# Collider transverse impedance and stability studies

D. Amorim, E. Métral
Thanks to F. Batsch, F. Boattini, L. Bottura, D. Calzolari, C. Carli, A. Chancé, H. Damerau, A. Grudiev, I. Karpov, A. Lechner, K. Skoufaris

Muon collider collaboration – Annual meeting
2022-10-12 / 15:15 - 15:35

Swiss Accelerator Research and Technology

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# Goal and scope of the study

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

- Investigate **different materials** for the chamber

- Important input for the optics, the magnet, the muon decay shielding, the vacuum etc. design (see presentations from K. Skoufaris, L. Bottura, A. Lechner et al.)

# Goal and scope of the study

- Simulations first performed for the **3 TeV collider** (1.5 TeV muon beam)
- Second set of simulations for the **10 TeV collider** (5 TeV muon beam)

# *3 TeV collider: Assumptions and simulation parameters*

# 3 TeV: Impedance simulations parameters

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

Machine parameters

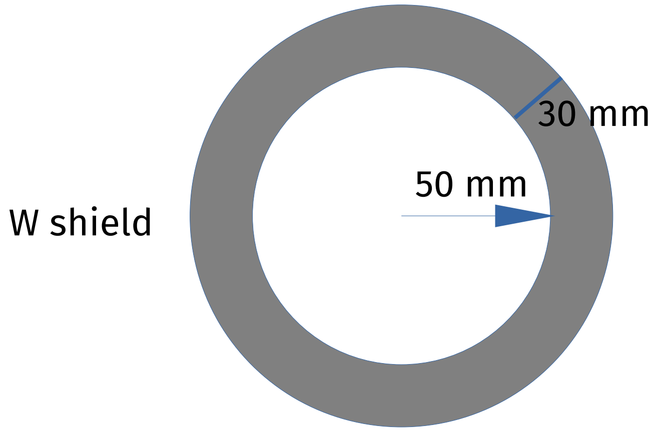
| | Unit | Value |
|---|---|---|
| Circumference | m | 4500 |
| Chamber length | m | 4500 |
| Chamber geometry | | Circular |
| Chamber material | | Tungsten 300 K / Tungsten 80K<br>Copper 300 K / Copper 20 K |
| Chamber thickness | m | Inf. |
| Chamber radius | mm | 10 to 40 |
| Avg. beta x/y | m |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

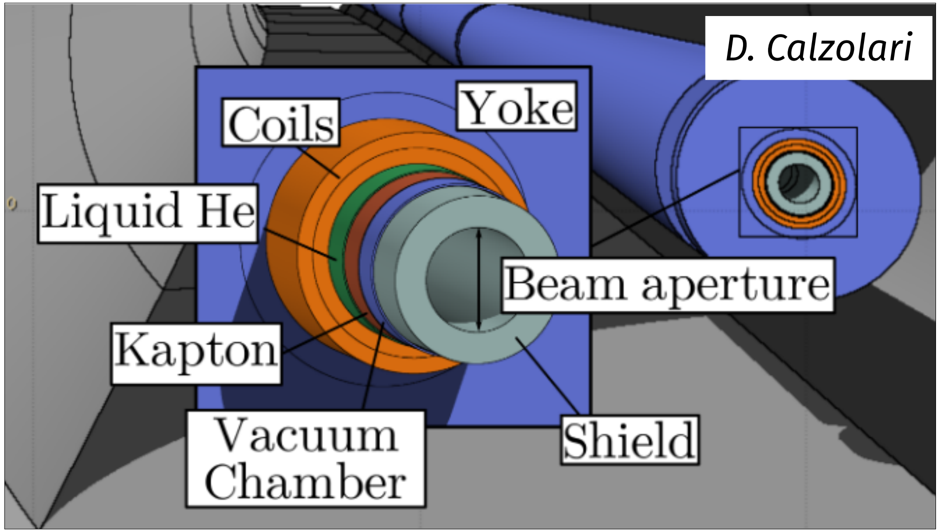
# Materials considered for the beam chamber

- 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

# Liner design to protect from muon decay product

- Power deposition and radiation damage studies done by D. Calzolari et al., presented at IPAC 22 (see also his presentation today)
- 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

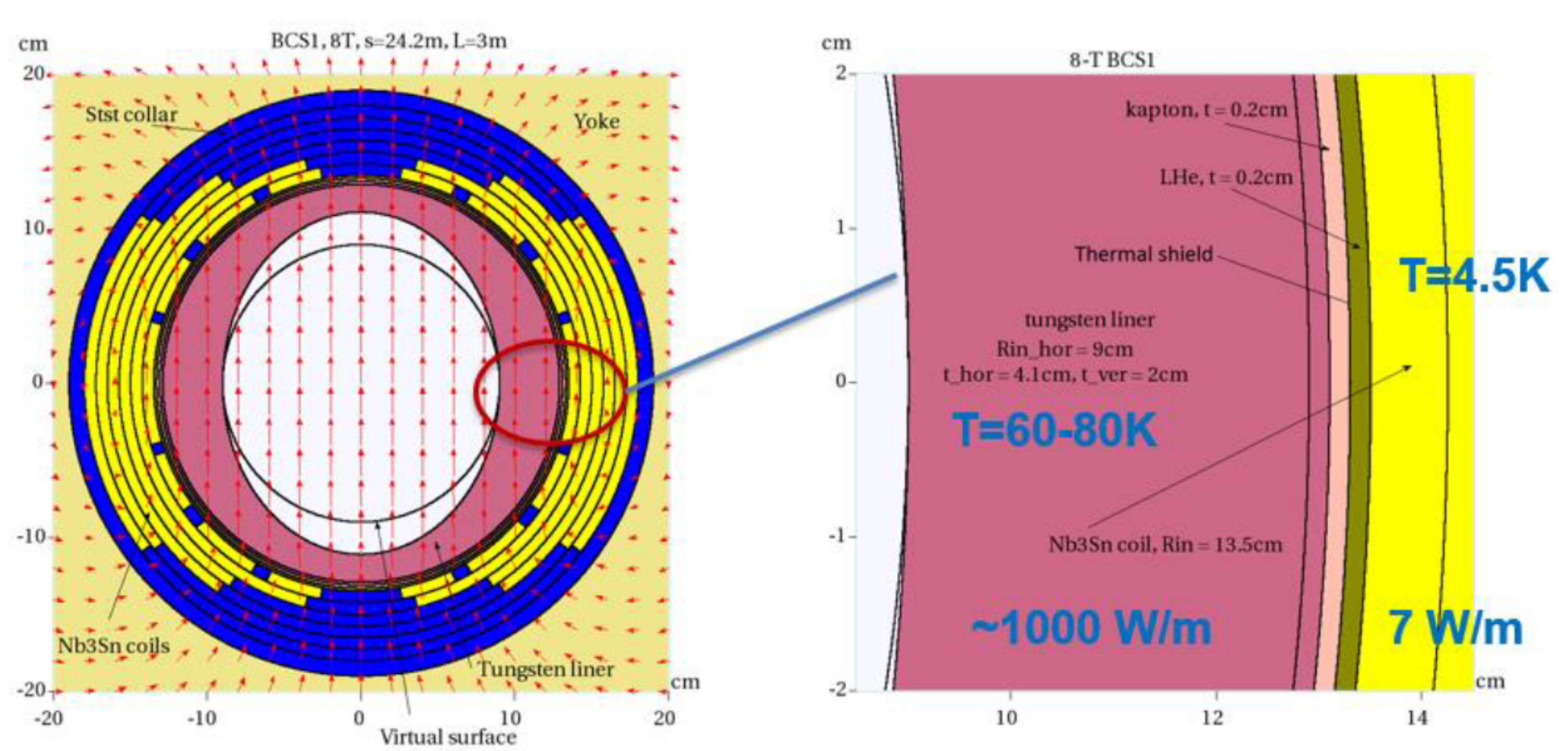
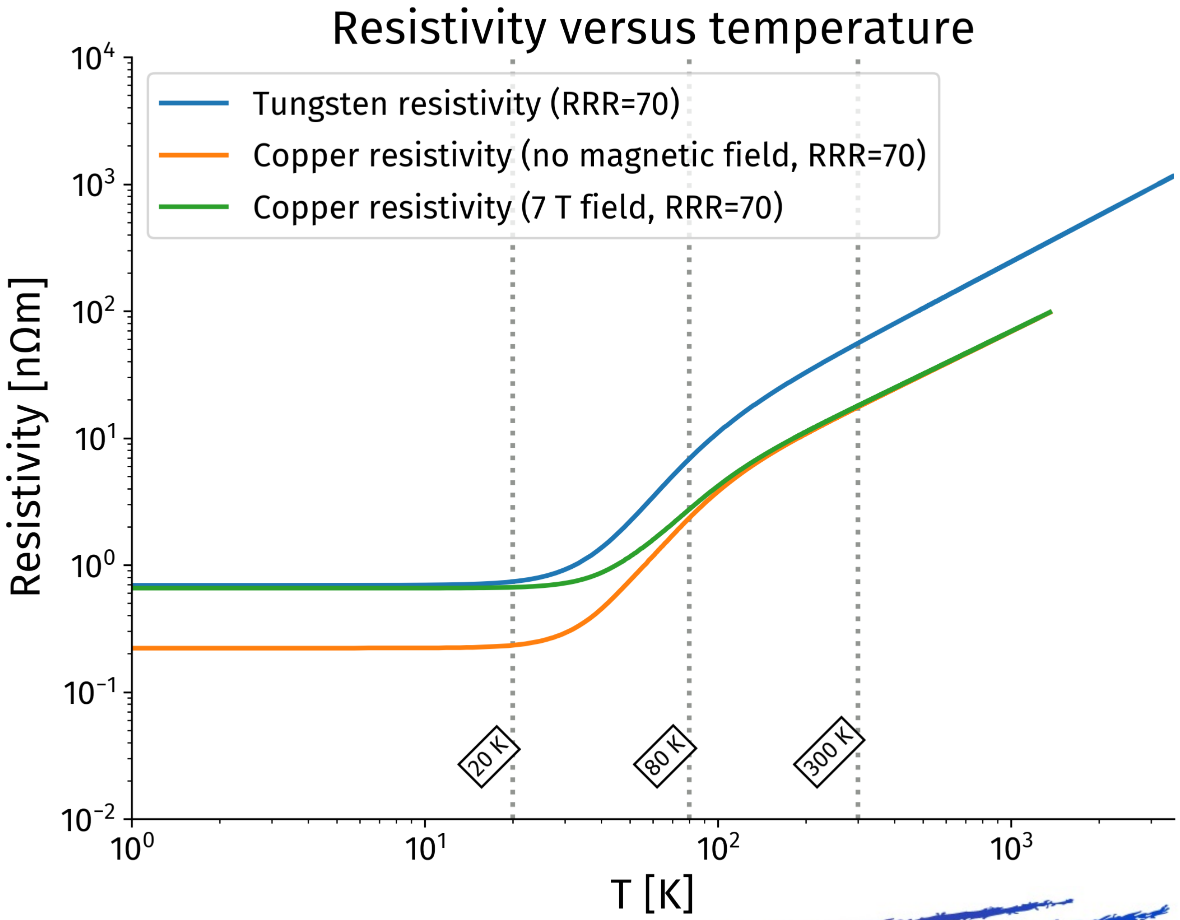



