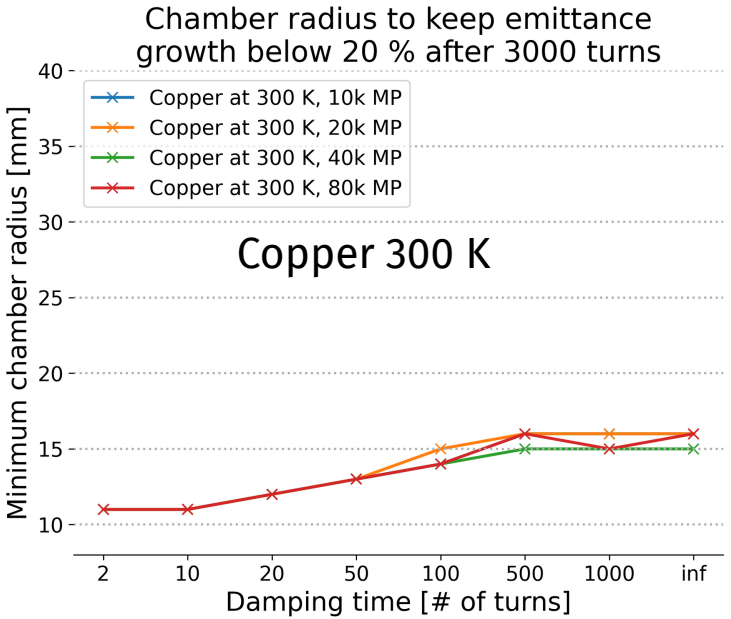
- Continue to investigate the interplay of beam-beam and impedance
  - Currently performing cross-check between tracking simulations and Circulant Matrix Model formalism (BimBim code)
  - Include the damper effect
  - Simulate the effect the effect of chromaticity, without and with beam-beam

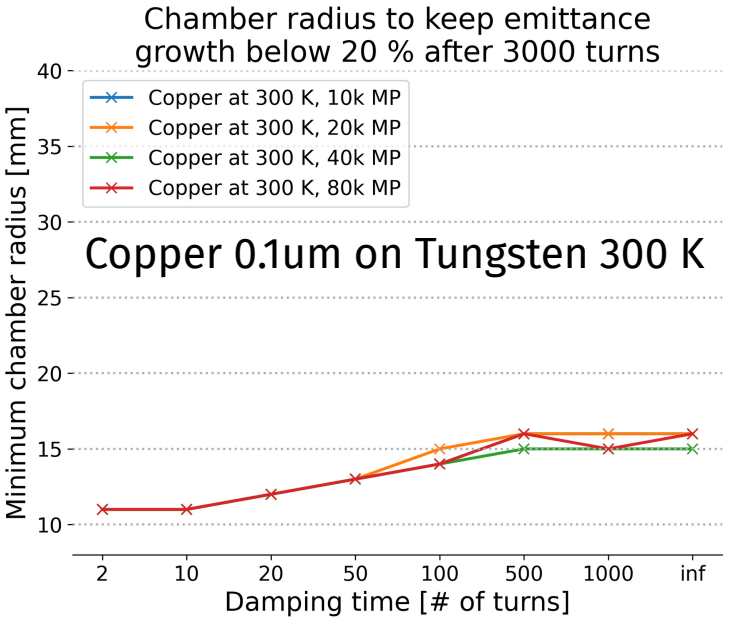
International MUON Collider Collaboration

Thank you for your attention

Check convergence versus number of macroparticles

- Simulation with a 10k, 20k, 40k or 80k, for a given material
- Similar results obtained with 40k and 80k macroparticles → the 50k macroparticles used in simulations should be converged





Beam-beam modes and transverse instabilities

- Two beam-beam modes (π and σ), can interact with headtail modes when impedance is present
- See S. White, X. Buffat et al. PRAB 17 041002

