3TeV collider transverse beam stability studies

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General design meeting
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Goal and scope of the study

- Get a first estimate of the vacuum chamber radius achievable w.r.t transverse beam stability

- Investigate different materials for the chamber

- Important input for the magnet design
  - Chamber radius is an input for the radial build model (see L. Bottura presentation https://indico.cern.ch/event/1162890/)

Assumptions and simulation parameters

Impedance simulations parameters

- 1.5 TeV per beam, 4.5 km long beam chamber
- Scan the chamber radius from 10 mm to 40 mm
- Scan also the chamber material

Machine parameters

	Unit	Value
Circumference	m	4500
Chamber length	m	4500
Chamber geometry		Circular
Chamber material		Tungsten 300 K / Tungsten 80K Copper 300 K / Tungsten 20 K
Chamber thickness	m	Inf.
Chamber radius	mm	10 to 40
Avg. beta x/y	m	100 / 100

Impedance simulations parameters: materials

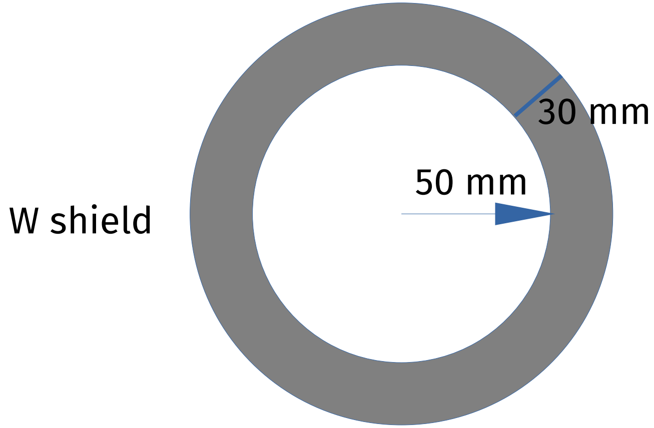
- Past Muon collider studies suggested to use a tungsten liner to intercept muon decay products
  - Decrease the heat load and radiation dose sustained by the magnets
  - Proposal for a liner cooled at 80 K by N. V. Mokhov et al.
  - Also proposal for a tungsten liner at 300 K, see M. Green
- Impedance and stability simulations with four materials: Copper at 300 K, Copper at 20 K, Tungsten at 80 K, Tungsten at 300 K

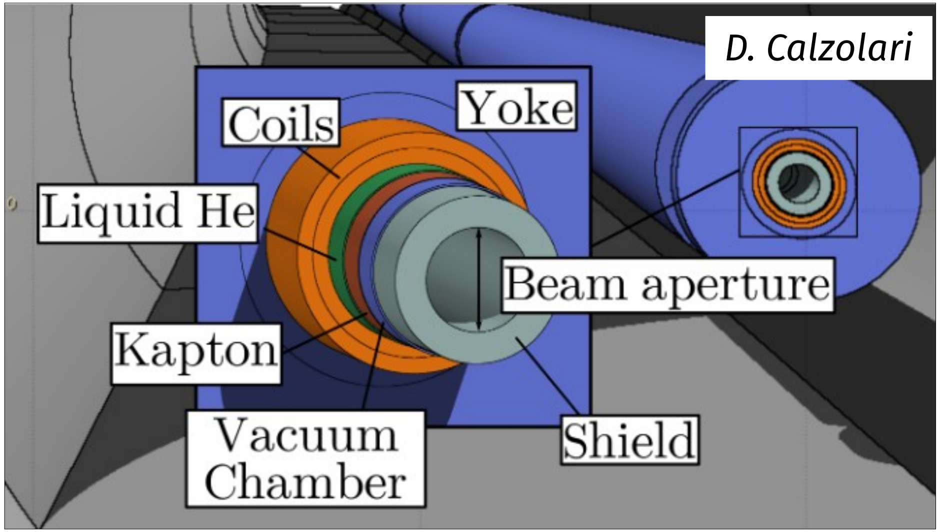
Liner design to protect from decay product

- Power deposition and radiation damage studies done by D. Calzolari et al., presented at IPAC 22

- 30 mm thick, 50 mm inner radius, tungsten shield

- Shield temperature not yet defined





Liner design to protect from decay product

Liner thickness varies according to magnet type and family

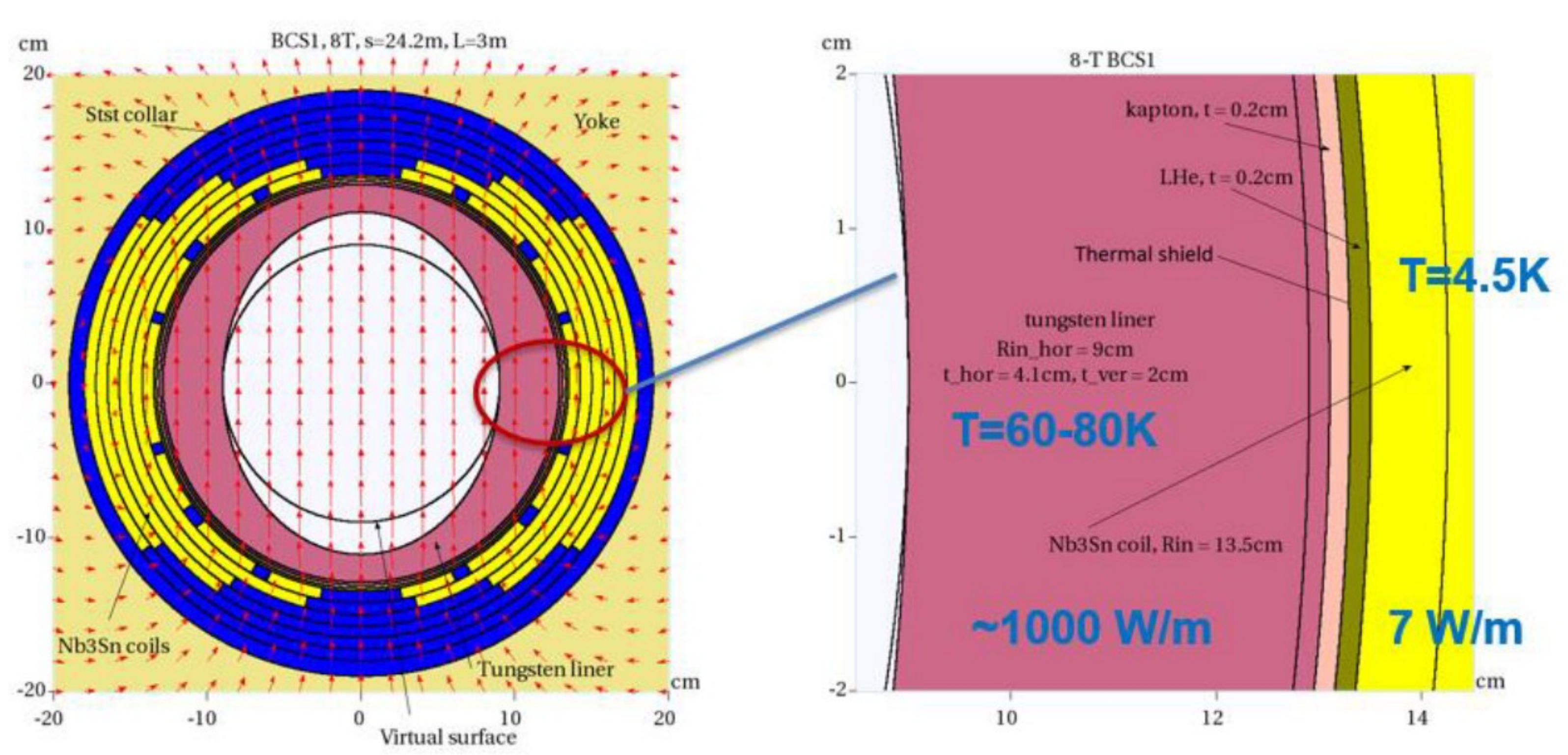


Figure 8. Elliptical tungsten liner inside BCS1 8 T dipole.

Tungsten liner design from N. V. Mokhov et al.

Impedance simulations parameters: materials

- Infinite thickness for all the chambers simulated

Copper at 20 K

	Unit	Value
Magnetic field	T	7
Temperature	K	20
RRR		70
DC resistivity	nOhm m	0.667

Copper at 300 K

	Unit	Value
Magnetic field	T	7
Temperature	K	300
RRR		70
DC resistivity	nOhm m	17.9

Tungsten at 80 K

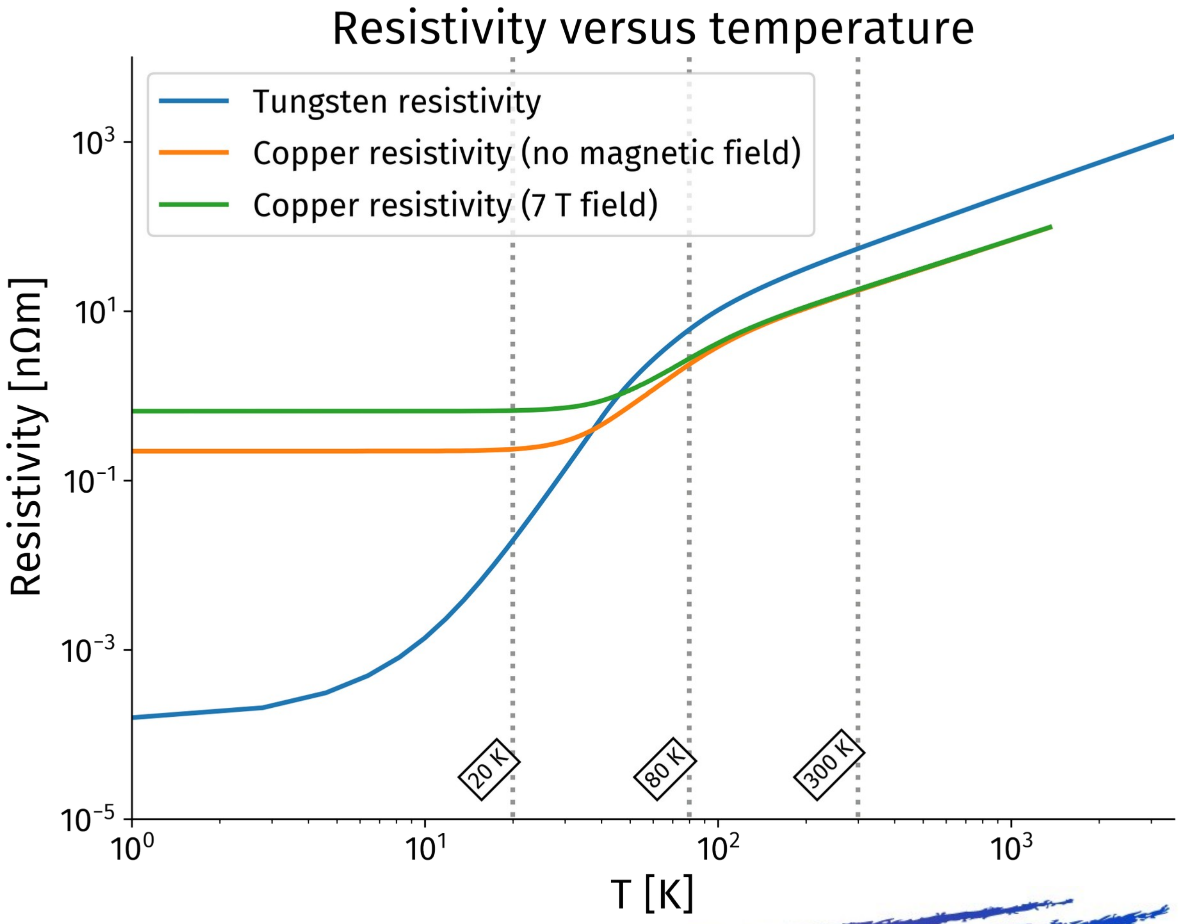
	Unit	Value
Temperature	K	80
DC resistivity	nOhm m	6.06