**Figure 8.** Elliptical tungsten liner inside BCS1 8 T dipole.

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

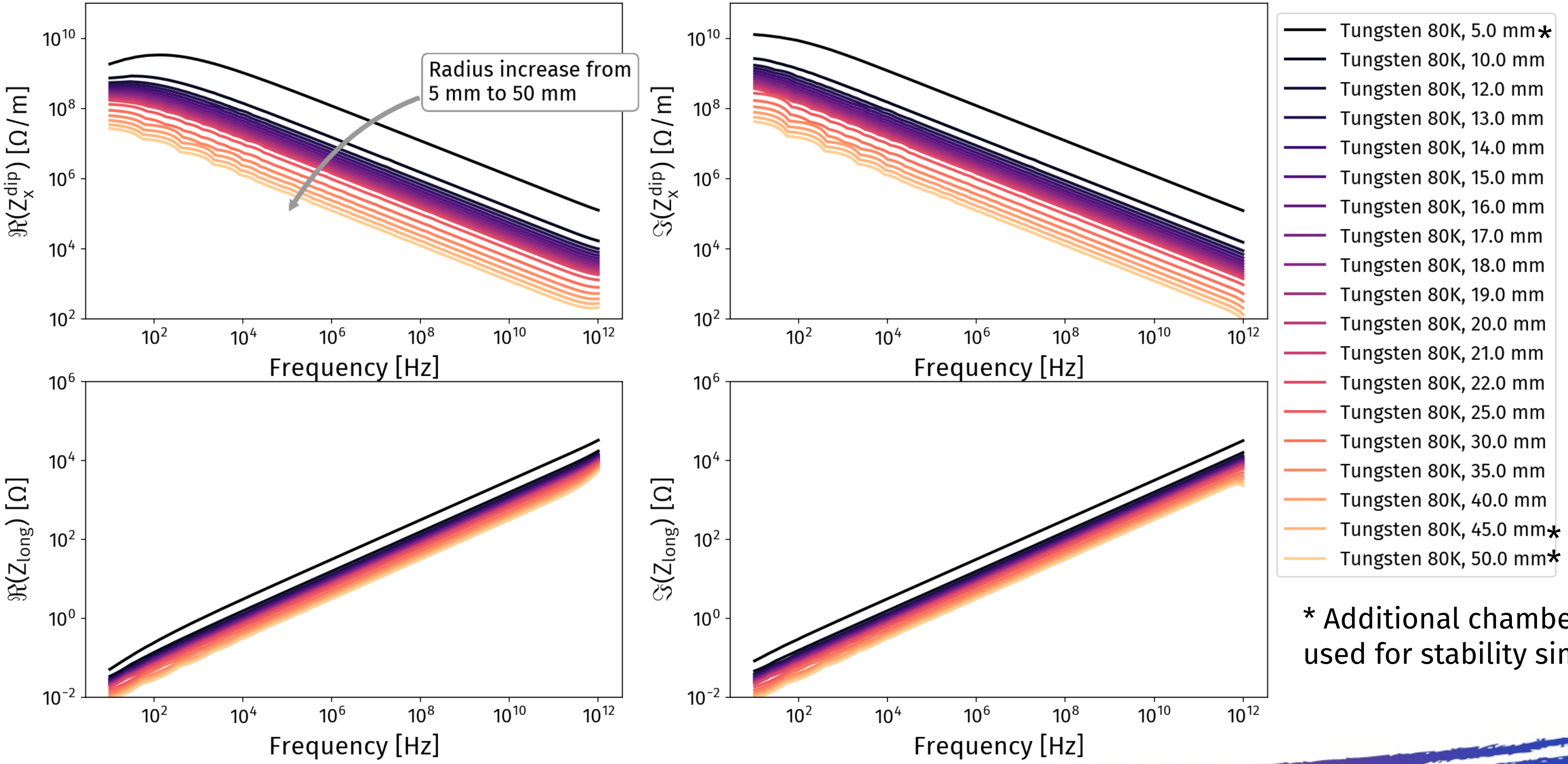
# Impedance simulations parameters: materials

- Resistive wall impedance and wake are proportional to √ρ
- Copper  and tungsten resistivity versus temperature and RRR from:
  - Simon, Drexler and Reed "Properties of c opper and copper alloys at cryogenic te mperatures", 1992
  - Hust and Landford, "Thermal Conducti vity of Aluminum, Copper, Iron, and Tu ngsten for Temperatures from 1 K to th e Melting Point", 1984
- A copper coating/lining would help reduce the vacuum chamber impedance



# 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

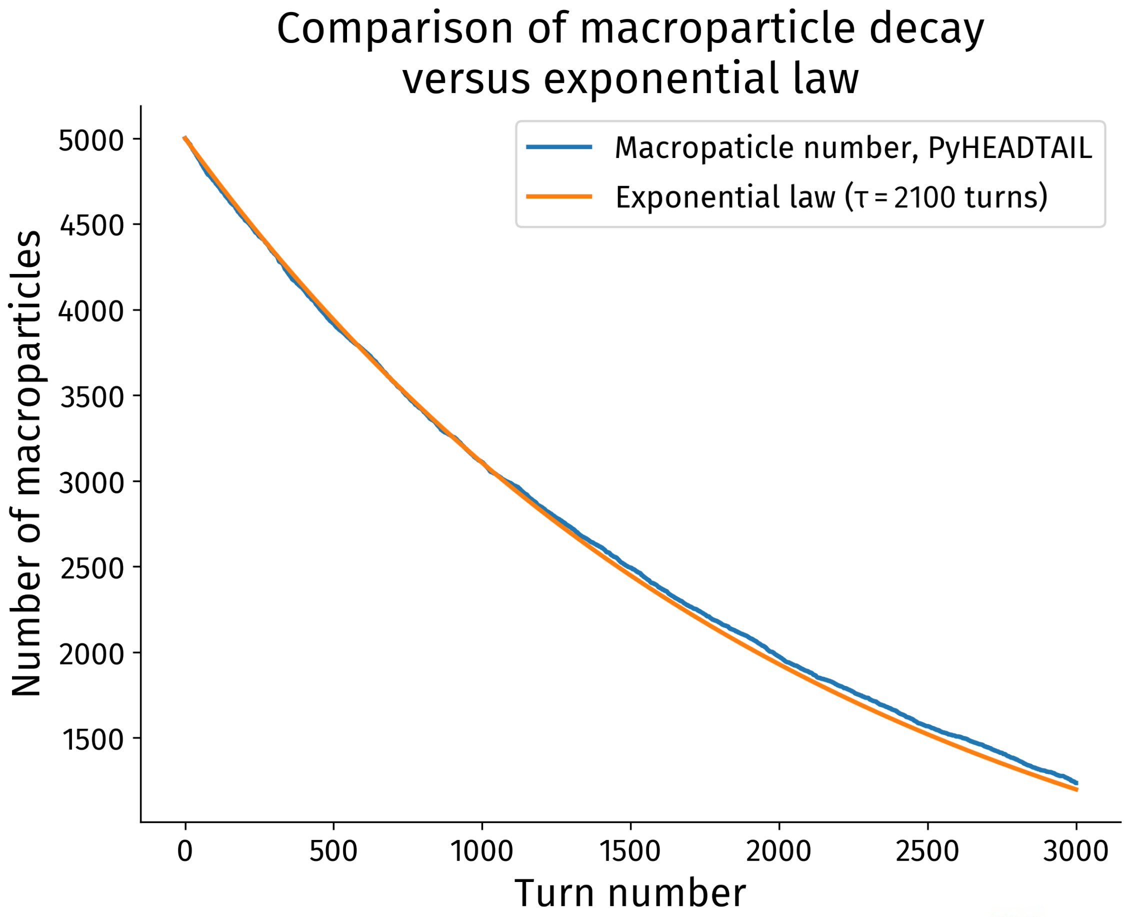
- Simulation including transverse map + longitudinal map (1 RF station) + **transverse wakefield + damper + muon decay**
- Tracking over 3000 turns, 5000 macroparticles with PyHEADTAIL, initial intensity **2.2 $10^{12}$ muons**, transverse emittance **25 µm rad** (detailed parameters in appendix)
- Chromaticity is corrected to 0/0 (**natural chromaticity is compensated**), no Landau octupoles included
- **Optionally: include muon decay effect**
  - Muon lifetime at 1.5 TeV: 14285 * 2.2 µs = 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**
- Scan the transverse damper gain from 2 to 500-turn damping time + no damper
- Horizontal and vertical planes have the same impedance (circular chamber), and same beam parameters → simulation results identical in the two planes

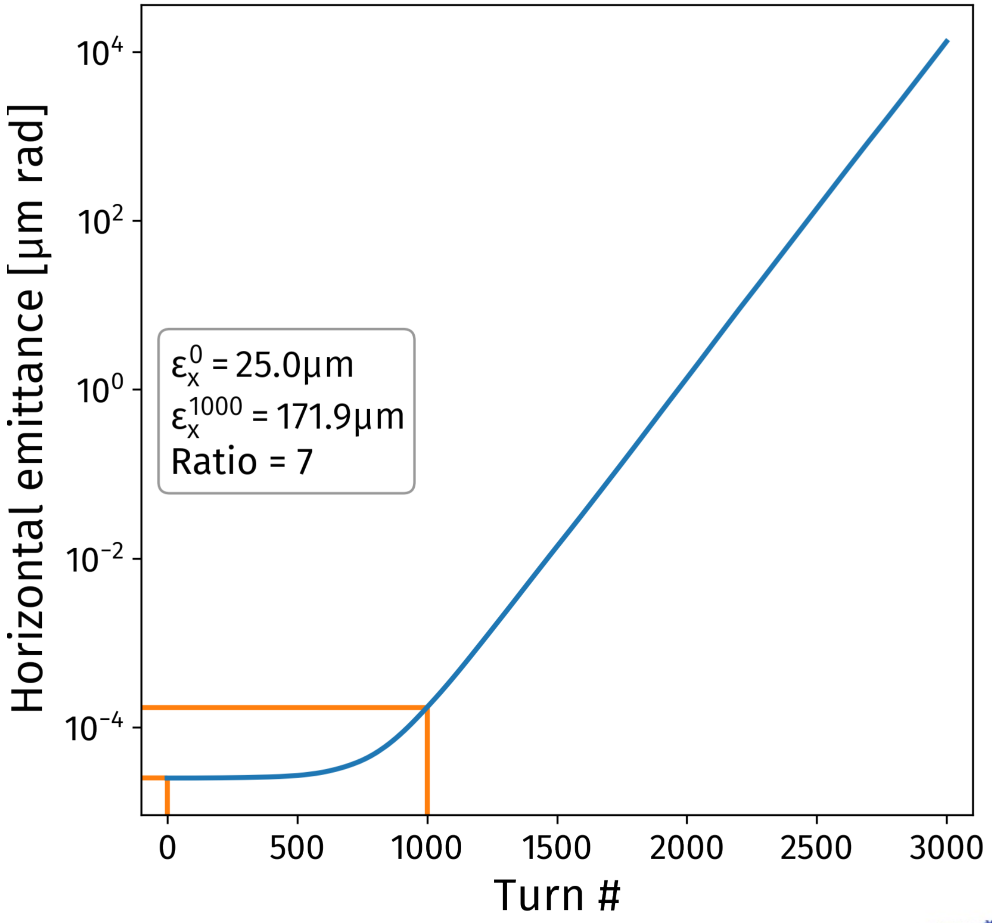
# Implementation of the muon beam decay

- Decay element in PyHEADTAIL
  - Input: decay time (in number of turns) of the beam
  - Use numpy `rand` function to randomly select the macroparticles 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



