Update on transverse collective effect studies for the 10 TeV collider: without and with beam-beam

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Summary

- Introduction and simulation setup
- First results of beam-beam studies

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Previous studies

- Two IPAC 2023 proceedings on transverse beam stability studies
  - Transverse Impedance and Beam Stability Studies for the Muon Collider RCS
  - Transverse Impedance and Beam Stability Studies for the Muon Collider Ring
- Impedance model studies for the 10 TeV Collider
  - Studied impact of various materials at different temperature
  - See presentations at HEMAC meeting series (18 Apr. 2023, 2 May 2023)

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

International MUON Collider Collaboration

- 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	2.82e-15
Muon	1.36e-17
Proton	1.53e-18

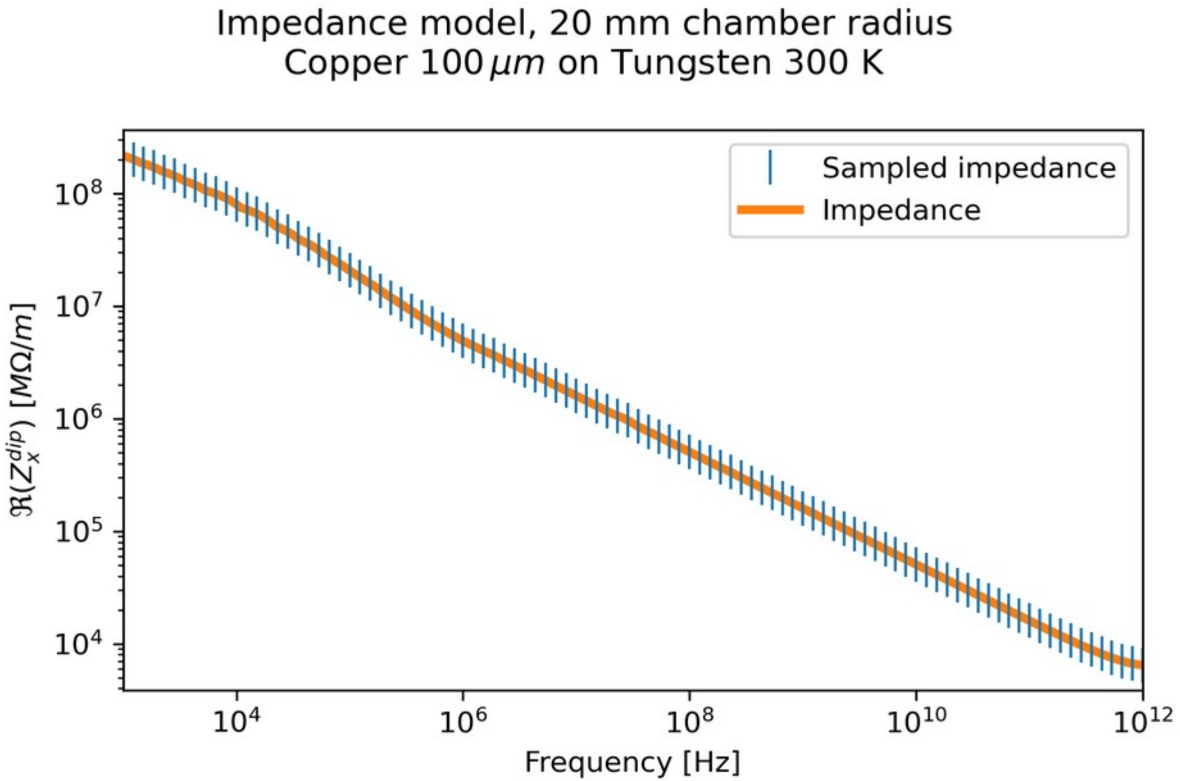
Main hypothesis for the study

International MUON Collider Collaboration

- Assume the chromaticity is corrected to zero **Q'_x=Q'_y=0**
- No detuning from octupoles, no transverse damper
- **Muon decay**, and subsequent intensity loss, **not included**
- **Single beam impedance** considered (equivalent to bunches traveling in separate chambers)
- Perform a **scan in bunch intensity**, from 1e11 to 5e12
  - Allows to check the transverse mode coupling instability threshold for the chosen impedance model
  - Compare different simulations techniques (particle tracking, analytic estimates, Vlasov solver)