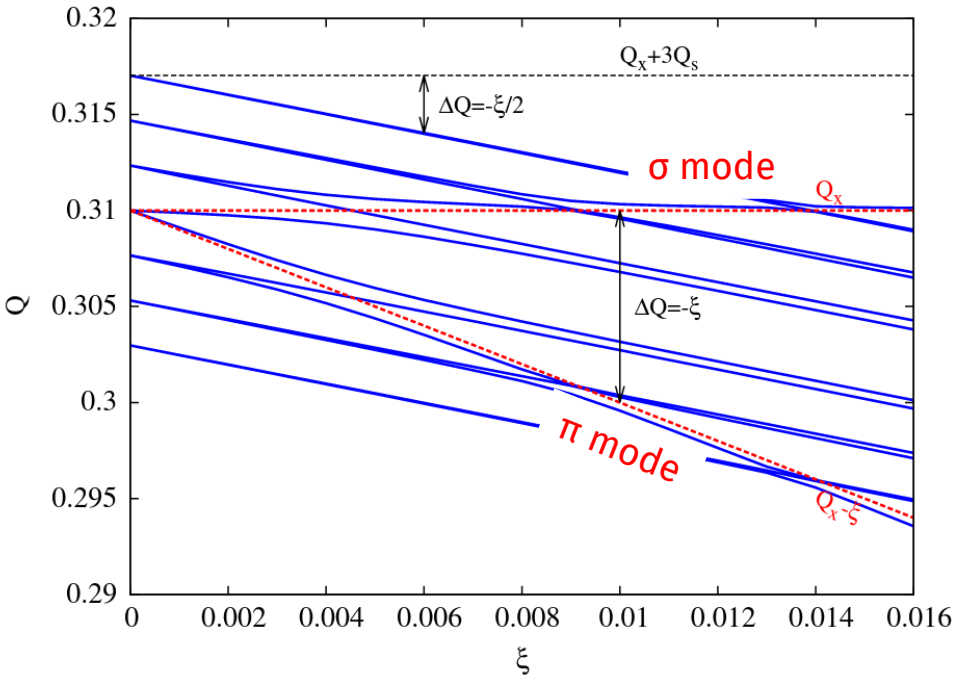
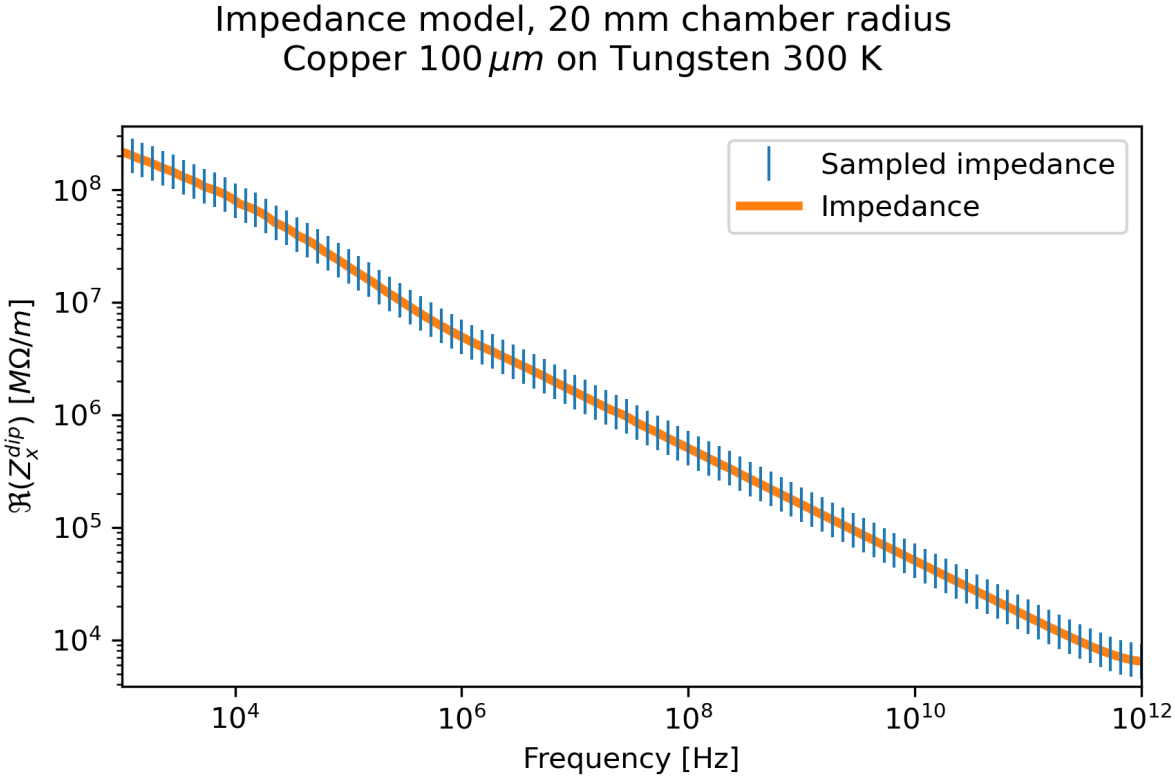