Tungsten at 300 K

	Unit	Value
Temperature	K	300
DC resistivity	nOhm m	54.4

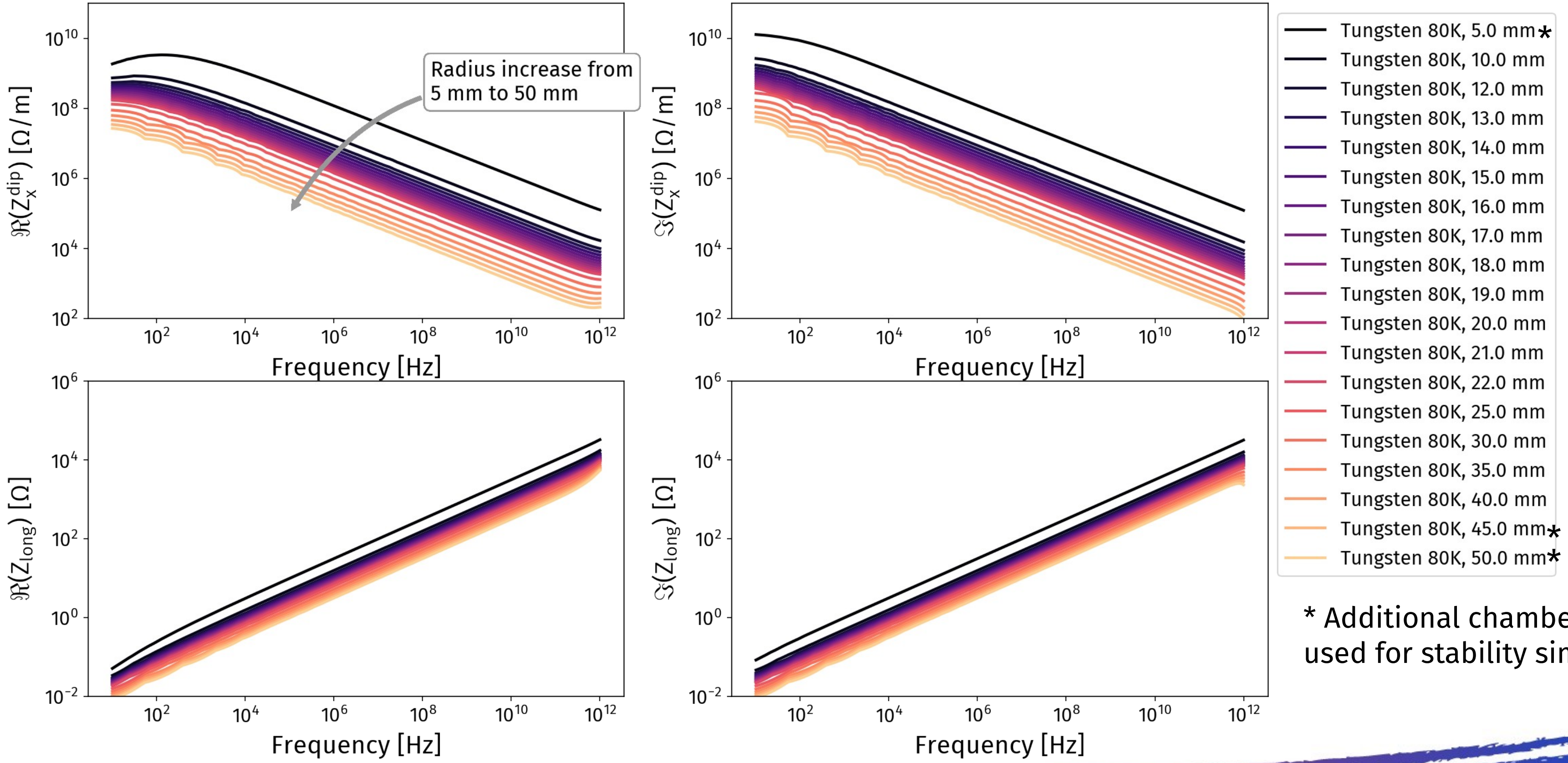
Impedance simulations parameters: materials

- Resistive wall impedance and wake are proportional to √ρ
- Copper resistivity versus temperature and magnetic field
  - Simon, Drexler and Reed “Properties of copper and copper alloys at cryogenic temperatures”, 1992
- Tungsten resistivity versus temperature
  - Desai et al. “Electrical Resistivity of Selected Elements”, 1984



Impedance results for chambers in Tungsten at 80 K

Transverse resistive wall impedance depends on $1/r^3$, longitudinal resistive wall impedance depends on $1/r$



* Additional chamber radii not used for stability simulations

Transverse stability simulation parameters in the 3 TeV collider

- Simulation including longitudinal map (1 RF station) + transverse map + **transverse wakefield** + damper + optionally muon decay
- Tracking over 3000 turns, 5000 macroparticles with PyHEADTAIL, initial intensity 2.2 10^{12} muons, transverse emittance 25 **µm rad** (detailed parameters in appendix)
- **Optionally: include muon decay effect**
  - Muon lifetime at 1.5 TeV: 14285 * 2.2 us = 31.4 ms
  - Revolution frequency ~66 kHz → **muon lifetime at 1.5 TeV is ~2100 turns**

Transverse stability simulation parameters in the 3 TeV collider

- Scan the **chamber radius from 10 mm to 40 mm**
  - 5 mm radius produces too strong wakefields, numerical errors quickly occur
- Scan the transverse damper from 2 to 500-turn gain + no damper
- Horizontal and vertical planes have the same impedance (circular chamber), and same beam parameters → simulation results identical in the two planes

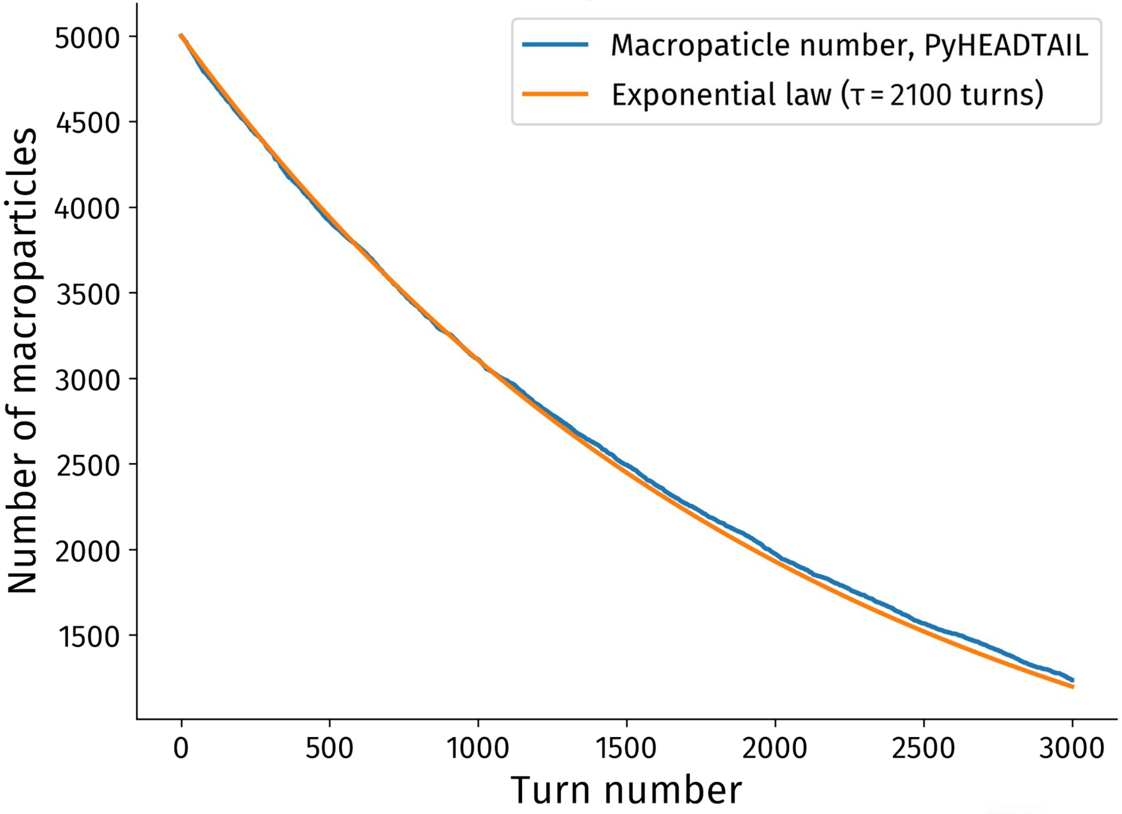
Implementation of the muon beam decay

- Decay element in PyHEADTAIL
  - Input: decay time (in number of turns) of the beam
  - Use numpy rand function to randomly select the macroparticle that will be deleted, according to the decay time