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)



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

Collider parameters used

Machine parameters

	Unit	Value
Circumference	m	10000
Rel. gamma		47323
Rev. frequency	kHz	~30
RF frequency	MHz	1300
Harmonic number		43363
RF voltage	MV	1600
α_p		-2e-6
Avg. beta x/y	m	85 / 51
Tunes Qx/Qy		18.26/31.26
Chromaticity Q'_x/Q'_y		0 / 0
Detuning from octupoles x/y	m^{-1}	0 / 0

	Unit	Value
Synchrotron tune Q_s		2.12e-3
Synchrotron period	turns	471
Bunch length 1σ	**mm**	**1.5**
Bunch intensity	**Particles per bunch**	**1.8e12**
ε_x / ε_y	**µm rad**	**25**
Number of IPs		**2**
β* at IP	**mm**	**1.5**
# of macroparticles		10000

Impedance model: 20mm radius, Tungsten at 300 K with 100um copper coating

Scanned parameters

	Value
Bunch intensity	**1e11 to 5e12**

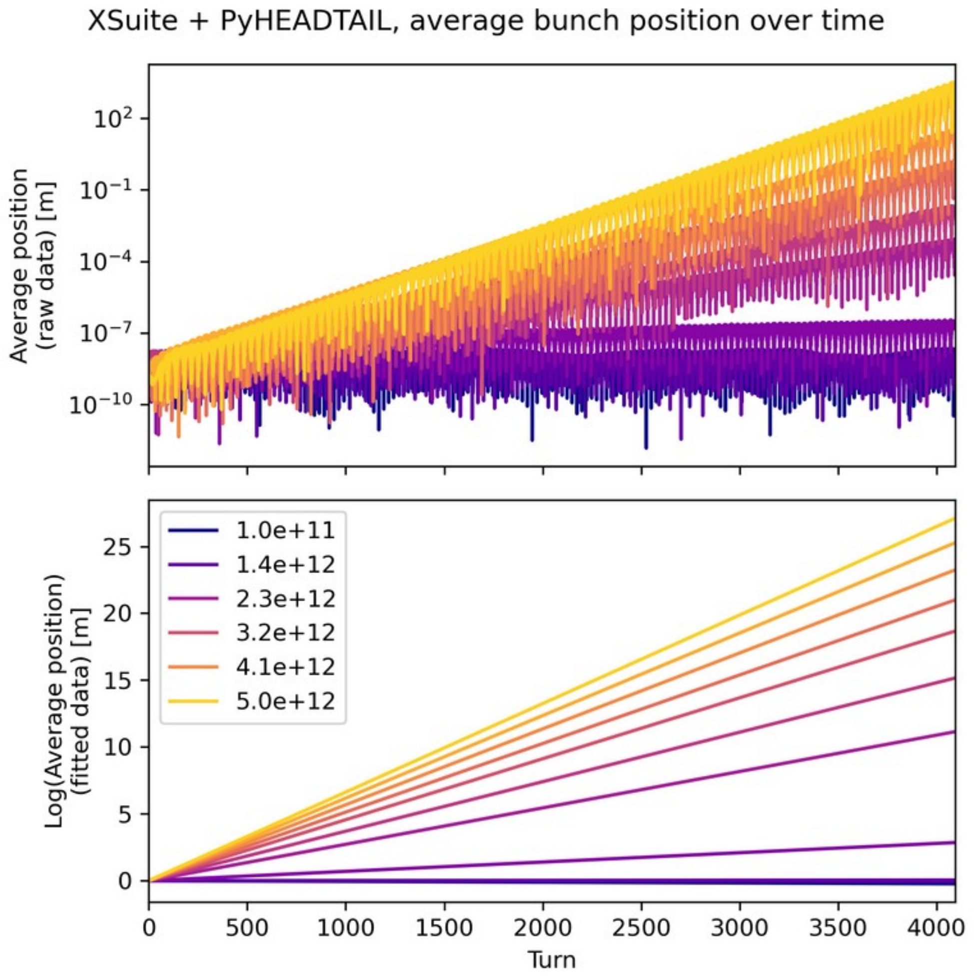
Summary

- Introduction and simulation setup
- First results of beam-beam studies

Beam tracking results, without beam-beam

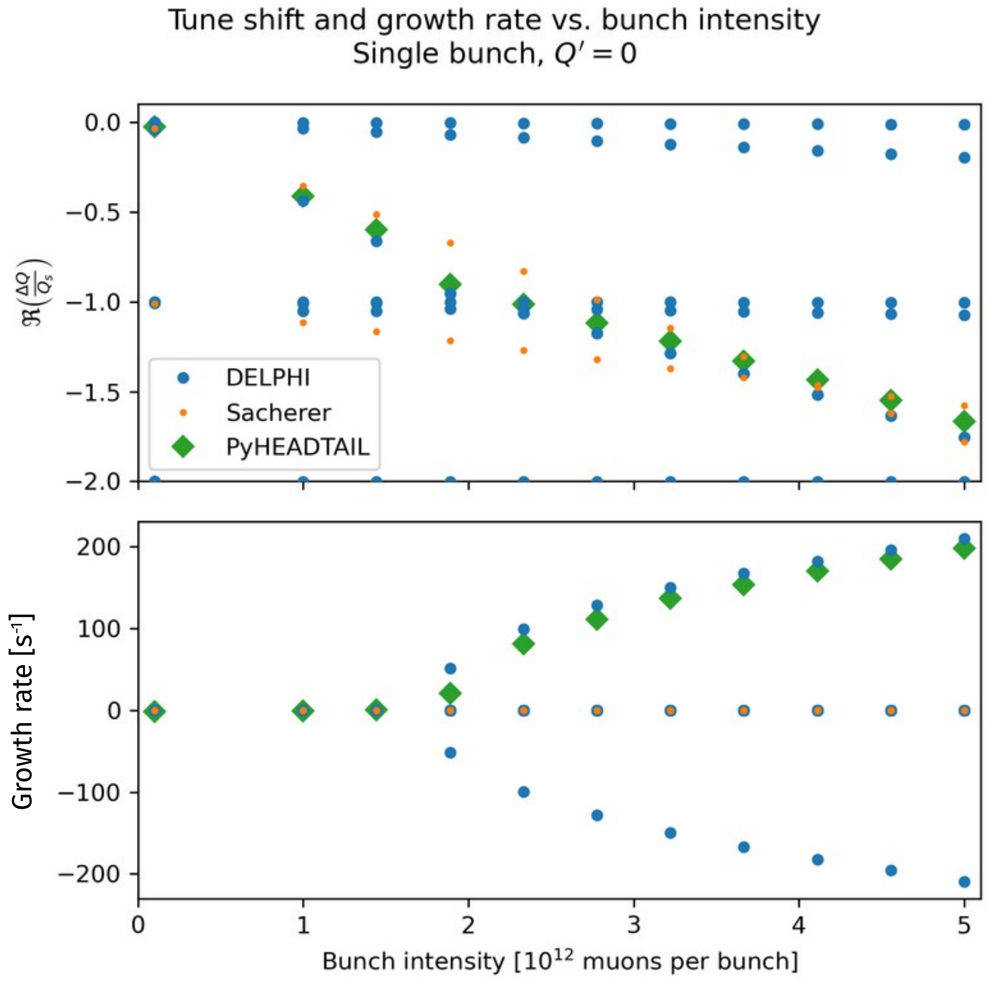
- Clear instability signal in tracking for bunch intensities > 2e12

- Perform FFT or Harmonic analysis with PyNAFF of the position signal provide the bunch tune