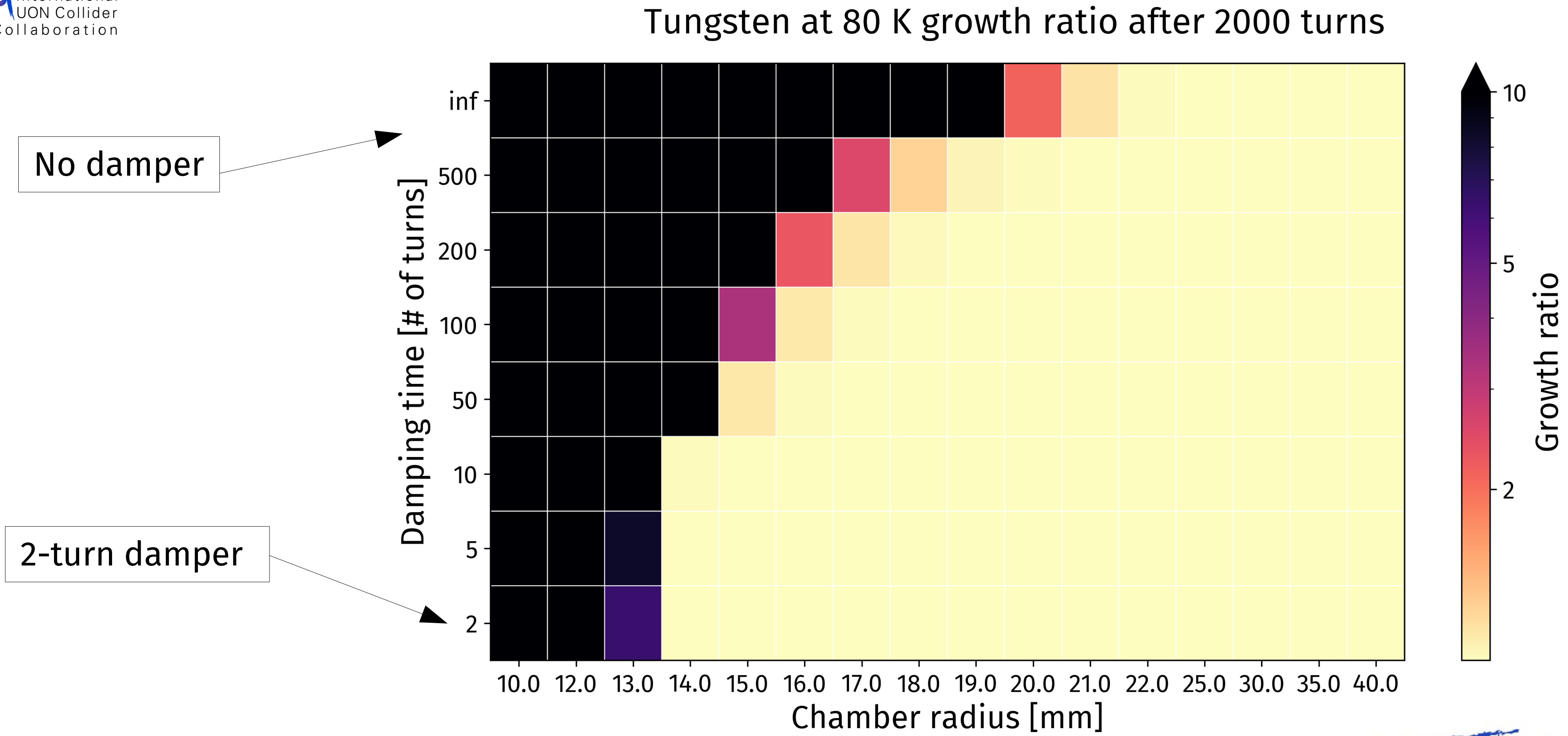
# Growth ratio plots

- 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

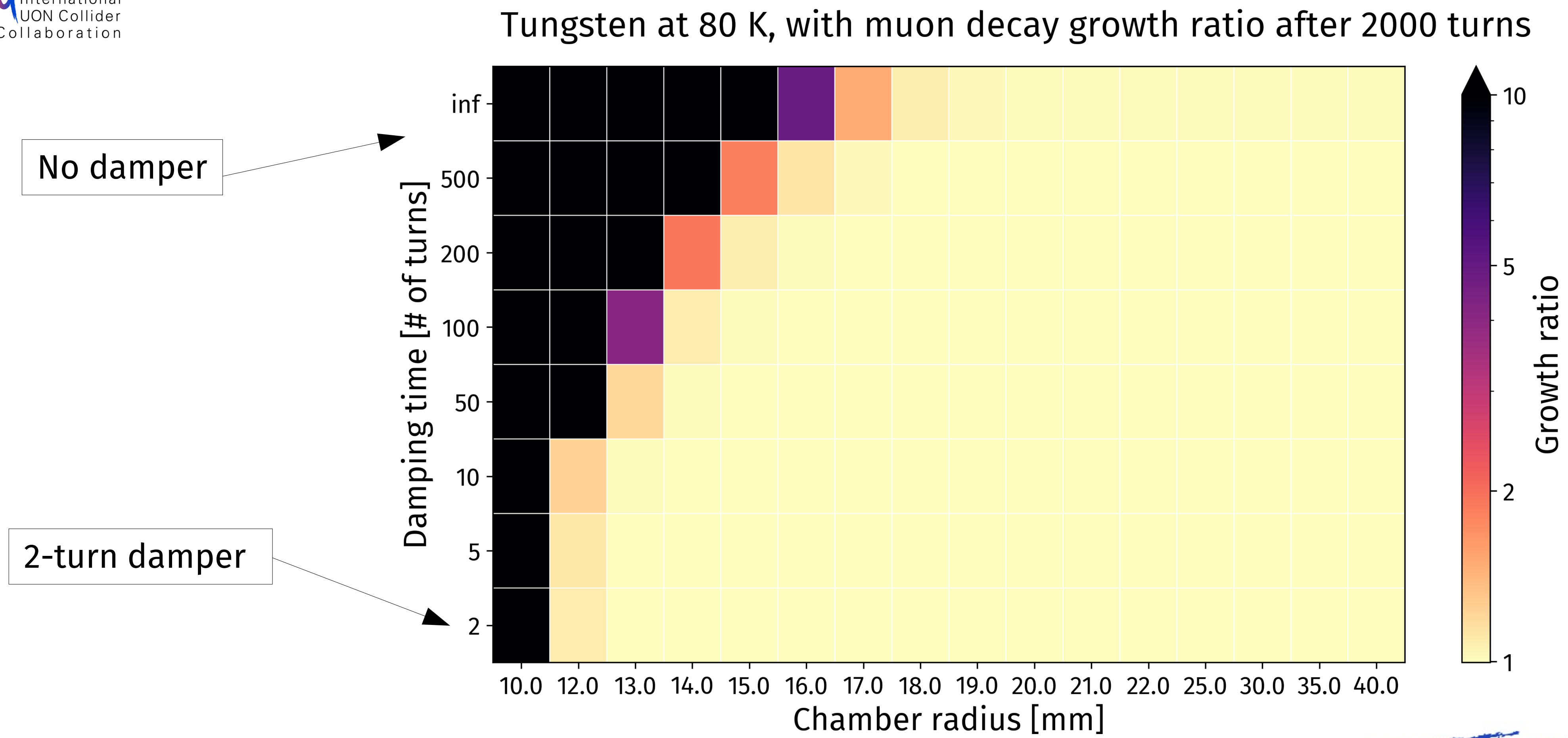


# *3 TeV collider: Simulation results*

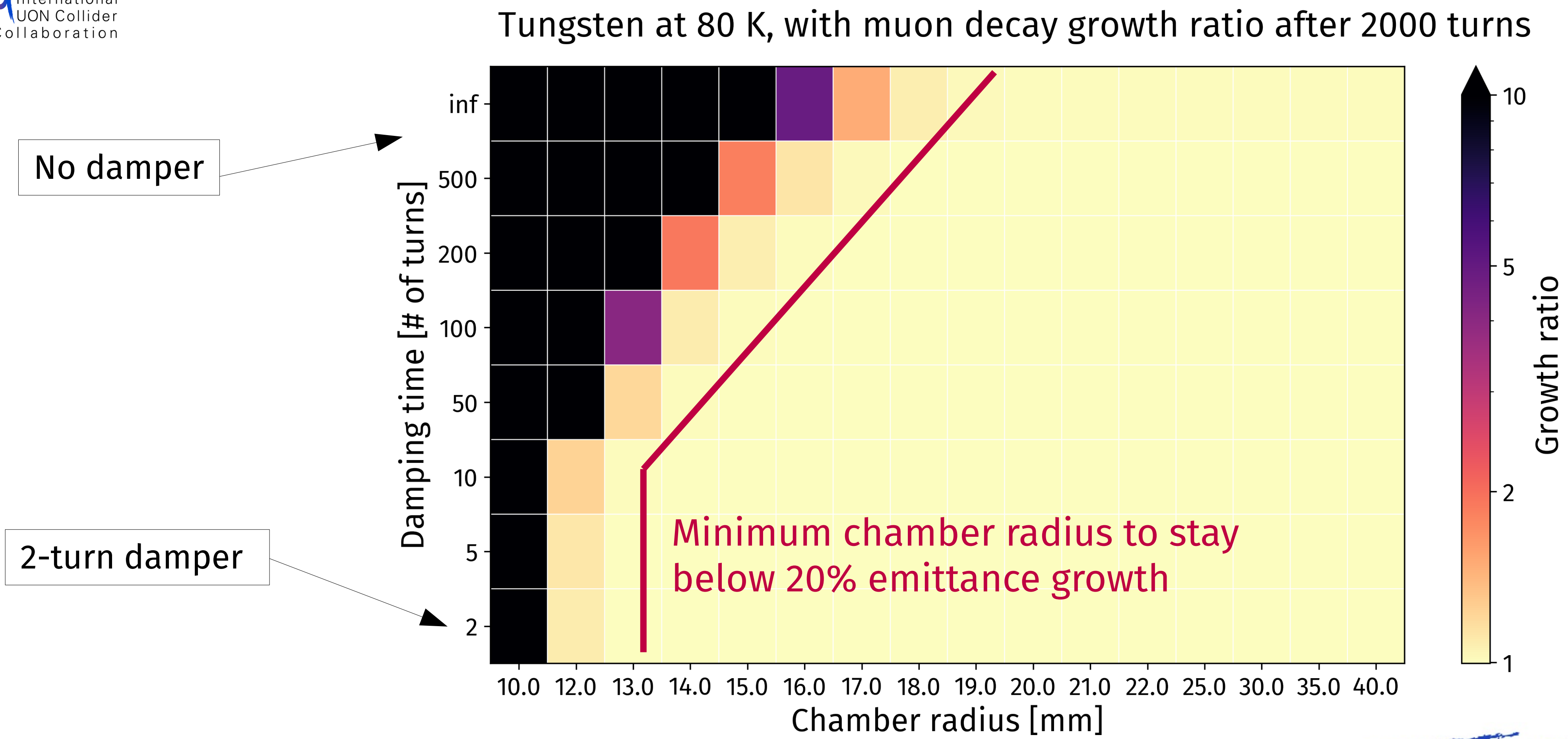
# Tungsten 80 K, WITHOUT muon decay



# Tungsten 80 K, WITH muon decay

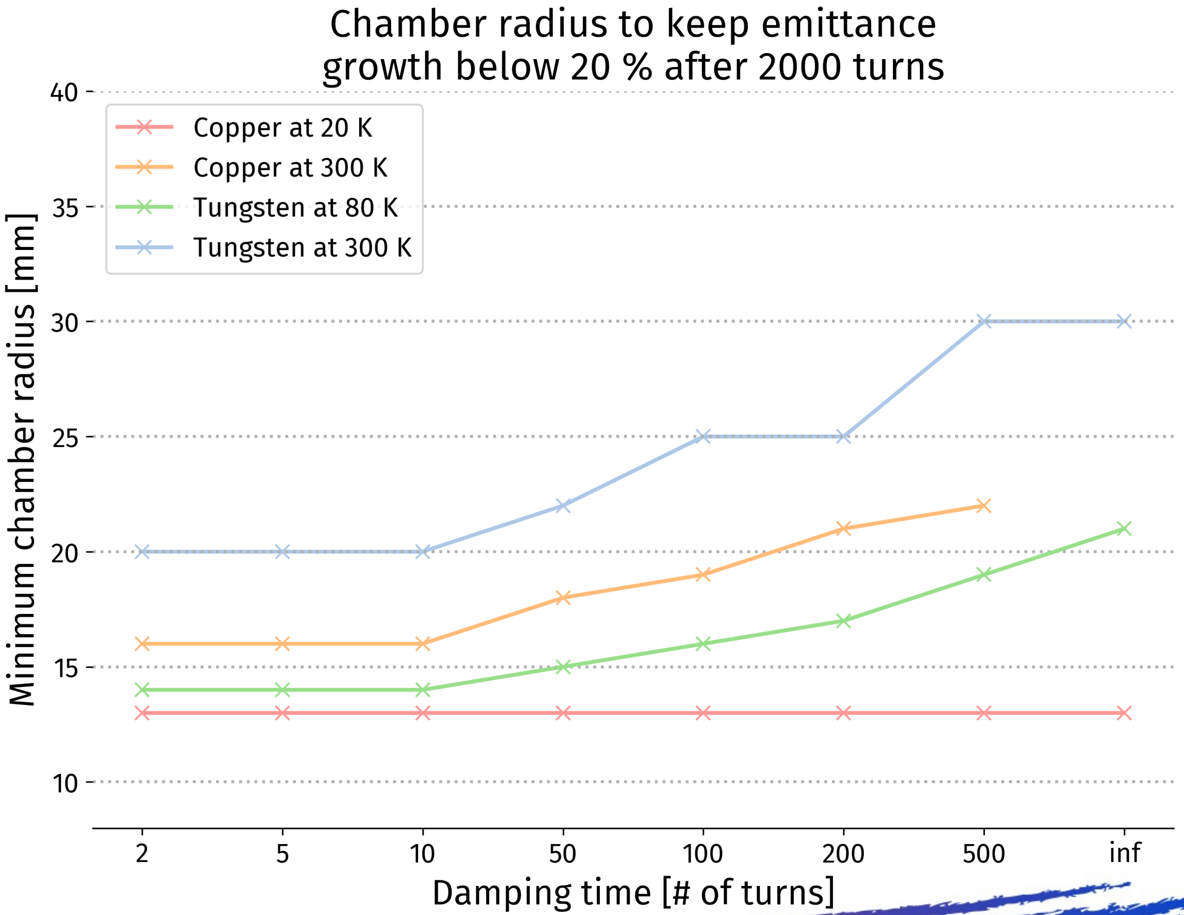


# Tungsten 80 K, WITH muon decay



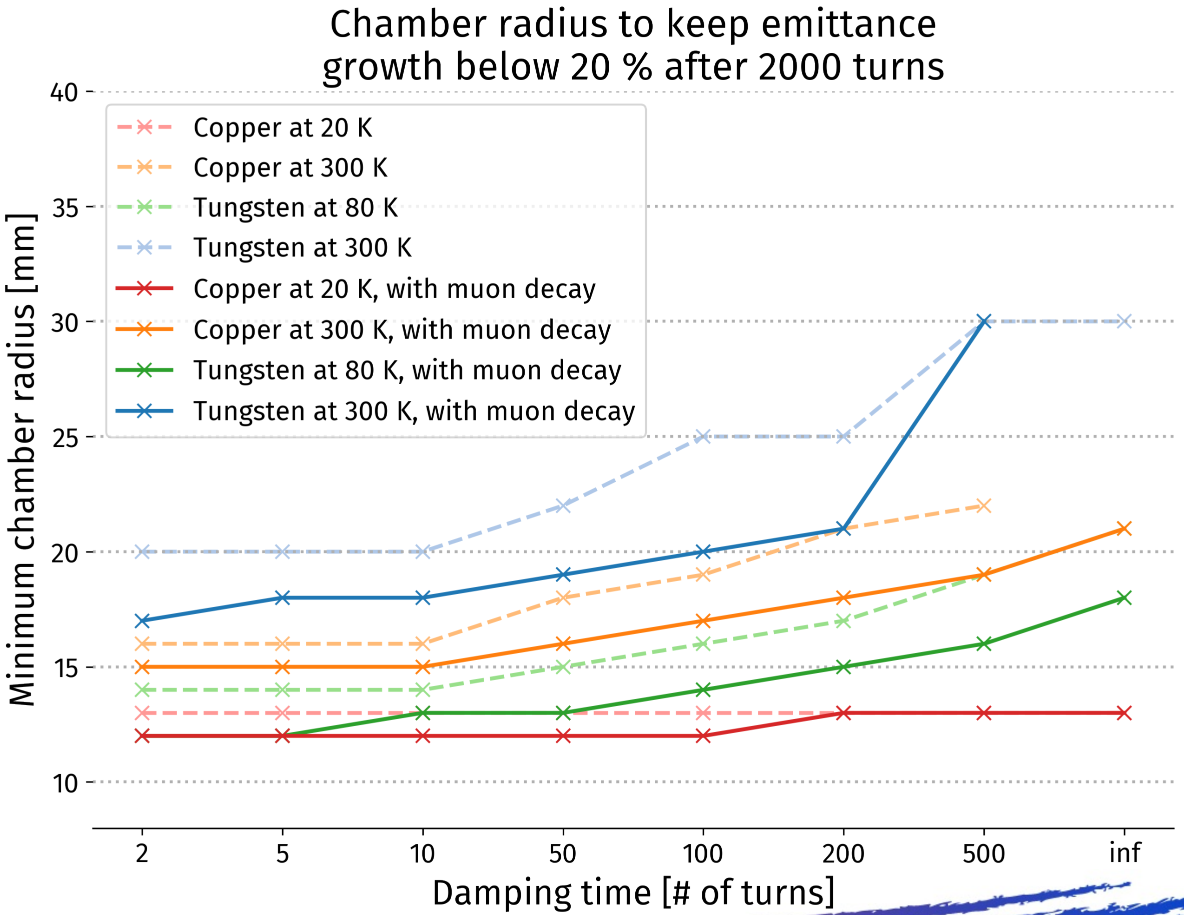
# Minimum chamber radius versus material, without muon decay

- 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

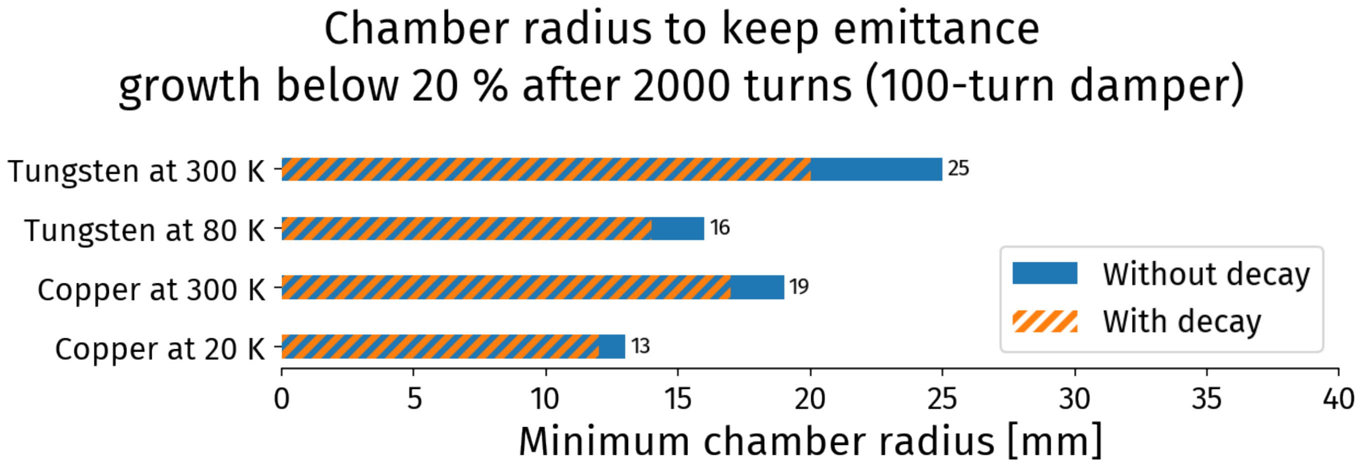


# Minimum chamber radius versus material, with muon decay

- 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**
  - No point for a damper setting means that the beam was always unstable



# Minimum chamber radius versus material




- With a 100-turn damper transverse beam stability would require at least **25 mm radius with Tungsten at 300 K for the 3 TeV collider (without decay)**
- A copper pipe allows to go below 20 mm radius: copper lining or coating would help stability
- Muon decay adds some margin on the radius (up to 5 mm)