- Exponential decay behavior reproduced in simulations

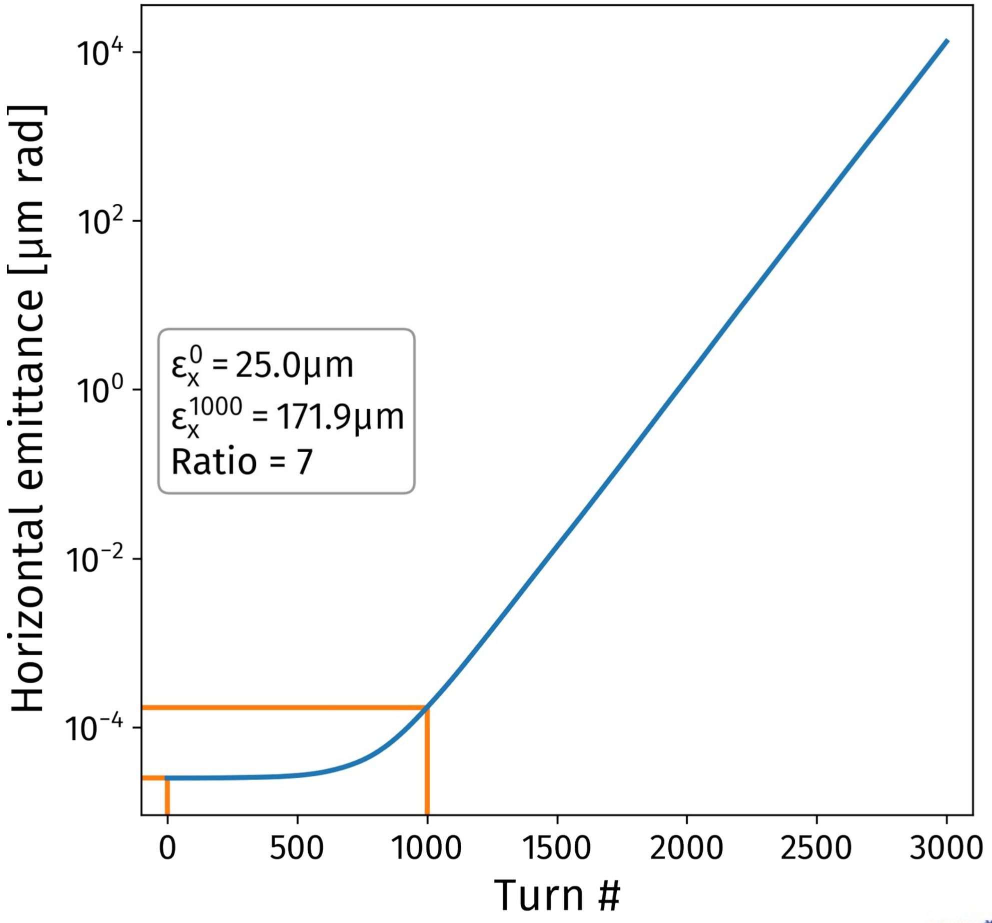
- Bunch intensity reduced by 50 % after ln(2)*2100 = 1450 turns

Comparison of macroparticle decay versus exponential law



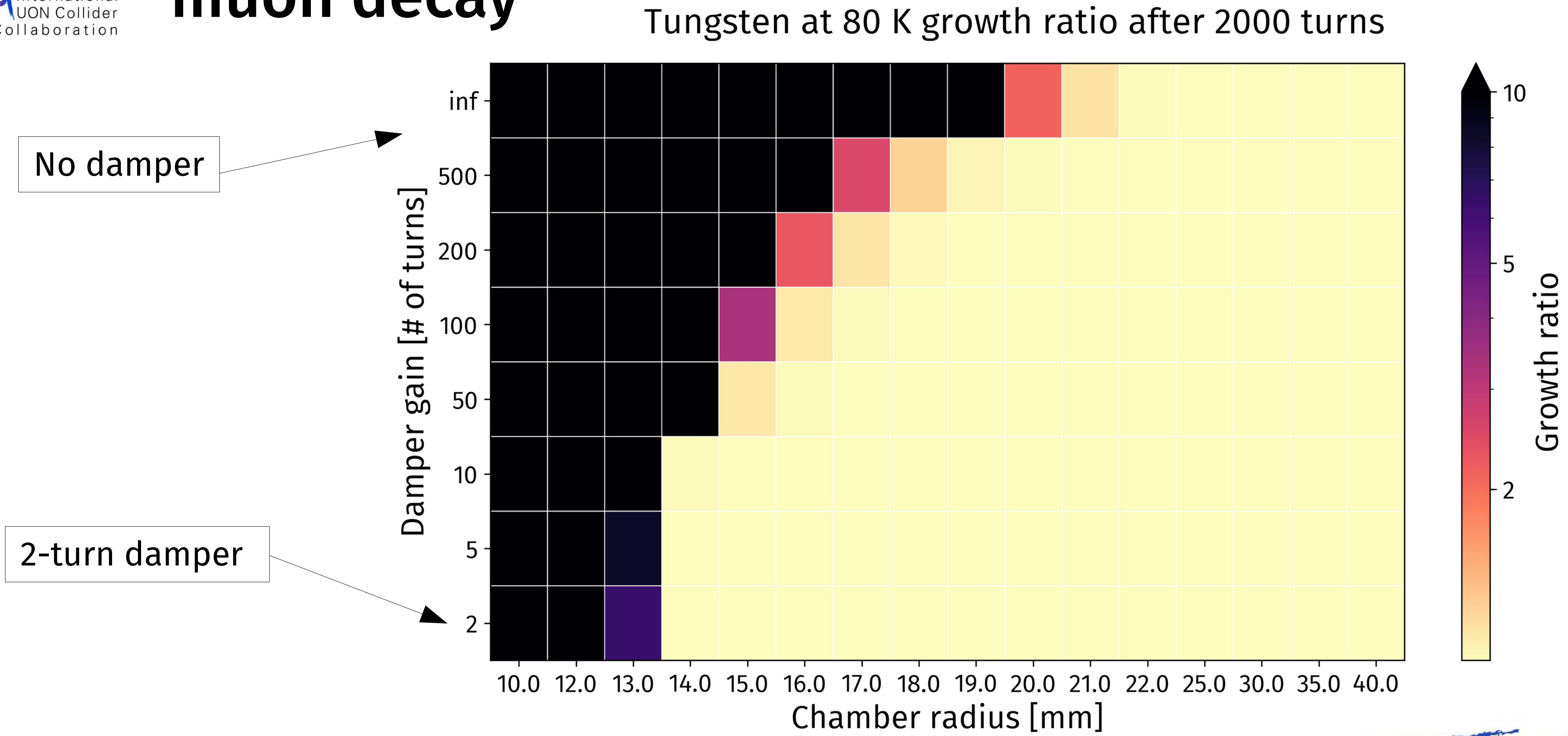
Growth ratio plots

- Compute the ratio of emittance after a certain time versus initial emittance (25 μm rad)
- For all damper settings and chamber radius, at different number of turns
- We will look at growth ratios after 2000 turns