Tune shift versus intensity result, without beam-beam effect

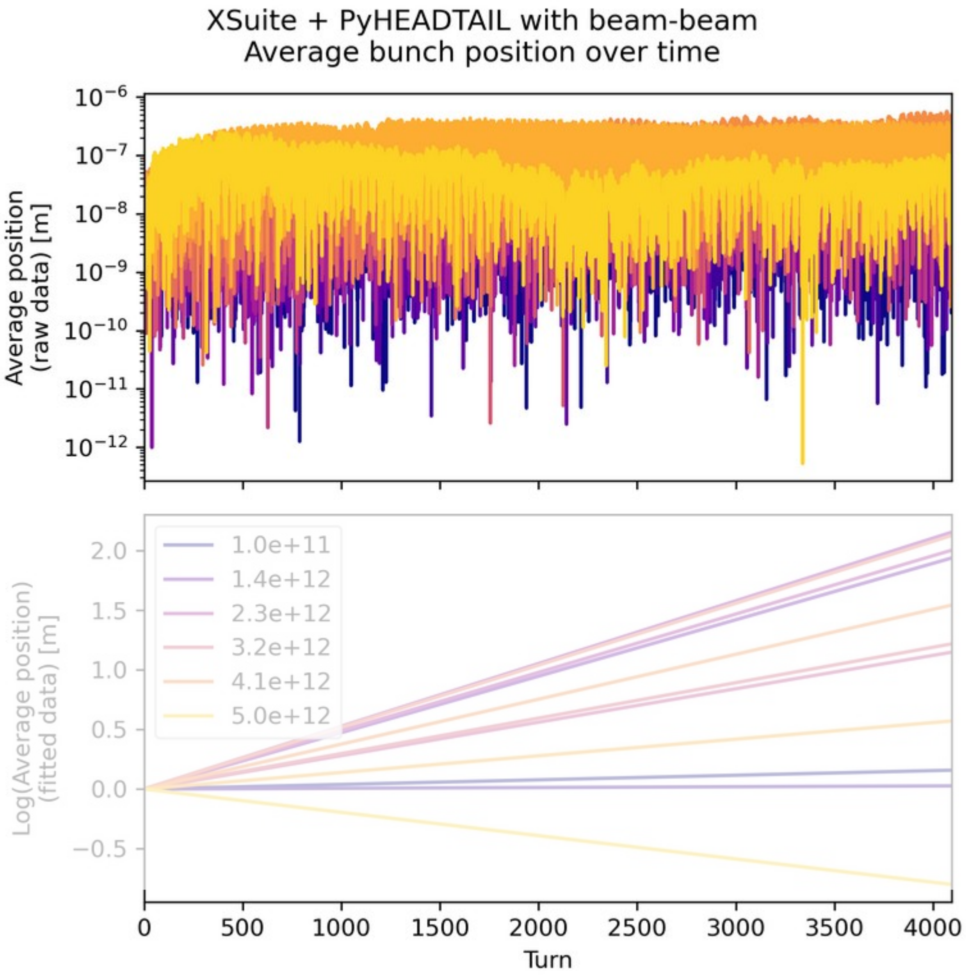
- Similar results between DELPHI (blue dots) and Tracking (green diamonds)
  - Mode coupling **instability** at **~1.8e12** muons per bunch
  - Similar to the nominal bunch intensity of 1.8e12 at injection
  - But **effect of muon decay is not included →** over time, the beam would becomes **less sensible to collective effects**