FIG. 1. Synchro-betatron modes as a function of the beam-beam parameter for $Q' = 0.0$ and $\beta^*/\sigma_s \approx 1$. Impedance was not included in this case. The σ and π modes in the 4D case are shown in red. Q_x is the unperturbed betatron tune and Q_s is the synchrotron tune.

Main hypothesis for the study: Impedance model

- For stability studies, use **copper coated tungsten**
  - 20 mm radius, 10 km long chamber
- For some simulations (Analytic and Vlasov solver), the impedance model is downsampled (blue markers on the plot)



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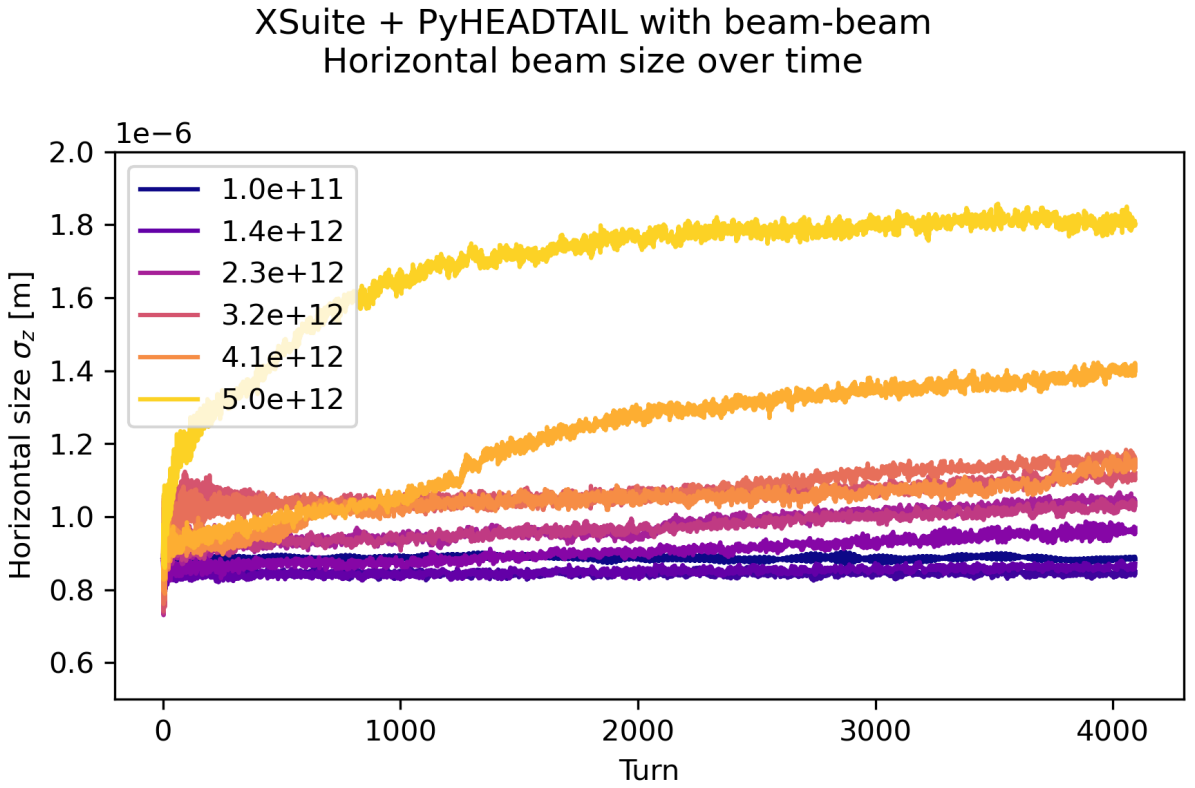
- But a transverse size σ_x growth can be observed over time
- It is significant only for very large intensities > 3e12