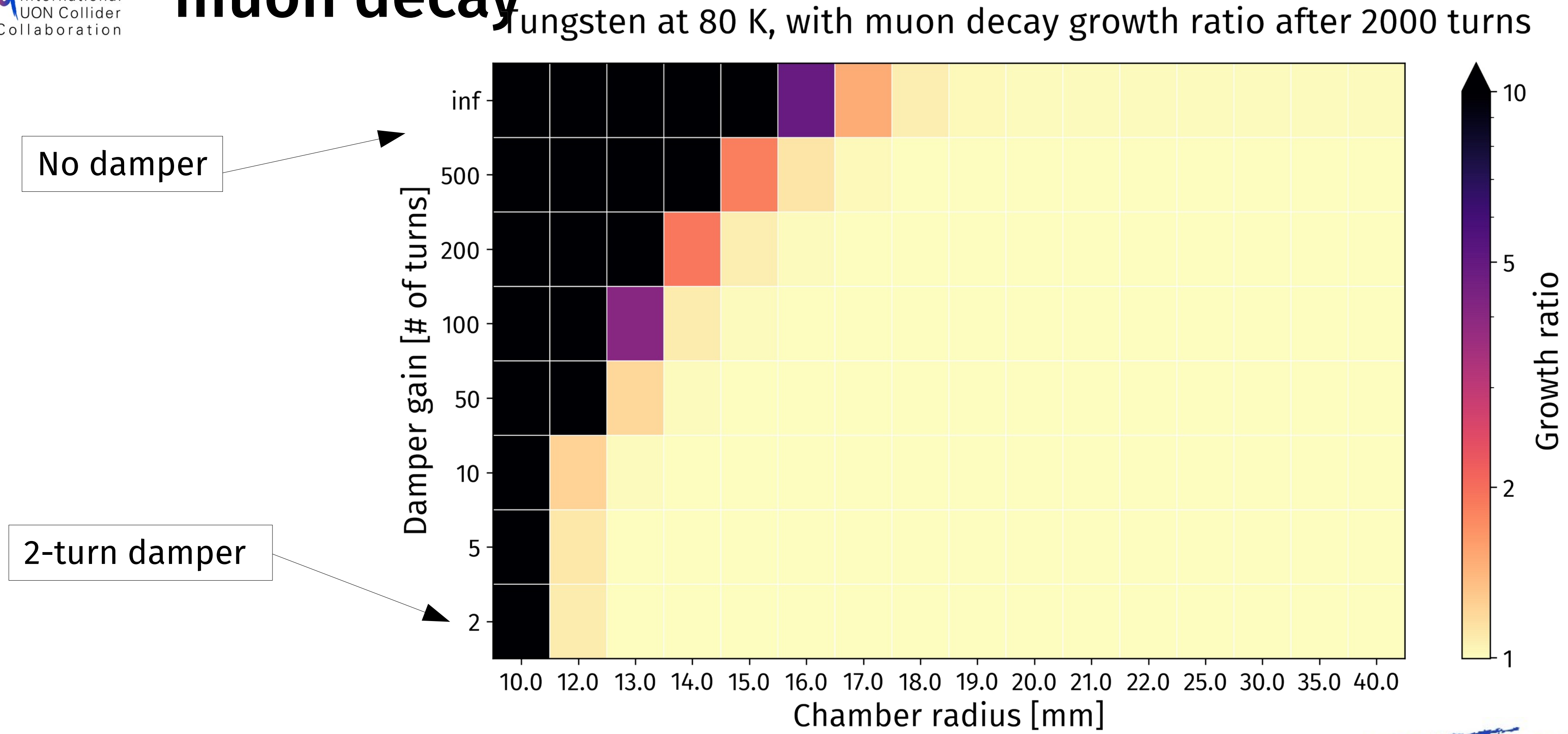


Simulation results

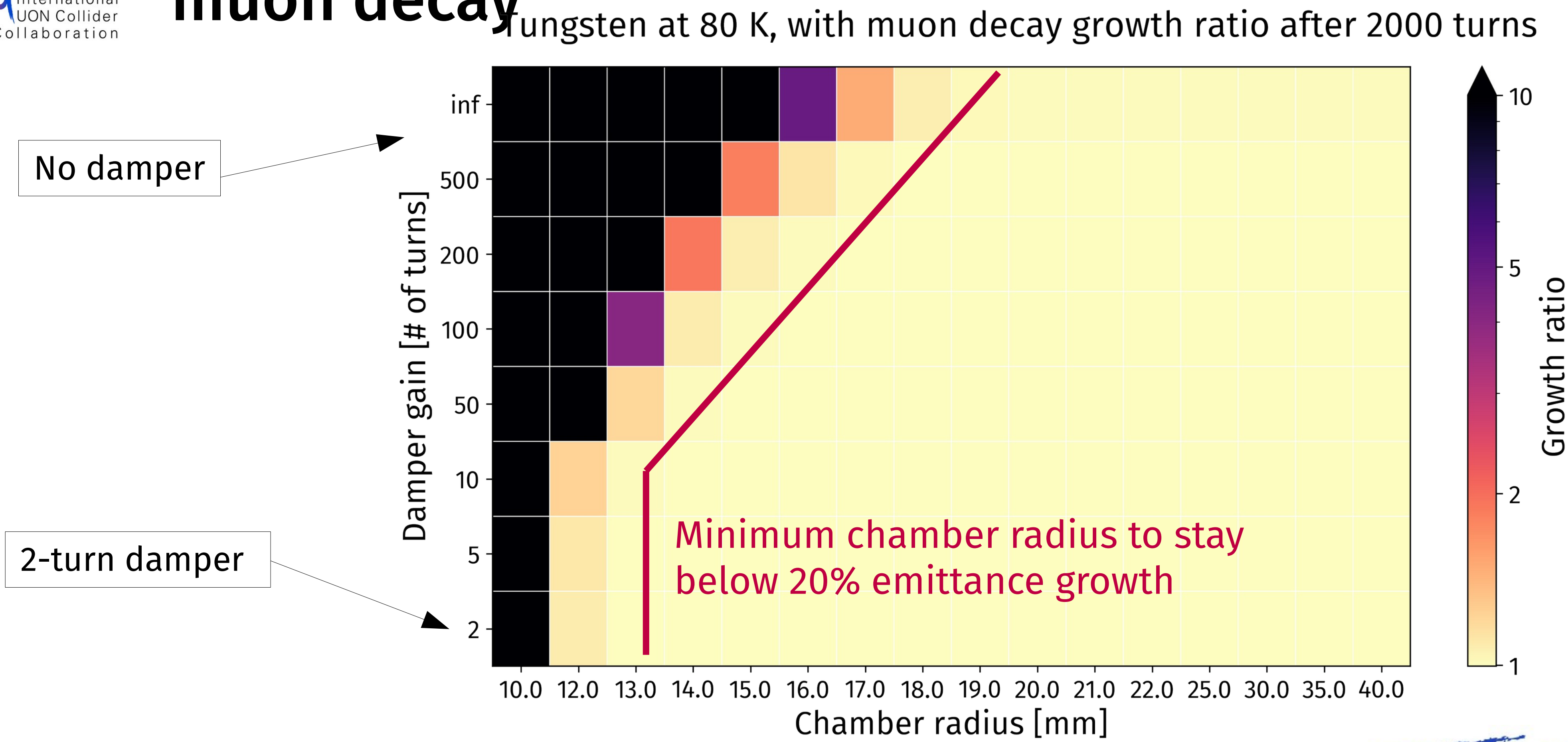
Tungsten 80 K, after 2000 turns, WITHOUT muon decay



Tungsten 80 K, after 2000 turns, WITH muon decay

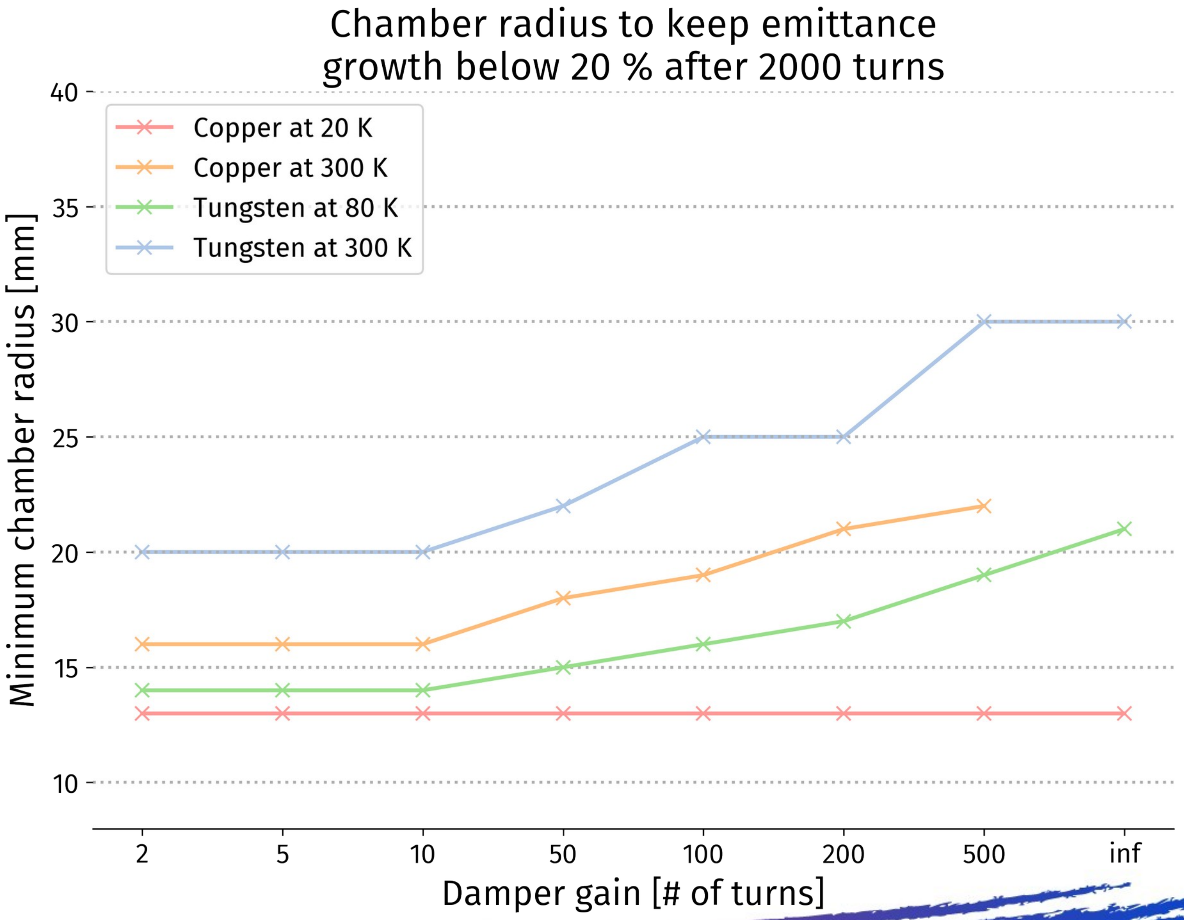


Tungsten 80 K, after 2000 turns, WITH muon decay



Minimum chamber radius versus material, without muon decay

- Summary plot for the case **without muon decay**
- For every damper gain, find the chamber radius such as the **emittance growth** stays **below 20 % after 2000 turns**
  - No point for a damper setting means that the beam was always unstable



Minimum chamber radius versus material, with muon decay

- Summary plot for the case **without and with muon decay**
- For every damper gain, find the chamber radius such as the **emittance growth** stays **below 20 % after 2000 turns**
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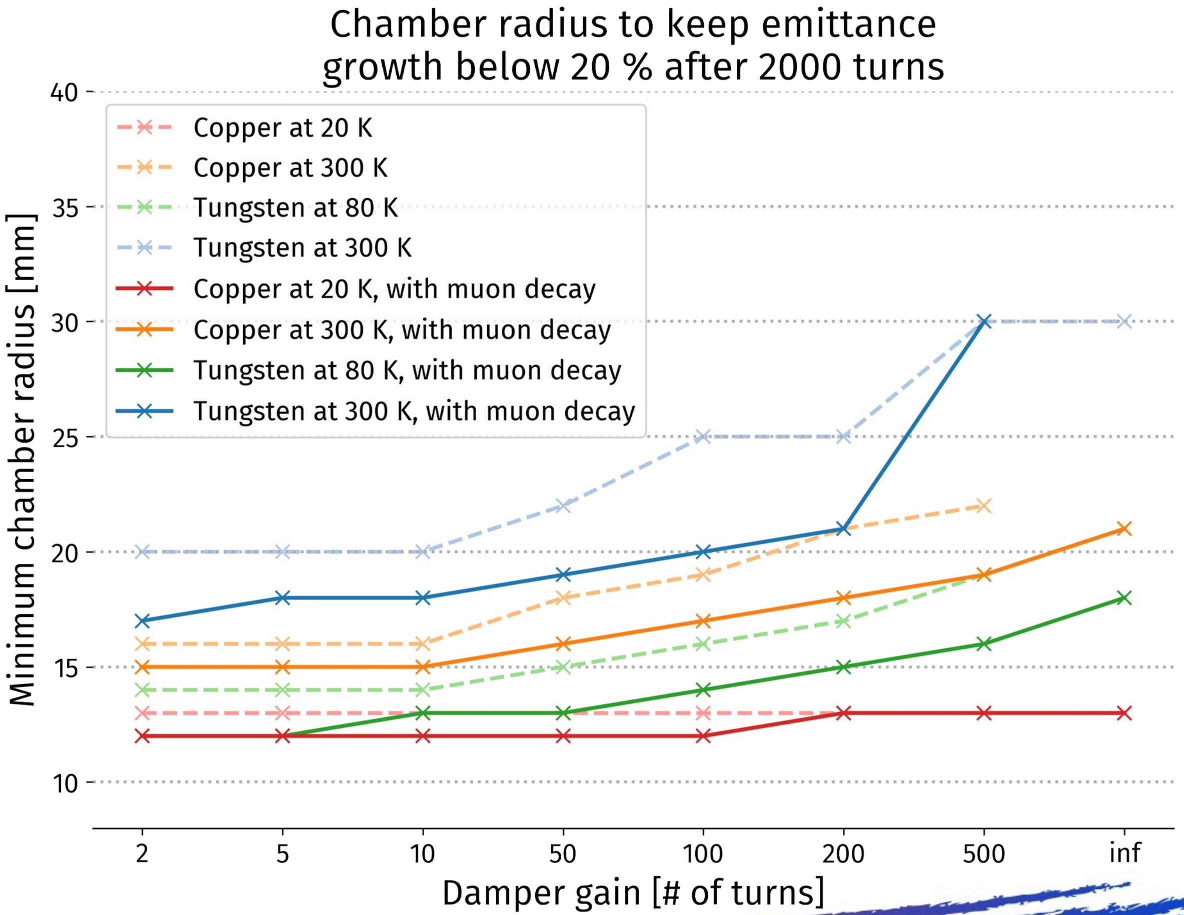