Beam tracking results, including beam-beam

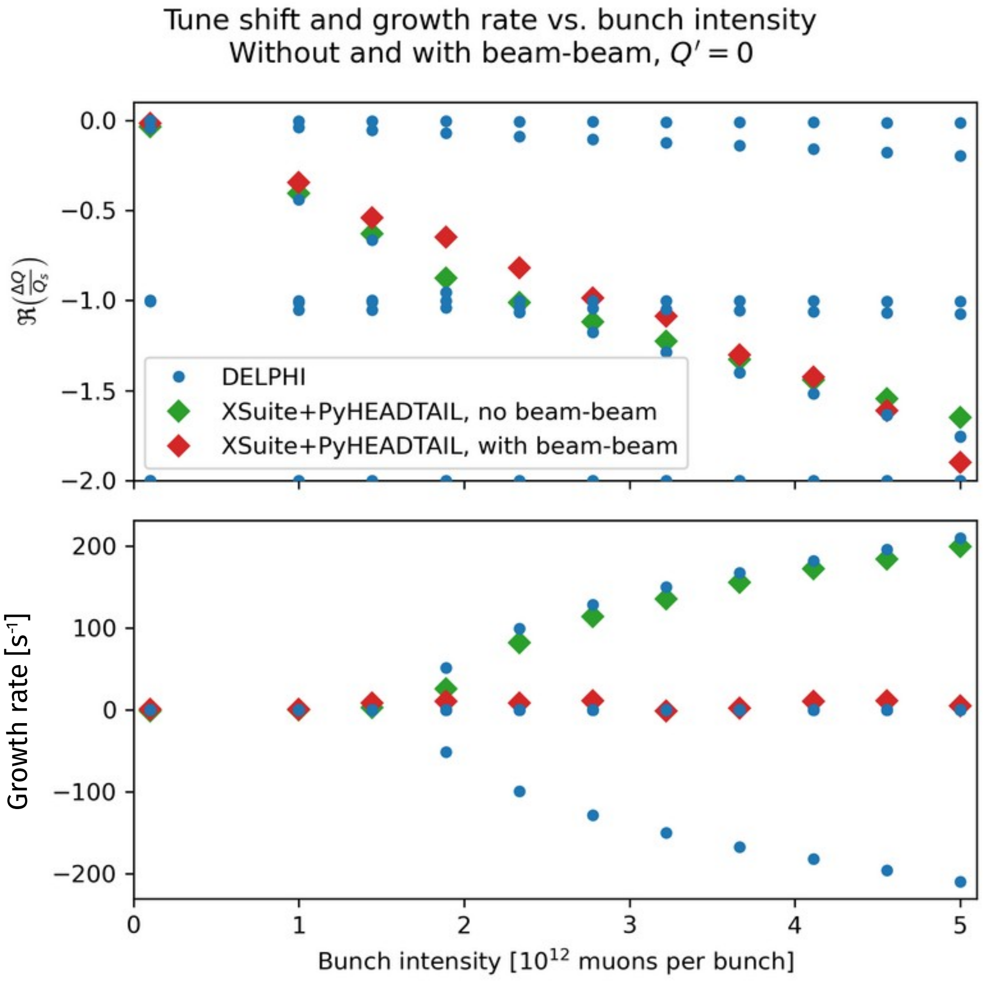
- No large transverse position excursions, compared to the case without beam-beam