# *10 TeV collider: Assumptions and simulation parameters*

# 10 TeV: Impedance simulations parameters

- 5 TeV per beam, 10 km long beam chamber
- Other parameters are also modified: average beta functions (input from optics design by K. Skoufaris), Copper at 80 K instead of 20 K

Machine parameters

| | Unit | Value |
|---|---|---|
| Circumference | m | **10000** |
| Chamber length | m | **10000** |
| Chamber geometry | | Circular |
| Chamber material | | Tungsten 300 K / Tungsten 80K<br>Copper 300 K / **Copper 80 K** |
| Chamber thickness | m | Inf. |
| Chamber radius | mm | 10 to 40 |
| Avg. beta x/y | m | **85 / 51** |

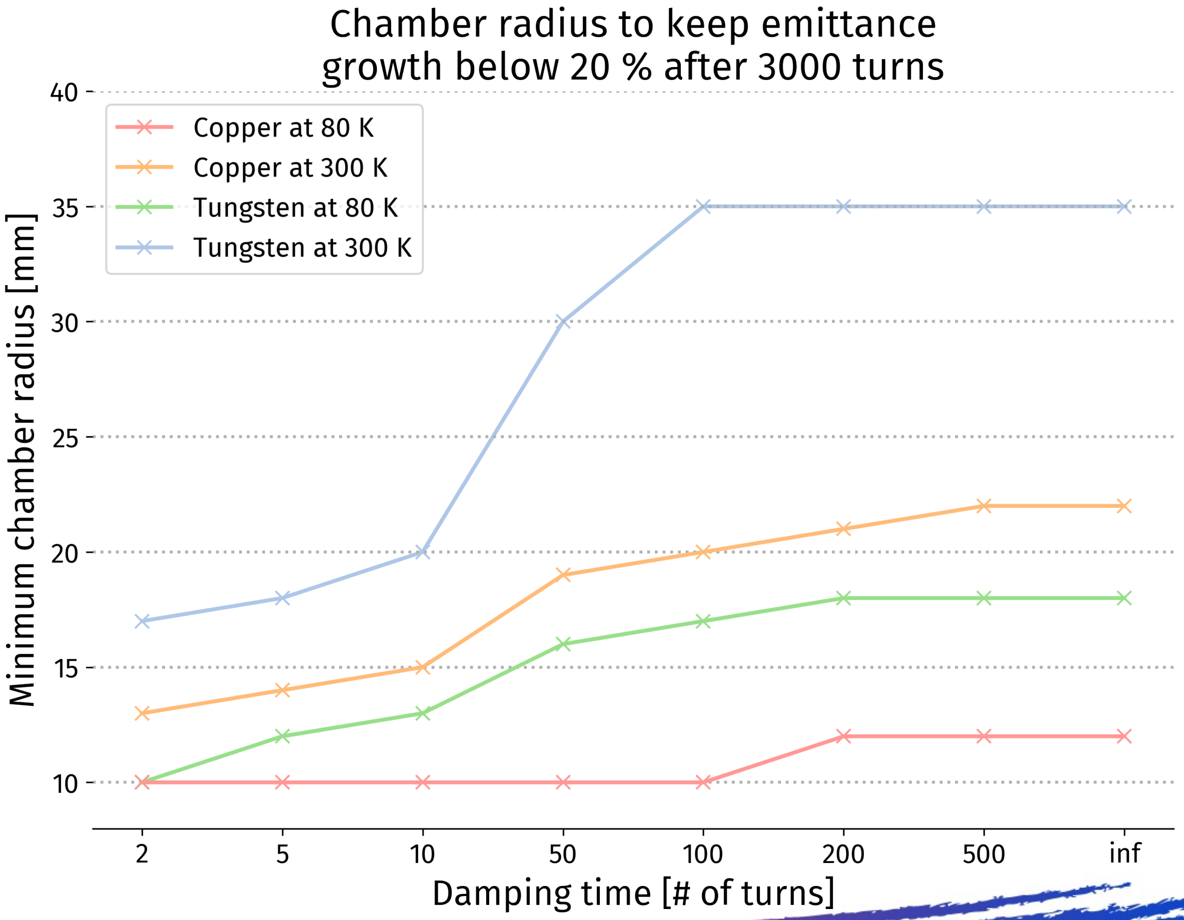
# Transverse stability simulation parameters in the 10 TeV collider

- Simulation including transverse map + longitudinal map (1 RF station) + **transverse wakefield** + **damper** + **muon decay**
- Tracking over 5000 turns, 20000 macroparticles with PyHEADTAIL, initial intensity 1.8 $10^{12}$ muons, transverse emittance **25 µm rad** (detailed parameters in appendix)
- **Optionally: include muon decay effect**
  - Muon lifetime at 5 TeV: 47323 * 2.2 µs = 104 ms
  - Revolution frequency ~30 kHz → **muon lifetime at 5 TeV is ~3120 turns**