Summary of transverse stability simulation in the 3 TeV collider

International MUON Collider Collaboration

- Simulation including longitudinal map (1 RF station) + transverse map + **transverse wakefield** + damper + **optionnaly muon decay**
- Tracking over 3000 turns, 5000 macroparticles with PyHEADTAIL
- Overall, chamber radii below 18 mm are challenging damper-wise or require cryogenic material
- Radii between 20 and 30 mm allow to use all material with classic damper setting (100, 200 or 500-turn damping)
- Muon decay has a beneficial effect on transverse beam stability
  - Gain between 1 and 5 mm on chamber radius for a given material and damper setting

Possible next steps for the colliders

- Ongoing: repeat the study for the 10 TeV c.o.m collider (10 km circumference)
- Investigate more complex chamber geometries
- If we want to use tighter (< 17 mm) beam chamber, investigate supplementary mitigation measures for beam instabilities
  - Effect of sextupoles (chromaticity)
  - Effect of octupoles (tune spread to enhance Landau damping)

Appendix

Stability simulation parameters

Machine parameters

	Unit	Value
Circumference	m	4500
Beam momentum	GeV/c	1500
Rev. frequency	kHz	66
RF frequency	MHz	800
Harmonic number		12008
RF voltage	MV	250
α_p		-2.15e-6
Avg. beta x/y	m	100 / 100
Chromaticity Q'_x/Q'_y		0/ 0
Detuning from octupoles x/y	m^{-1}	0 / 0

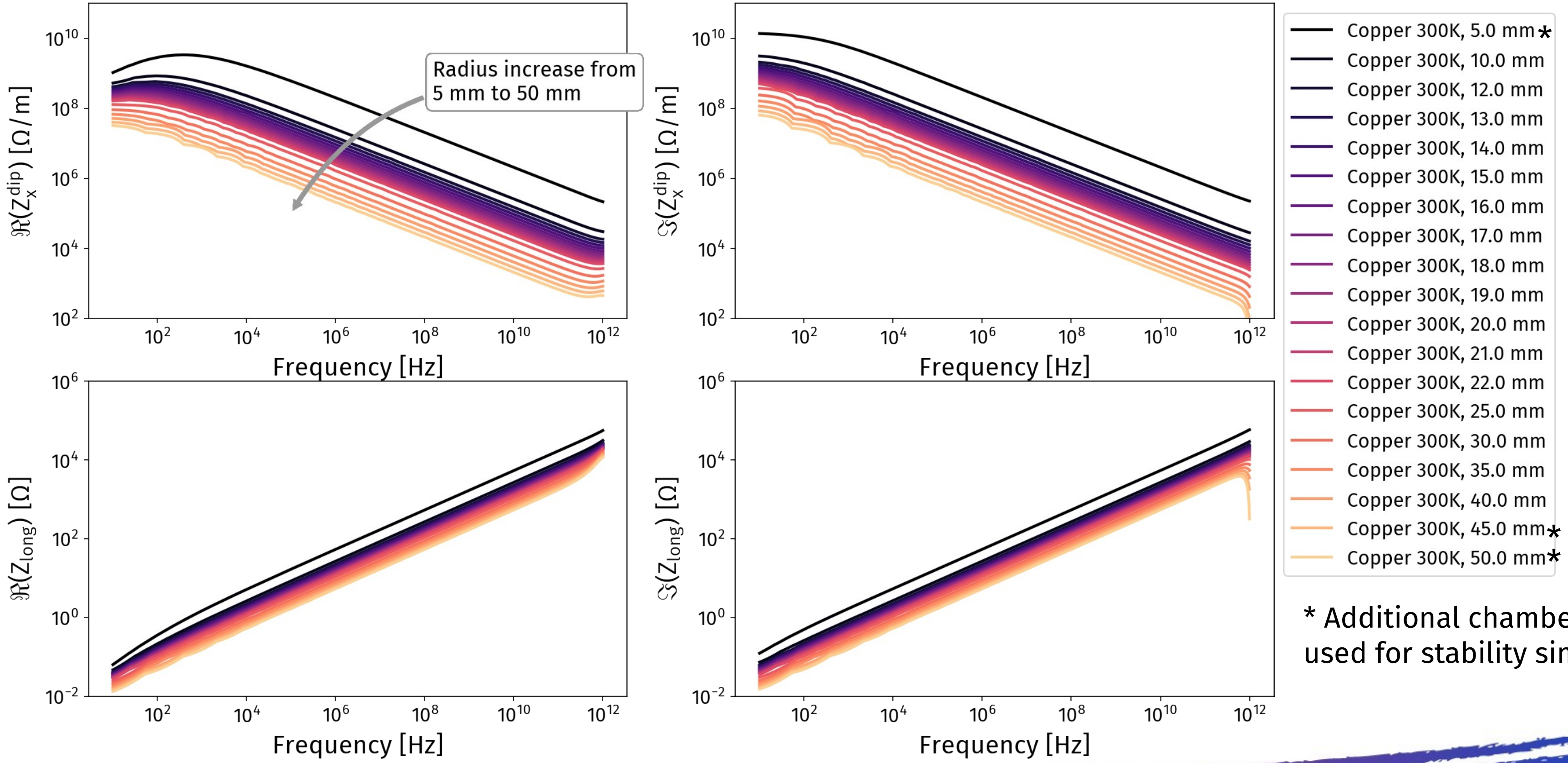
	Unit	Value
Synchrotron tune Q_s		0.000829
Synchrotron period	turns	1206
Bunch length 1σ	**mm**	**5**
Bunch intensity	**Particles per bunch**	**2.2e12**
ε_x / ε_y	**µm rad**	**25**
# of macropaticles		5000

Scanned parameters

	Unit	Value
Chamber radius	mm	10 to 40
Transverse damper		2 to 500 turns/No damper

Impedance for Copper at 300 K

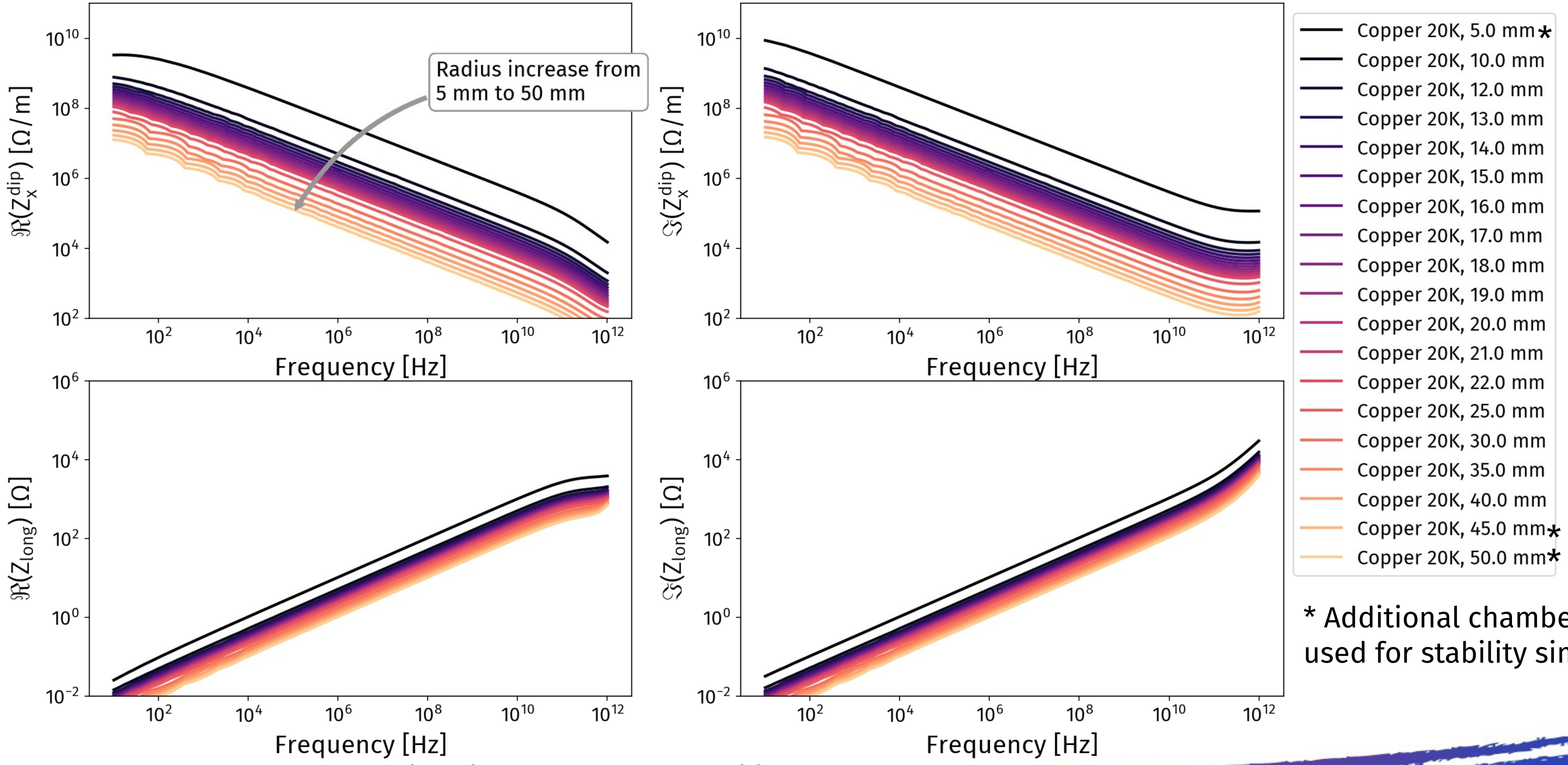
Transverse resistive wall impedance depends on $1/r^3$, longitudinal resistive wall impedance depends on $1/r$