- Growth-rate fit (bottom plot) are not a good indicator



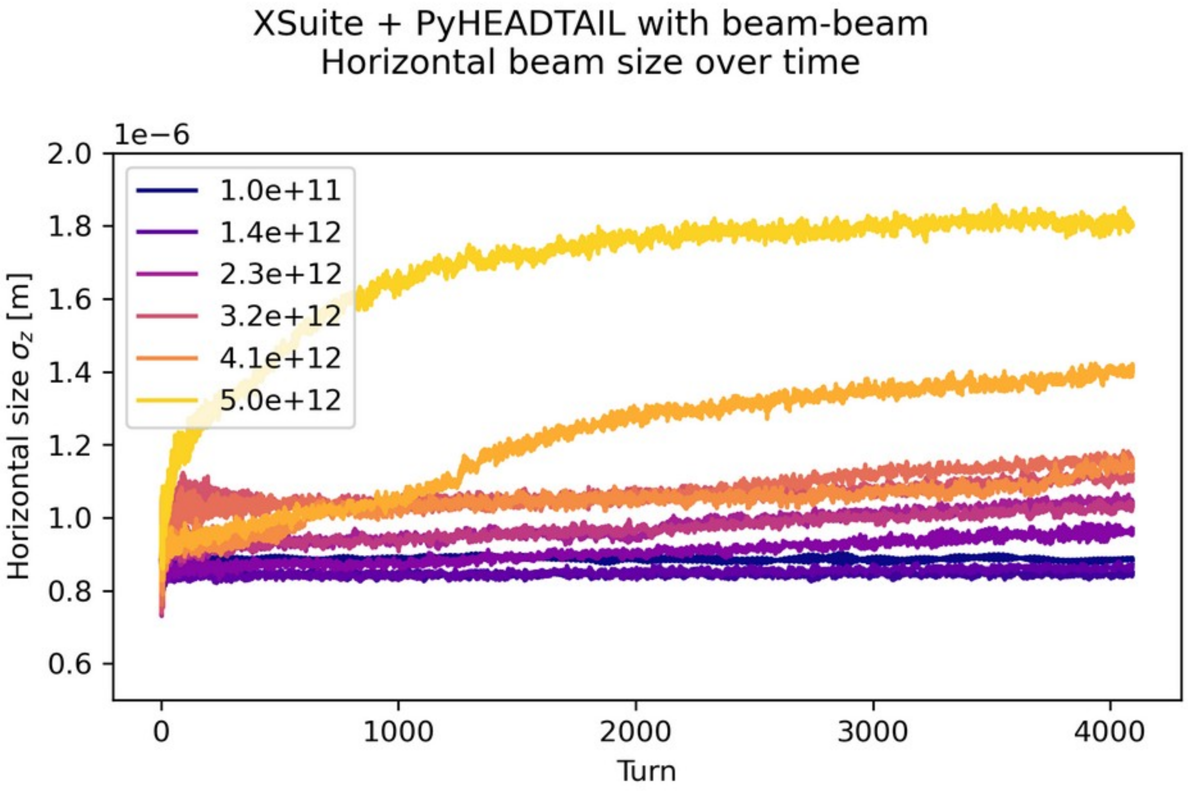
Tune shift versus intensity result, including beam-beam effect

- 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 appear suppressed in simulations
  - This should be checked with Circulant Matrix Model (CMM)



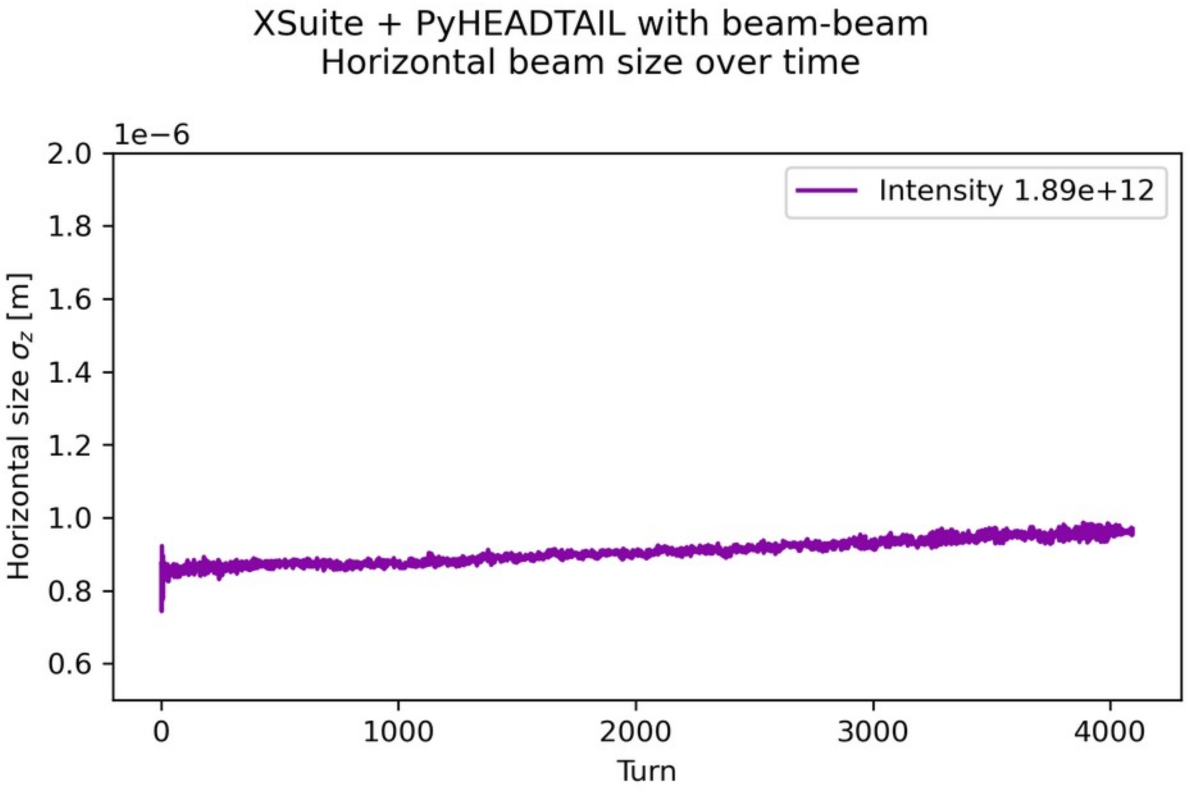
Transverse beam size evolution with beam-beam effect