# *10 TeV collider: Simulation results*

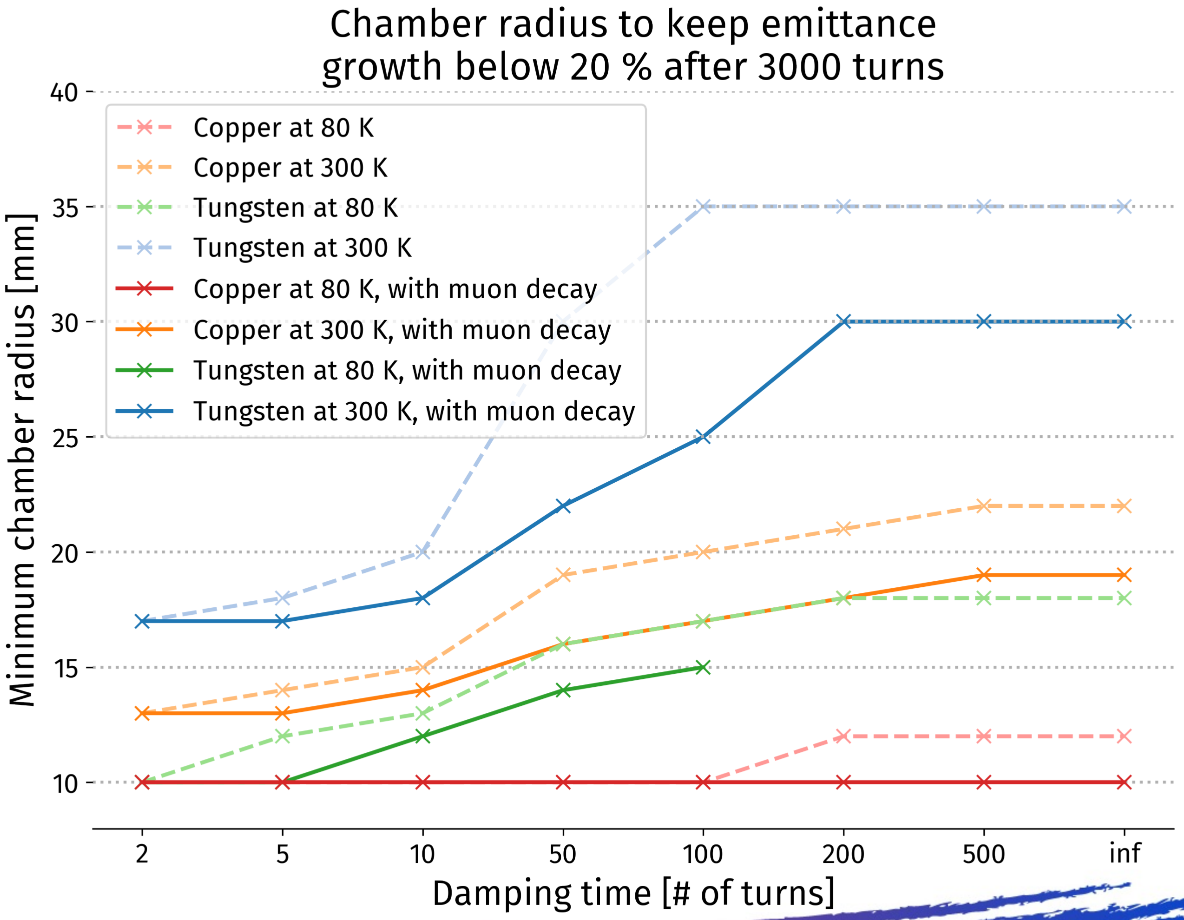
# Minimum chamber radius versus material, without muon decay

- 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 3000 turns**
  - No point for a damper setting means that the beam was always unstable

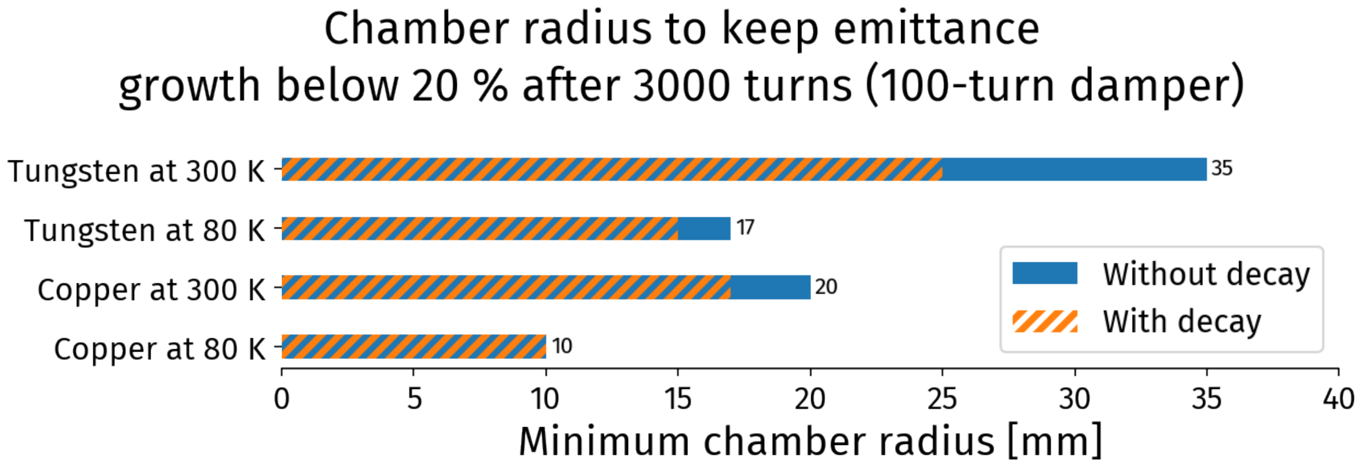


# Minimum chamber radius versus material, with muon decay

- 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 3000 turns**
  - No point for a damper setting means that the beam was always unstable

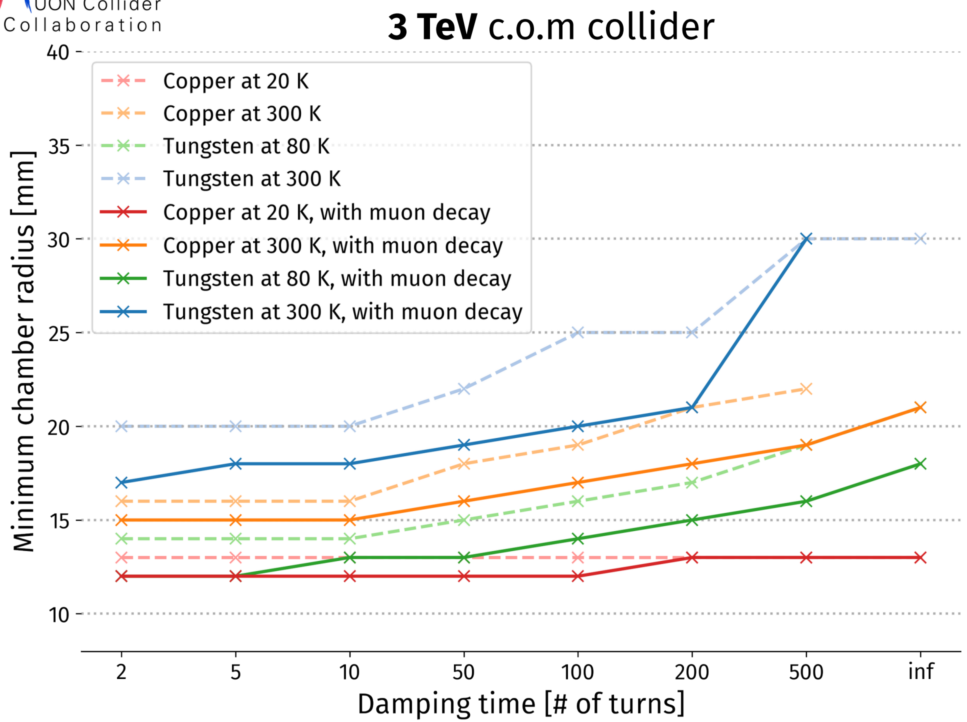


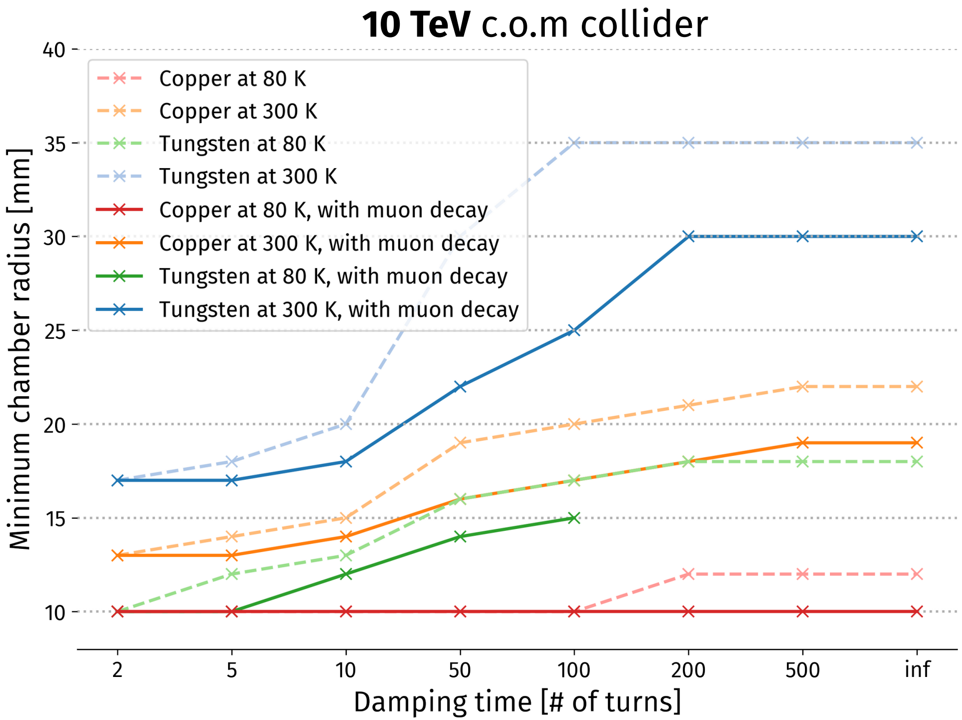
# Minimum chamber radius versus material




- With a 100-turn damper transverse beam stability would require at least **35 mm radius with Tungsten at 300 K for the 10 TeV collider (without decay)**
- A copper pipe allows to go to 20 mm radius range: copper lining or coating would help stability
- Muon decay adds some margin on the radius (up to 5 mm)

# Conclusion

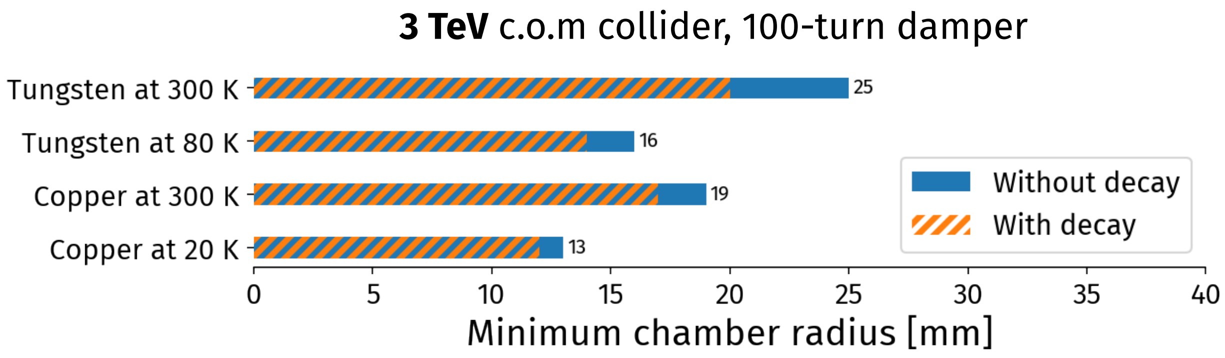


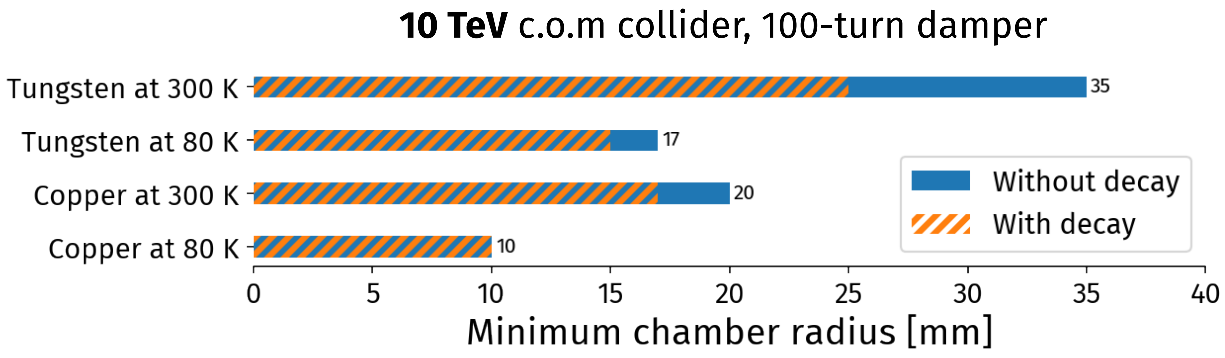




- Overall the 10 TeV collider requires larger apertures than the 3 TeV collider with Tungsten at 300 K
- Muon decay helps gaining some margin on the minimum chamber radius required for transverse stability

# Conclusion

- With a 100-turn damper transverse beam stability would require at least **35 mm radius with Tungsten at 300 K for the 10 TeV collider (without decay), 25 mm when including muon decay**




- A copper pipe allows to go to 20 mm radius range: copper lining or coating would help stability

# Next steps for the colliders

- Include additional instability mitigation measures to help reach tighter chamber radii (positive chromaticity, Landau damping with octupoles)
- Simulate a more detailed vacuum chamber built when the first specifications are found
  - Interaction with optics, magnet, shielding, vacuum etc. to define the required apertures (see K. Skoufaris, L. Bottura, A. Lechner et al.)
- Include the second, counter-rotating, beam effects
- Investigate other potential shielding materials
  - Suggestion from P. Sievers: Tungsten-Copper, Tungsten-Rhenium, Tantalum...