* Additional chamber radii not used for stability simulations

Impedance for Copper at 20 K

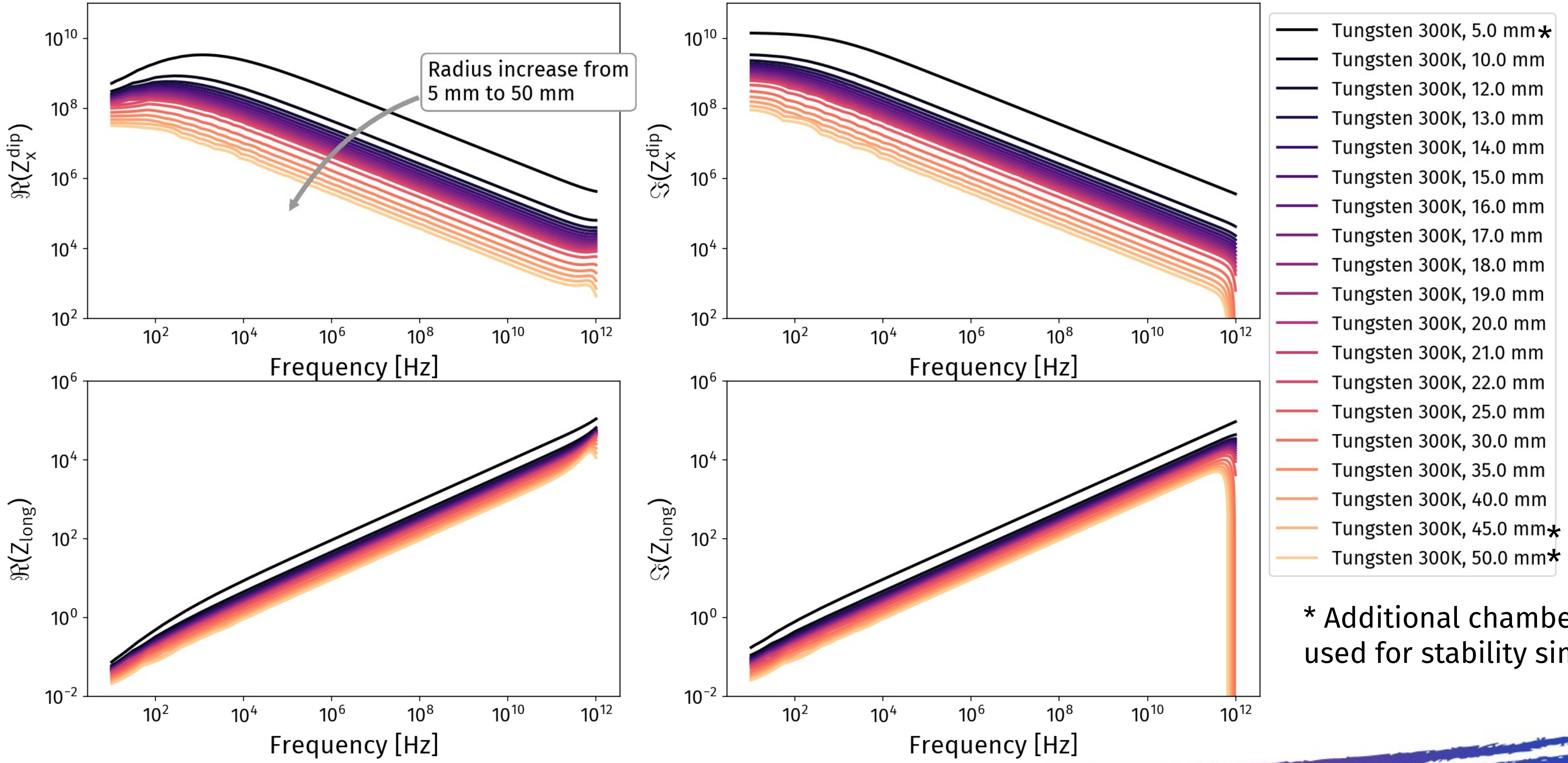
Transverse resistive wall impedance depends on $1/r^3$, longitudinal resistive wall impedance depends on $1/r$



* Additional chamber radii not used for stability simulations

Impedance for Tungsten at 300 K

Transverse resistive wall impedance depends on $1/r^3$, longitudinal resistive wall impedance depends on $1/r$



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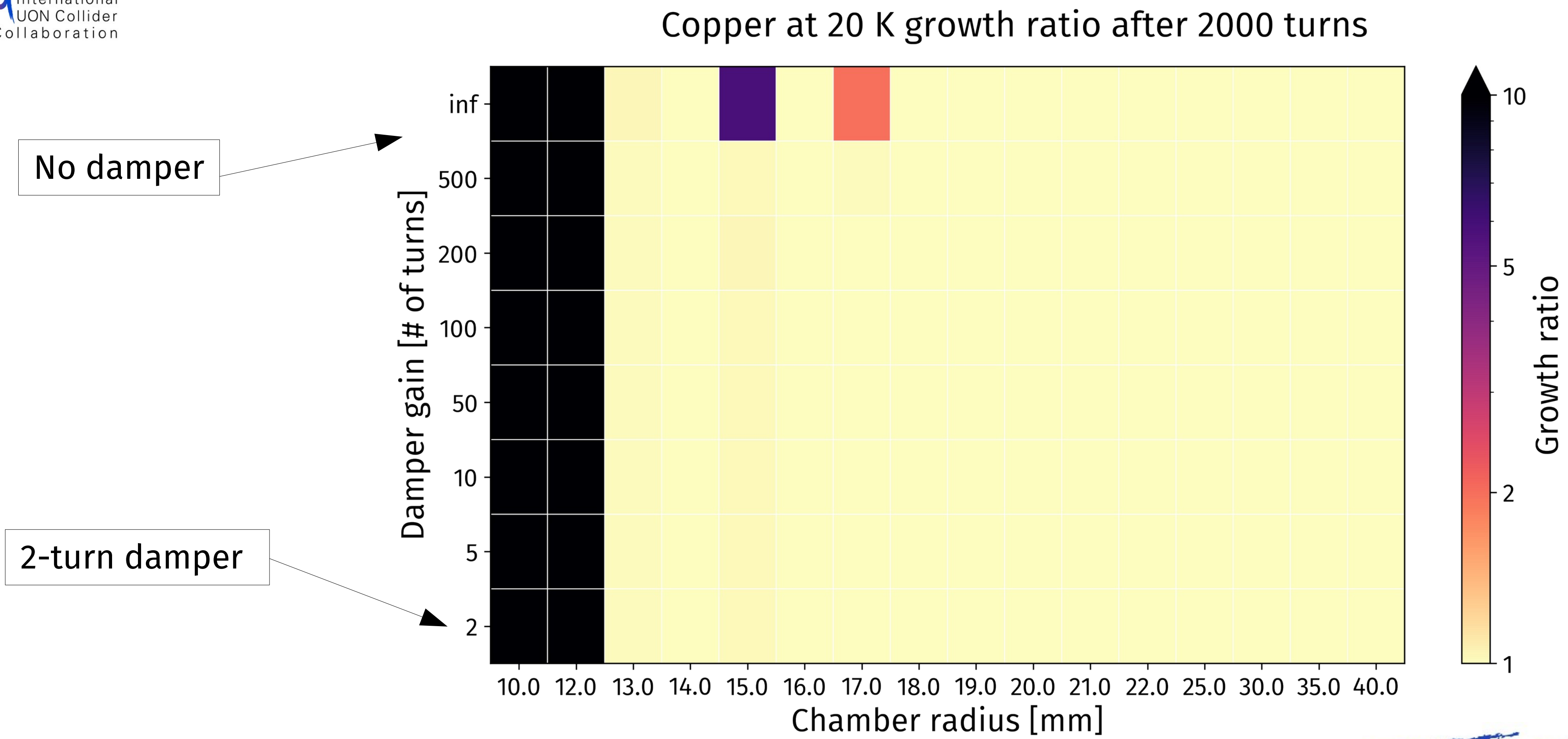
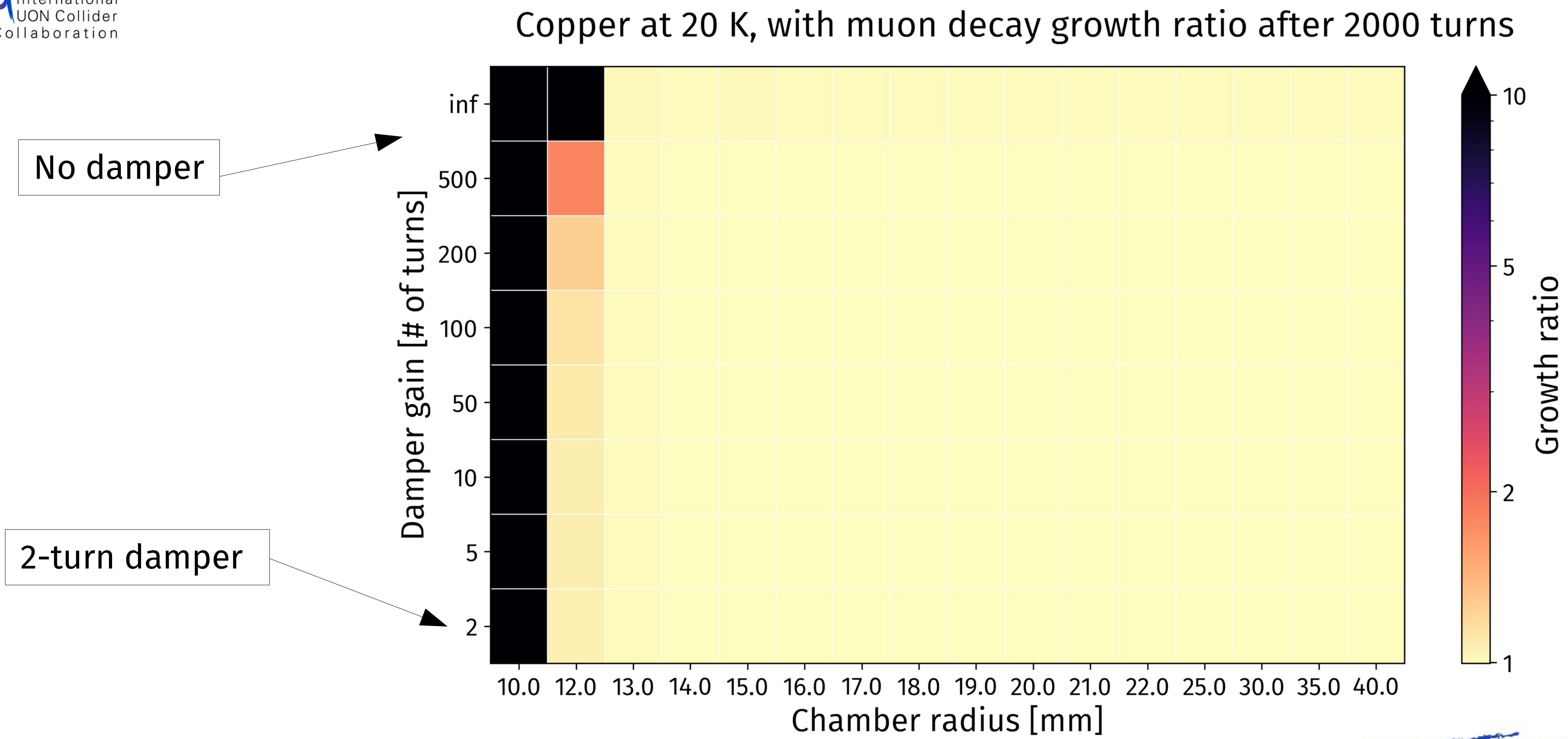
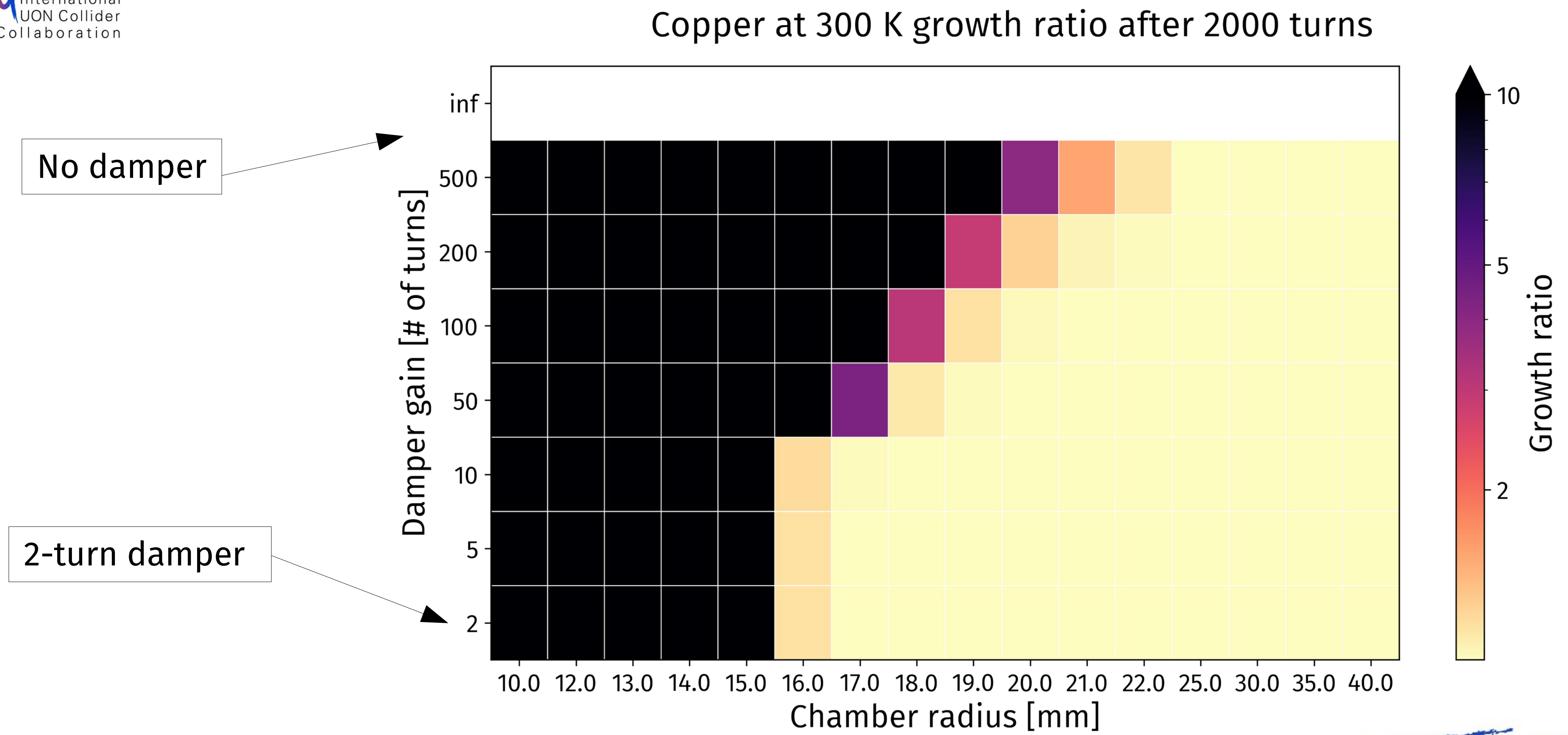
Copper 20 K, after 2000 turns