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



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



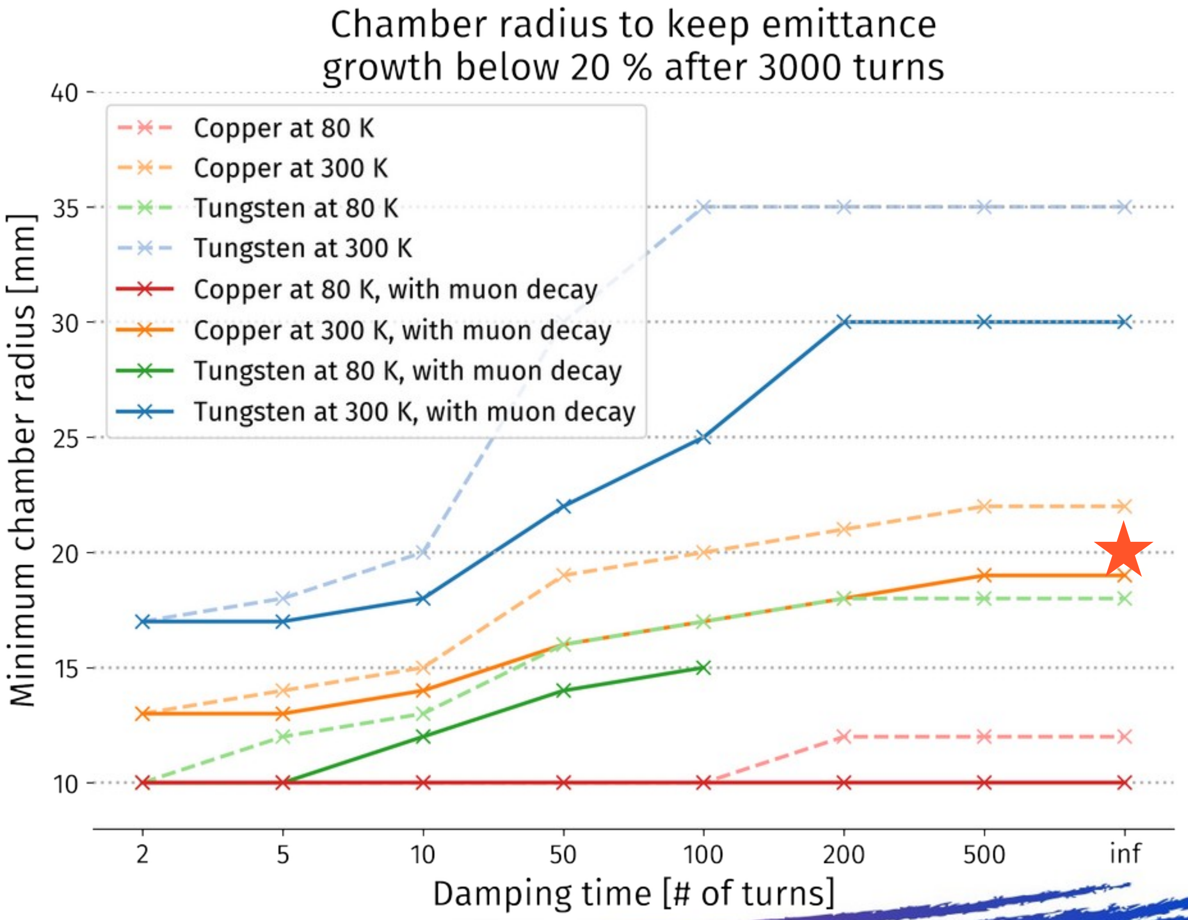
Next steps

- Investigate in more details the beam-beam effects
  - Cross-check tracking simulations with beam-beam results with Circulant Matrix Model formalism (BimBim code)
  - Investigate interplay of beam-beam, impedance and damper
  - Simulate the effect of chromaticity
- Include the two beam impedance effects
  - For example, beam induced heating can be a factor 4 larger compared to single beam heating
- Perform the simulations for the RCS