*Thanks for your attention*

# *Appendix: 3TeV collider*

# 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 |

# Stability simulation parameters

International MUON Collider Collaboration

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 |
| $\alpha_p$ | | -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 |

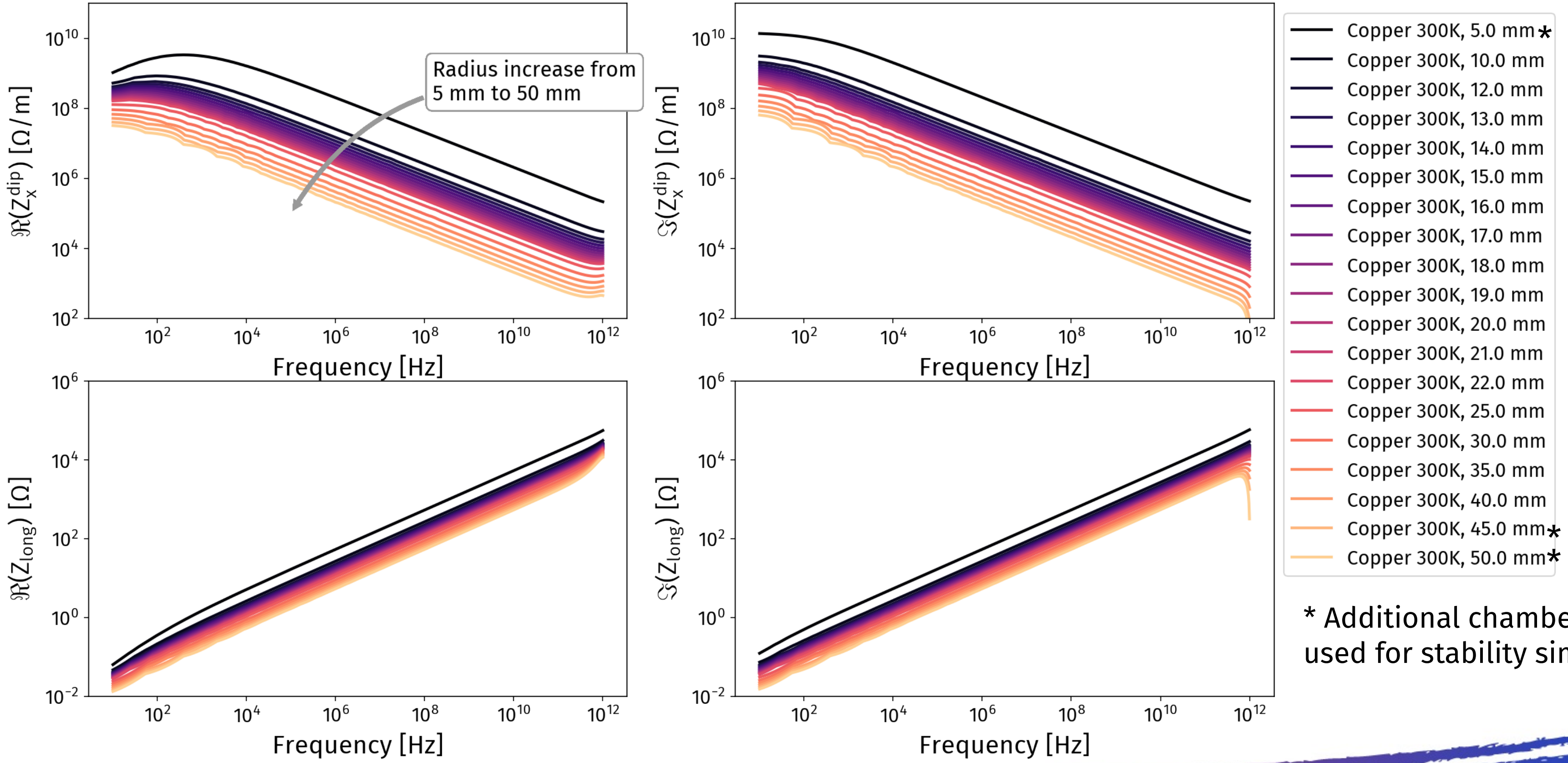
| | Unit | Value |
|---|---|---|
| Synchrotron tune $Q_s$ | | 0.000829 |
| Synchrotron period | turns | 1206 |
| **Bunch length 1σ** | **mm** | **5** |
| **Bunch intensity** | **Particles per bunch** | **2.2e12** |
| **$\varepsilon_x$ / $\varepsilon_y$** | **µm rad** | **25** |
| # of macropaticles | | 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

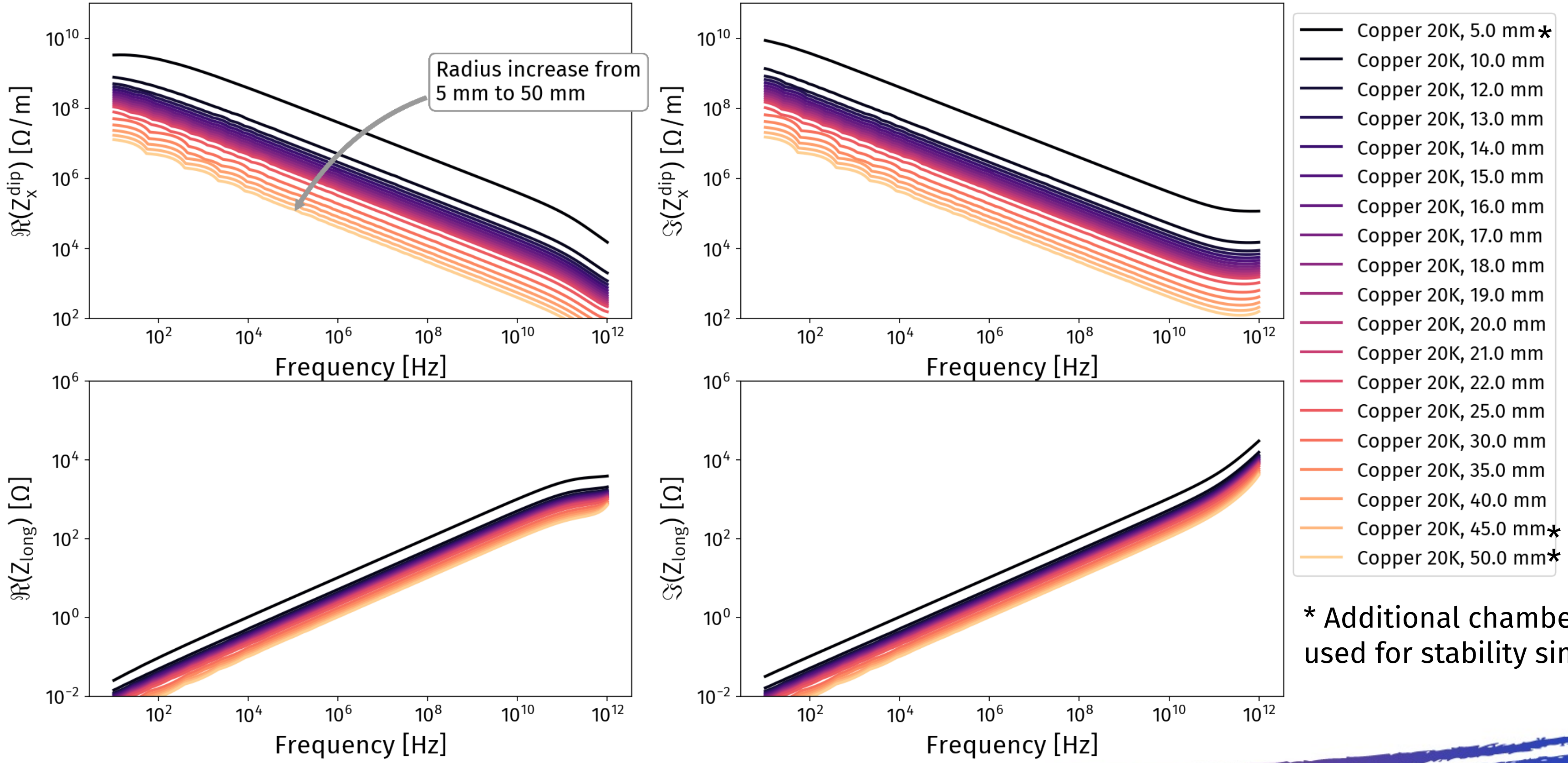
Transverse resistive wall impedance depends on 1/r³, longitudinal resistive wall impedance depends on 1/r




* Additional chamber radii not used for stability simulations

# Impedance for Copper at 20 K

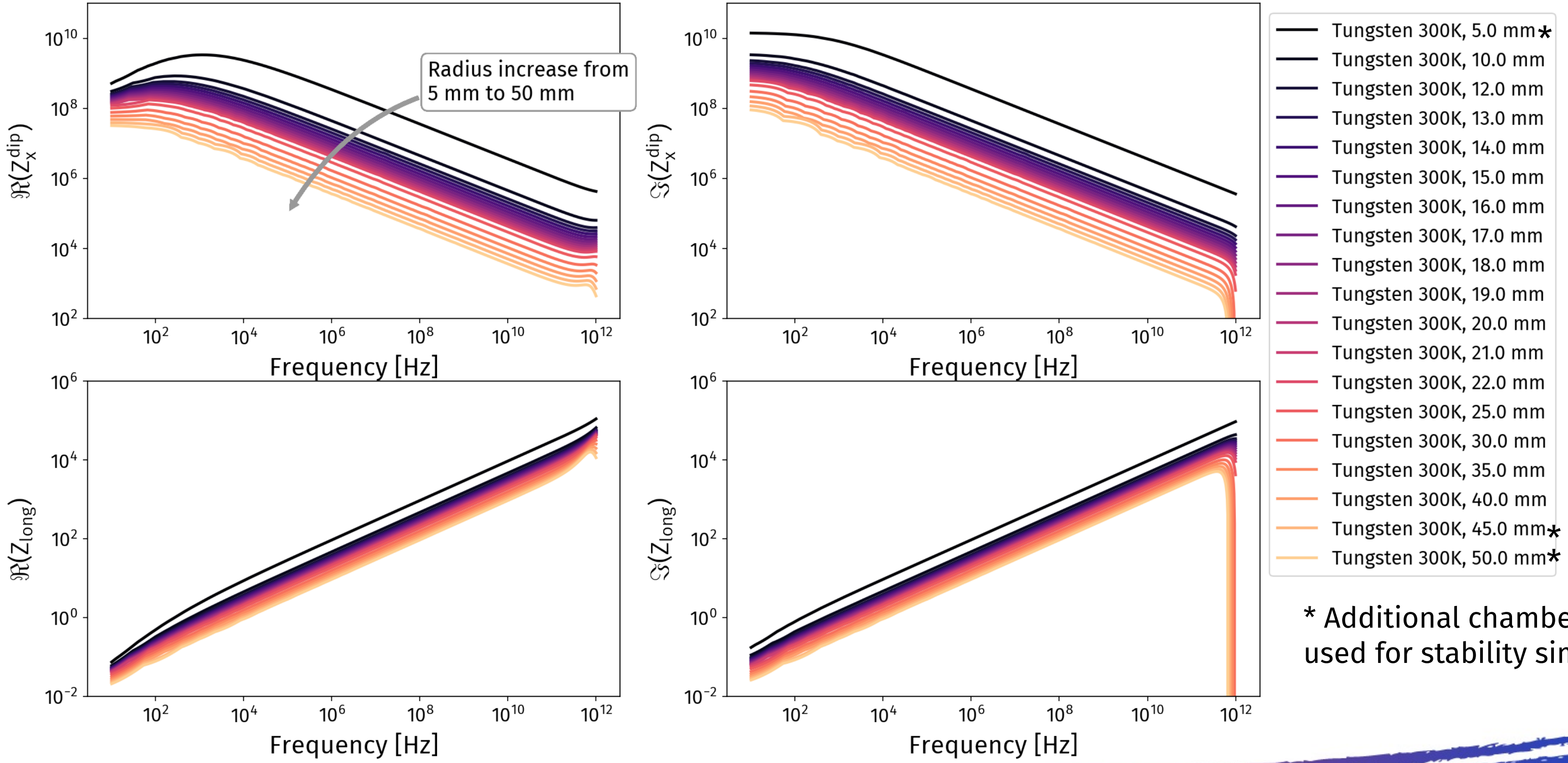
Transverse resistive wall impedance depends on $1/r^3$, longitudinal resistive wall impedance depends on $1/r$