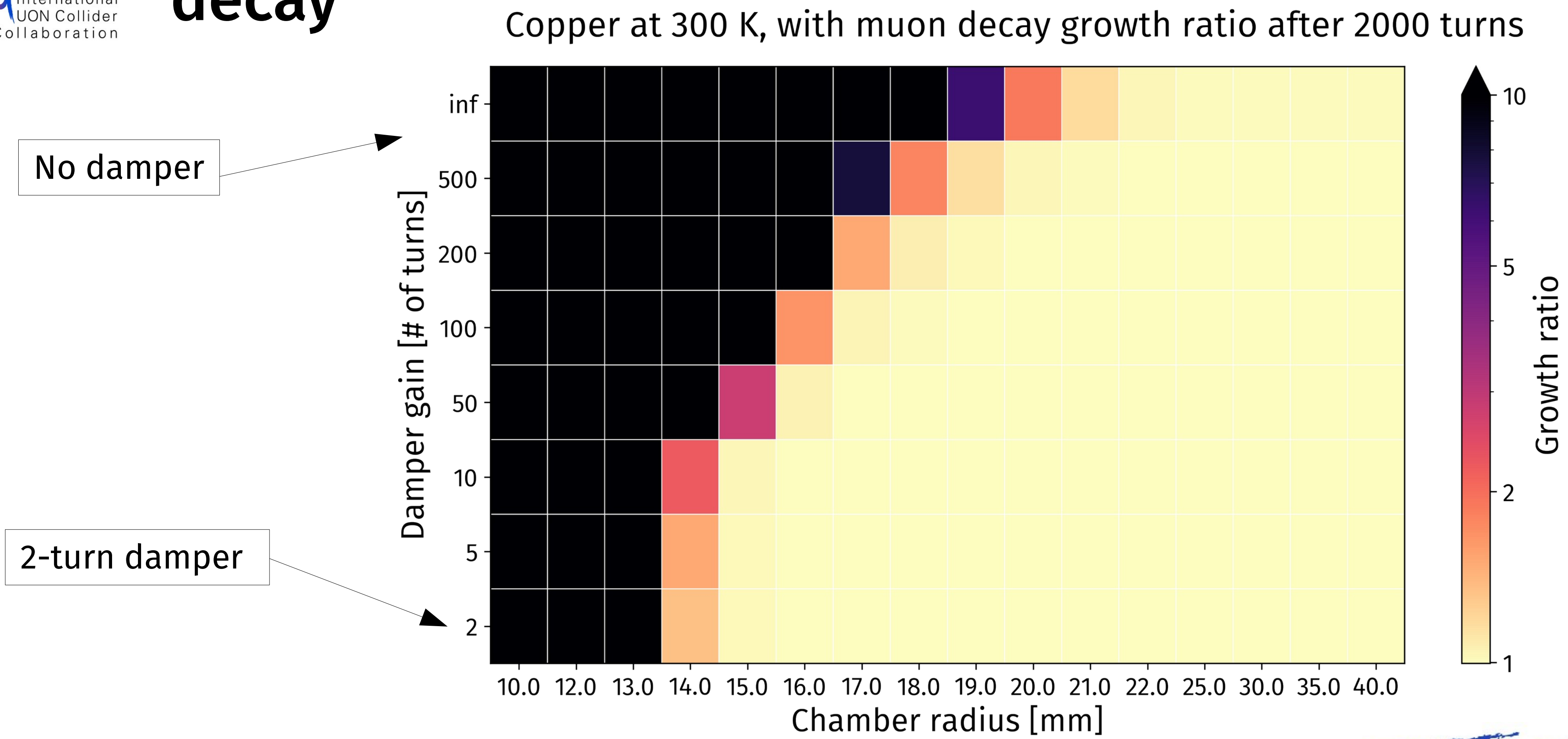
Copper 20 K, after 2000 turns, with muon decay