  - Investigate effect of beam separation at the crossing points on stability, check if a separation scheme is required at all

Thank you for your attention

Previous studies: minimum chamber radius versus material

- With a 20 mm copper chamber, without damper, a 20 mm chamber is close to instability



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

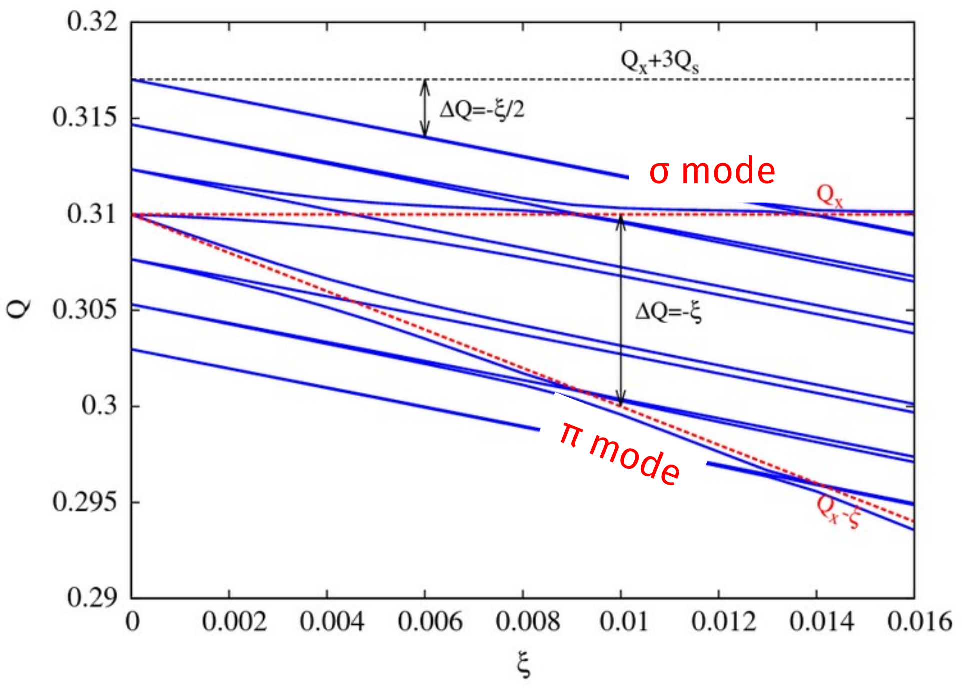


FIG. 1. Synchro-betatron modes as a function of the beam-beam parameter for $Q' = 0.0$ and $\beta^*/\sigma_s \approx 1$. Impedance was not included in this case. The σ and π modes in the 4D case are shown in red. Q_x is the unperturbed betatron tune and Q_s is the synchrotron tune.