* Additional chamber radii not used for stability simulations

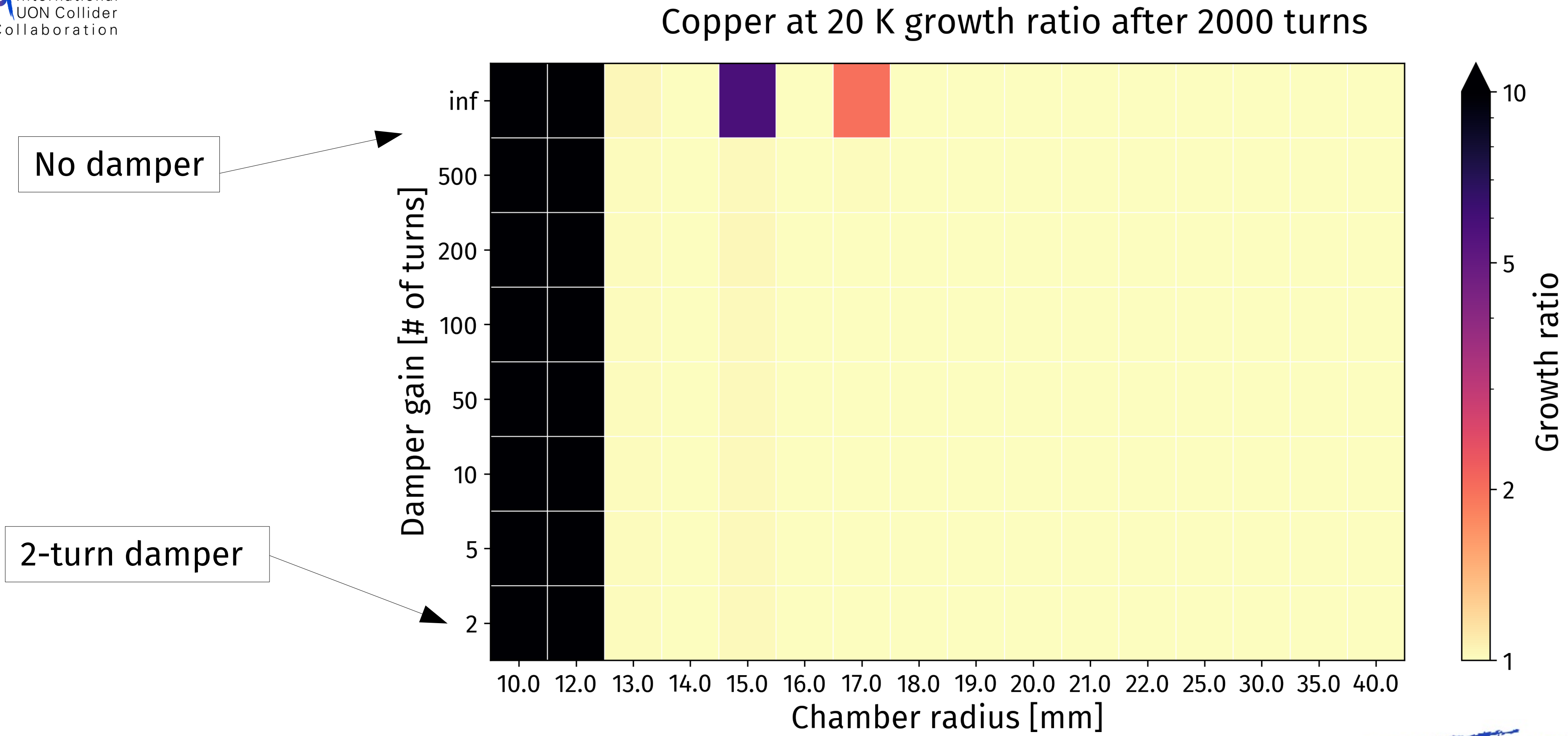
# Impedance for Tungsten at 300 K

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

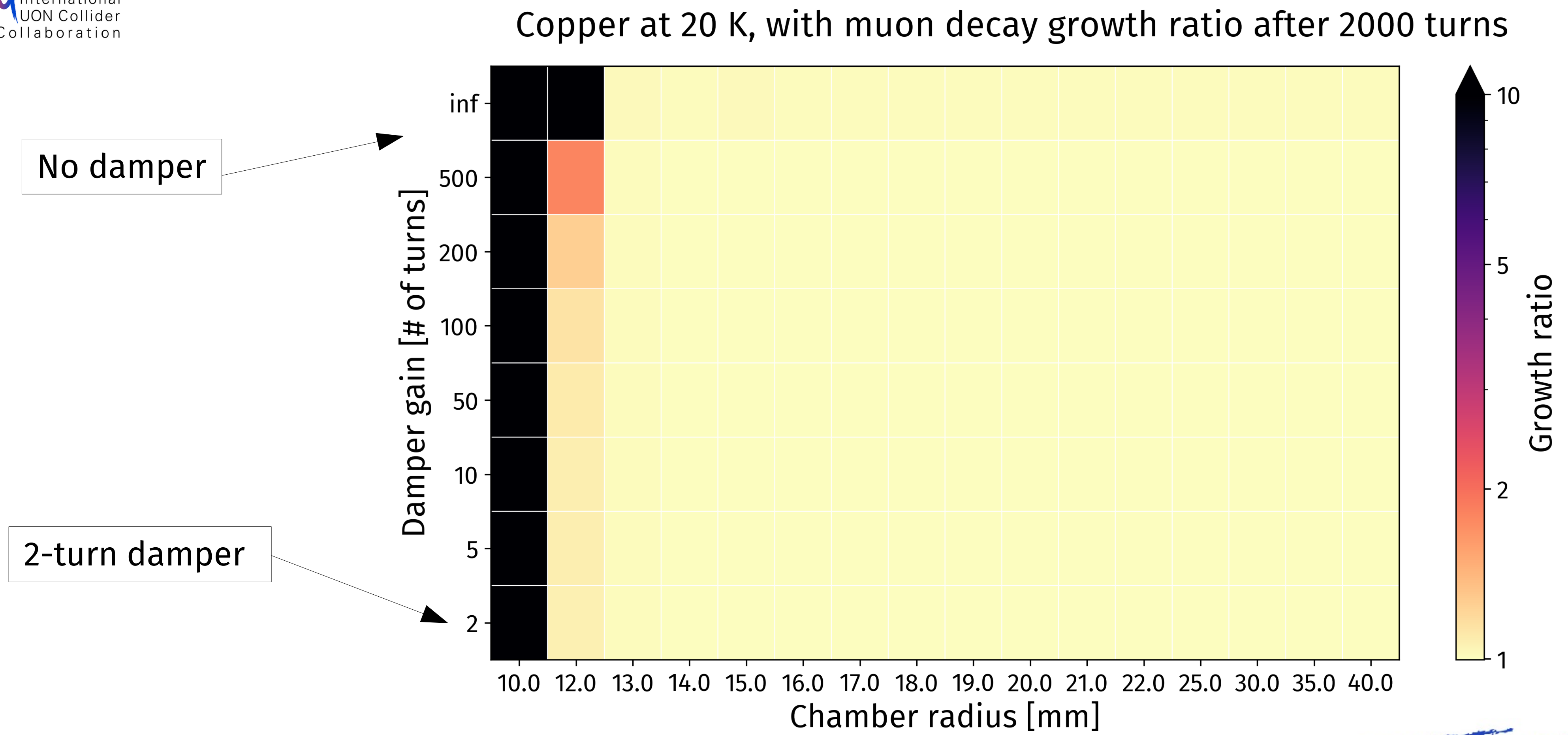



* Additional chamber radii not used for stability simulations

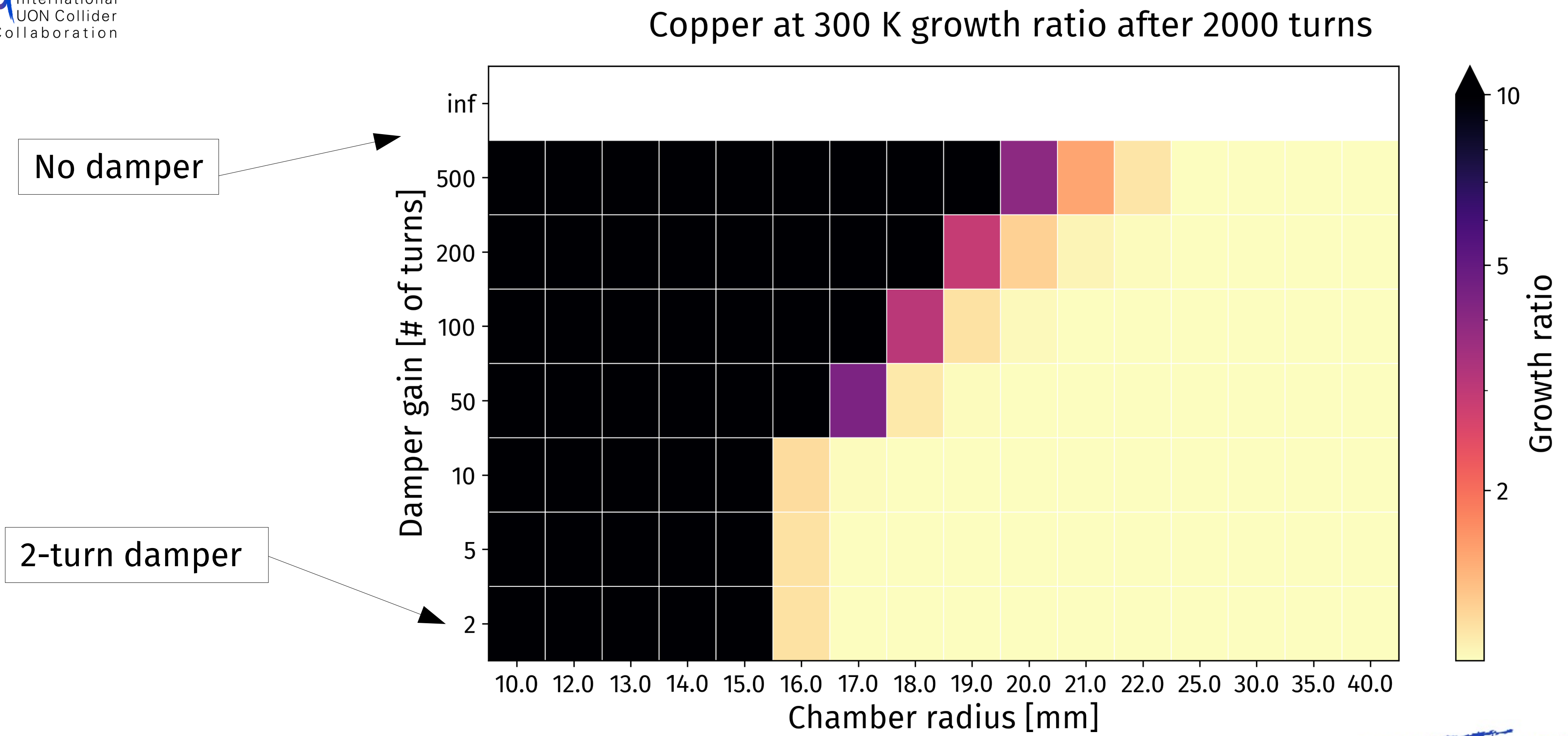