Copper 300 K, after 2000 turns



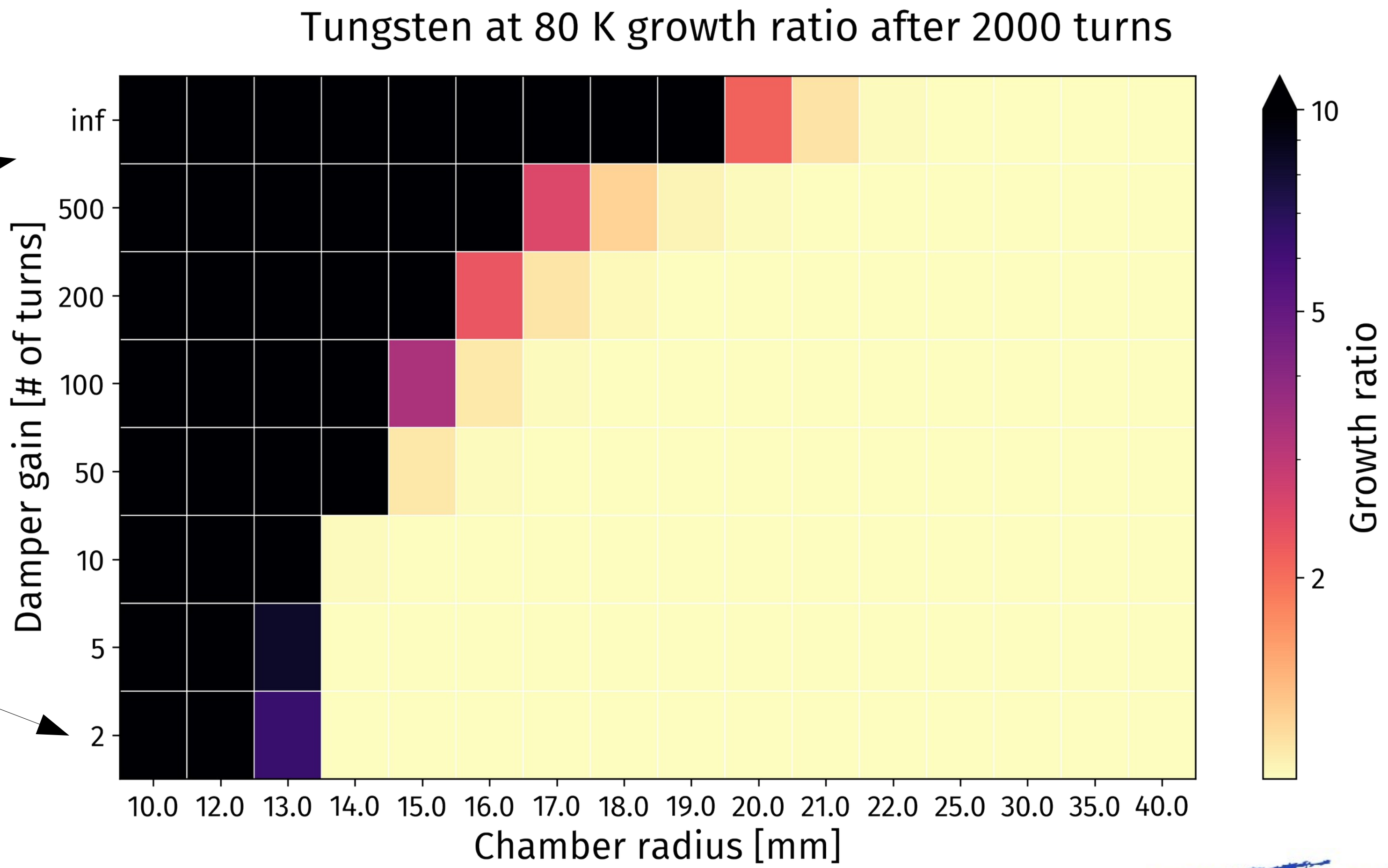
Copper 300 K, after 2000 turns, with muon decay



Tungsten 80 K, after 2000 turns

No damper

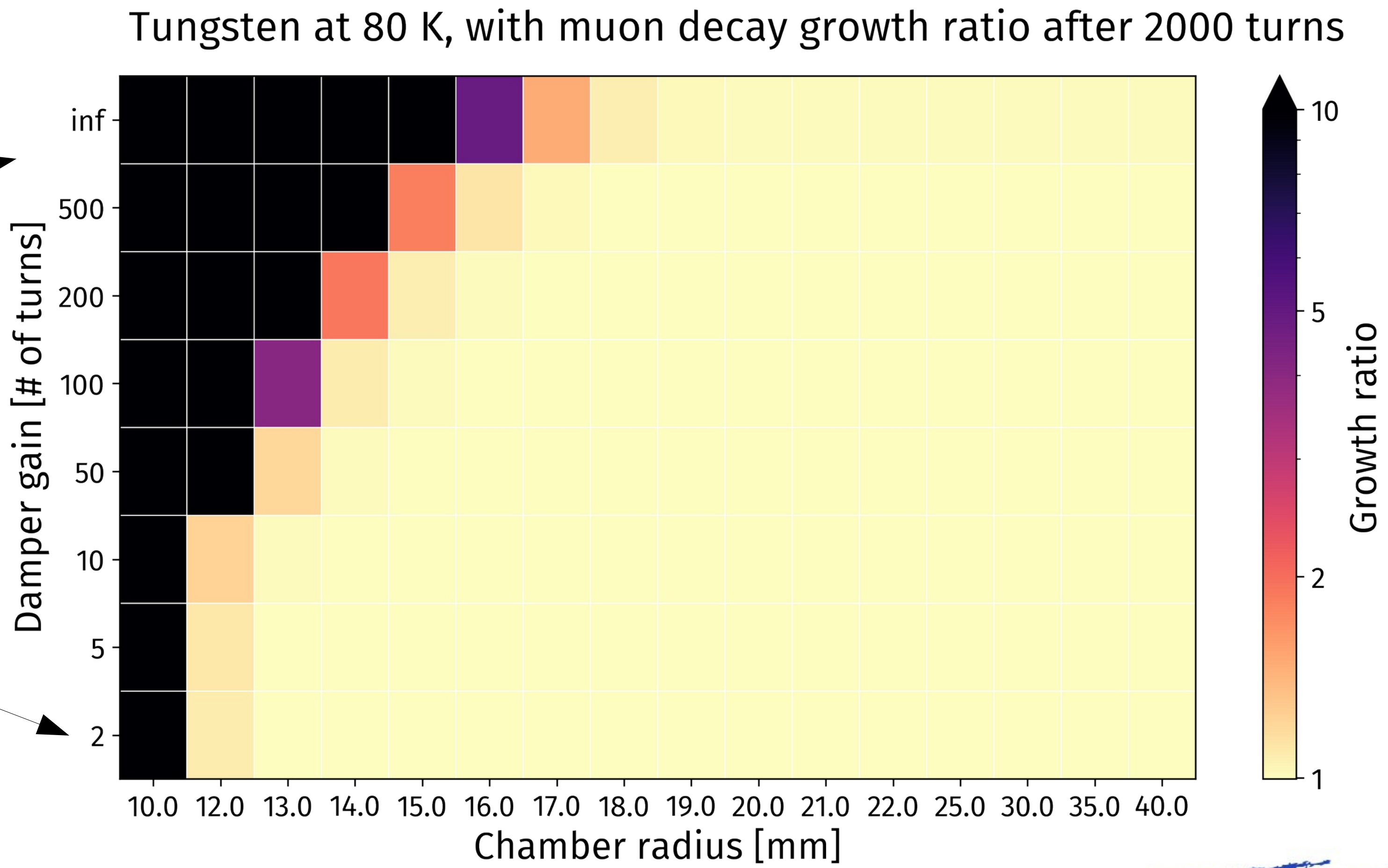
2-turn damper



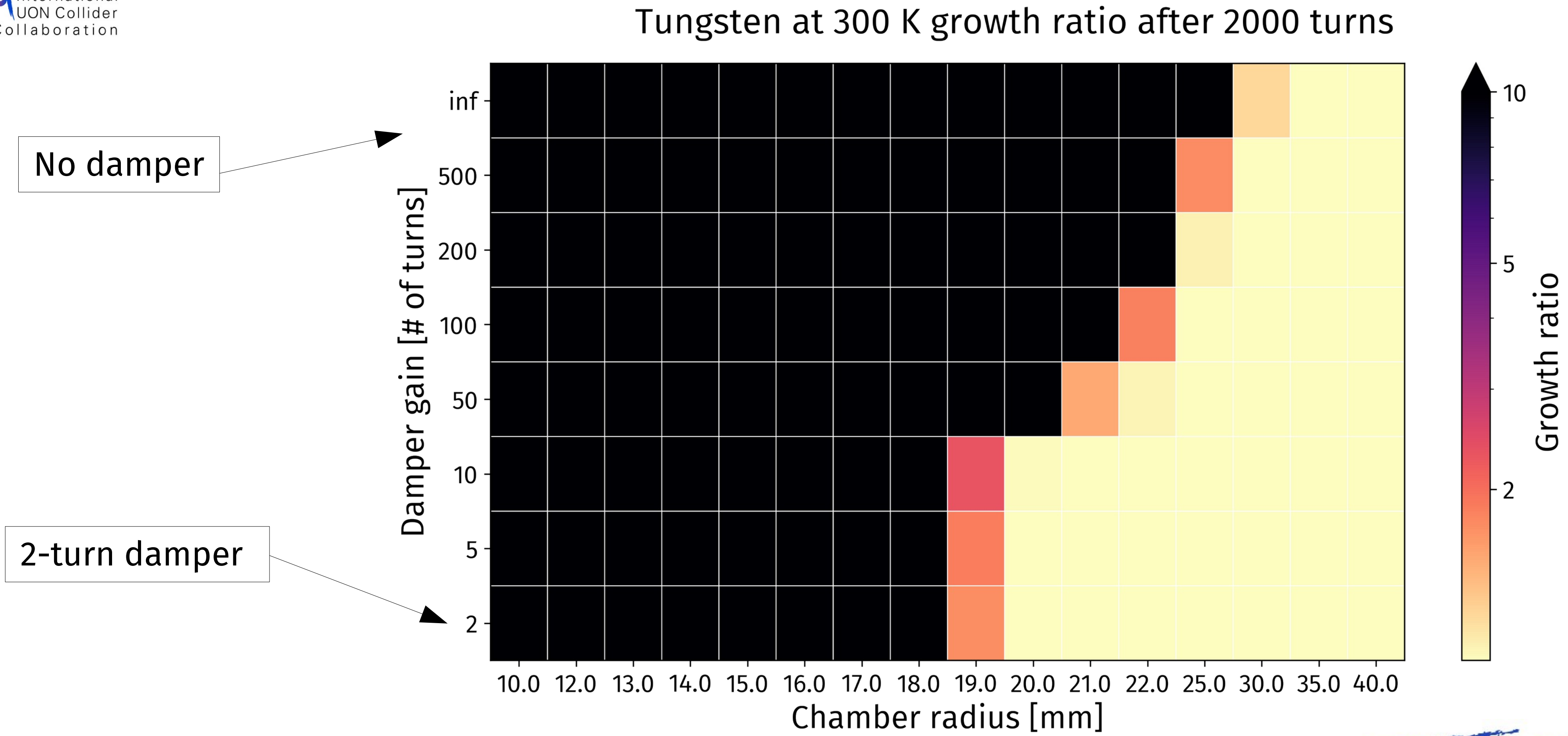
Tungsten 80 K, after 2000 turns, with muon decay

No damper

2-turn damper



Tungsten 300 K, after 2000 turns



Tungsten 300 K, after 2000 turns, with muon decay

No damper

2-turn damper