# Copper 20 K, after 2000 turns



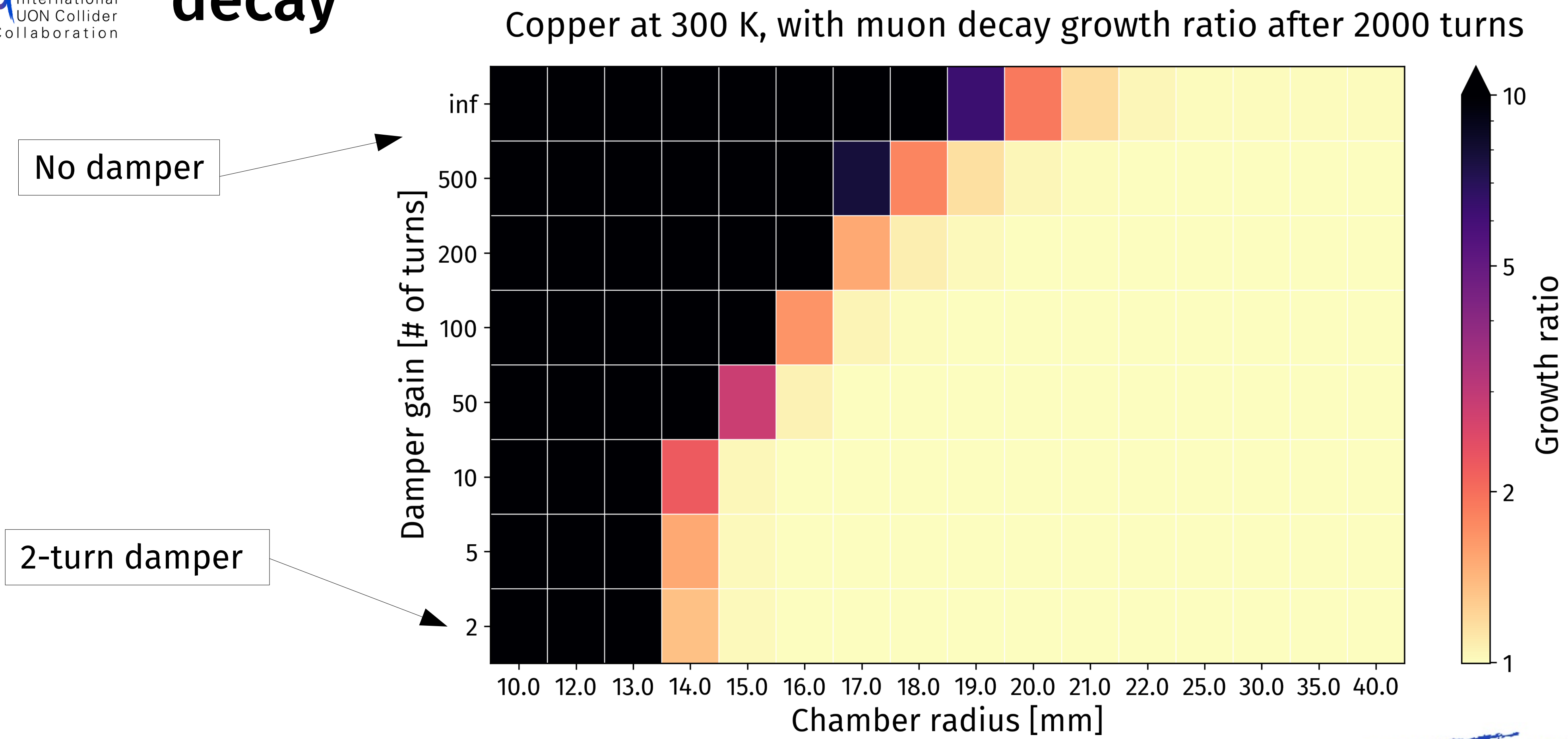
# Copper 20 K, after 2000 turns, with muon decay



# Copper 300 K, after 2000 turns



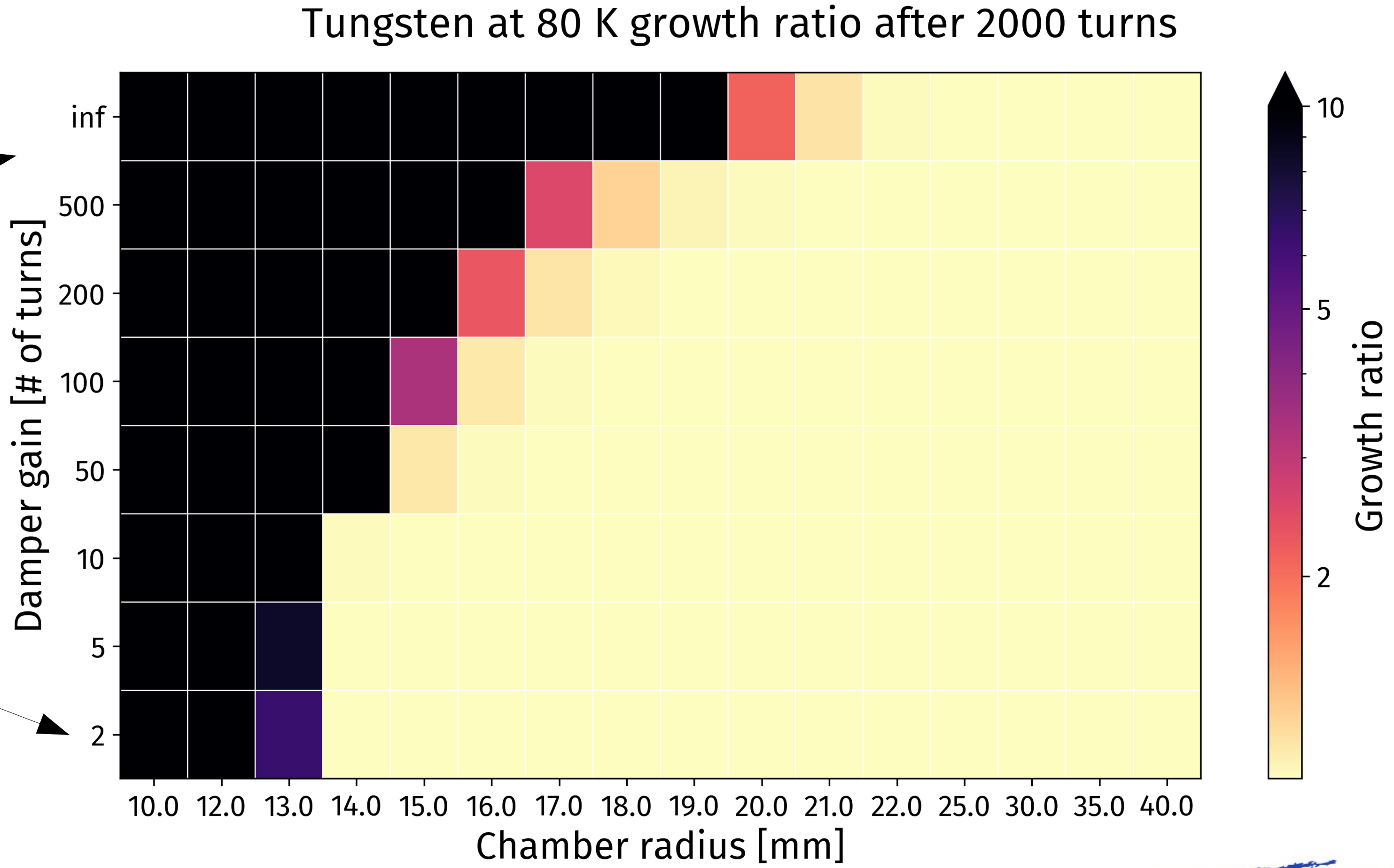
# Copper 300 K, after 2000 turns, with muon decay



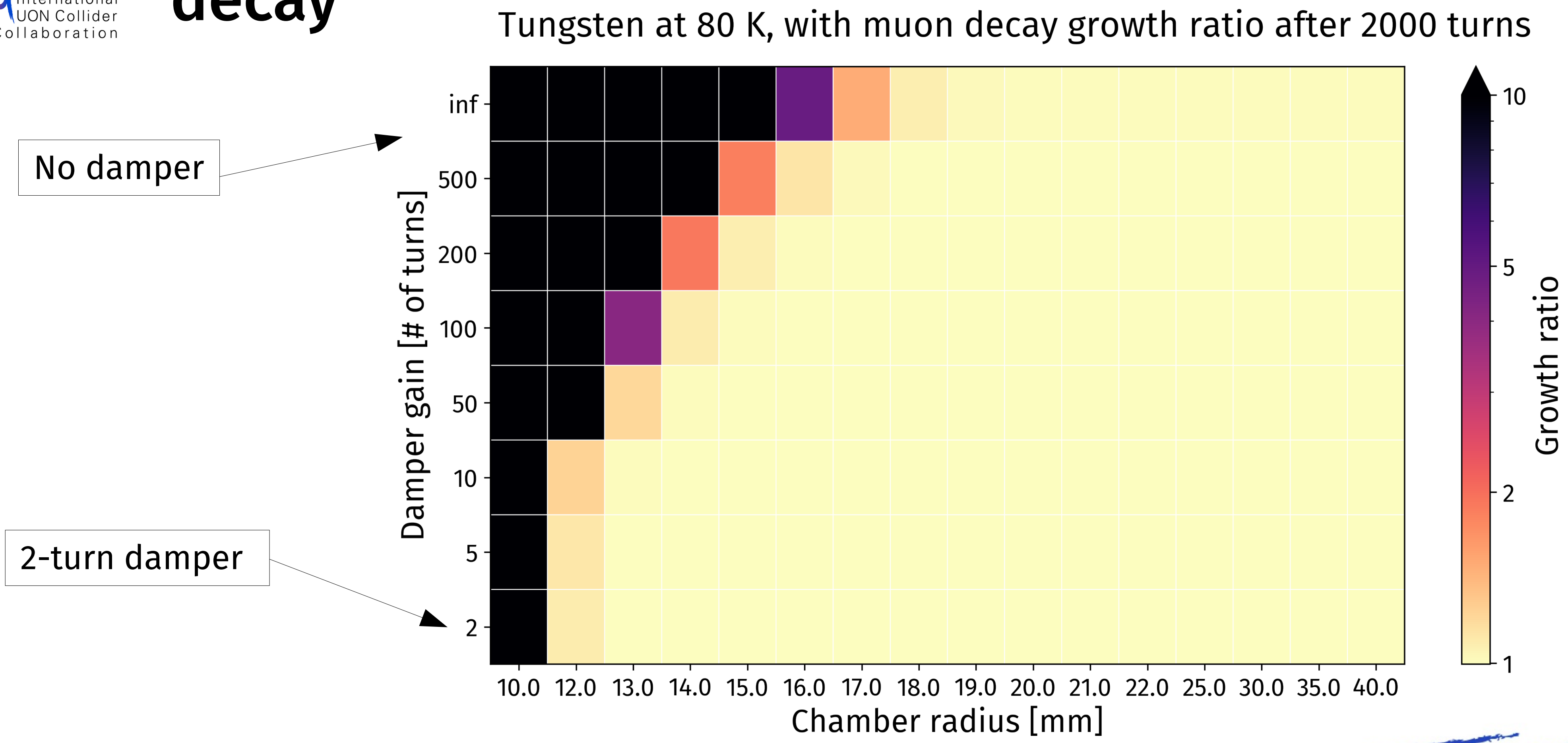
# Tungsten 80 K, after 2000 turns

No damper

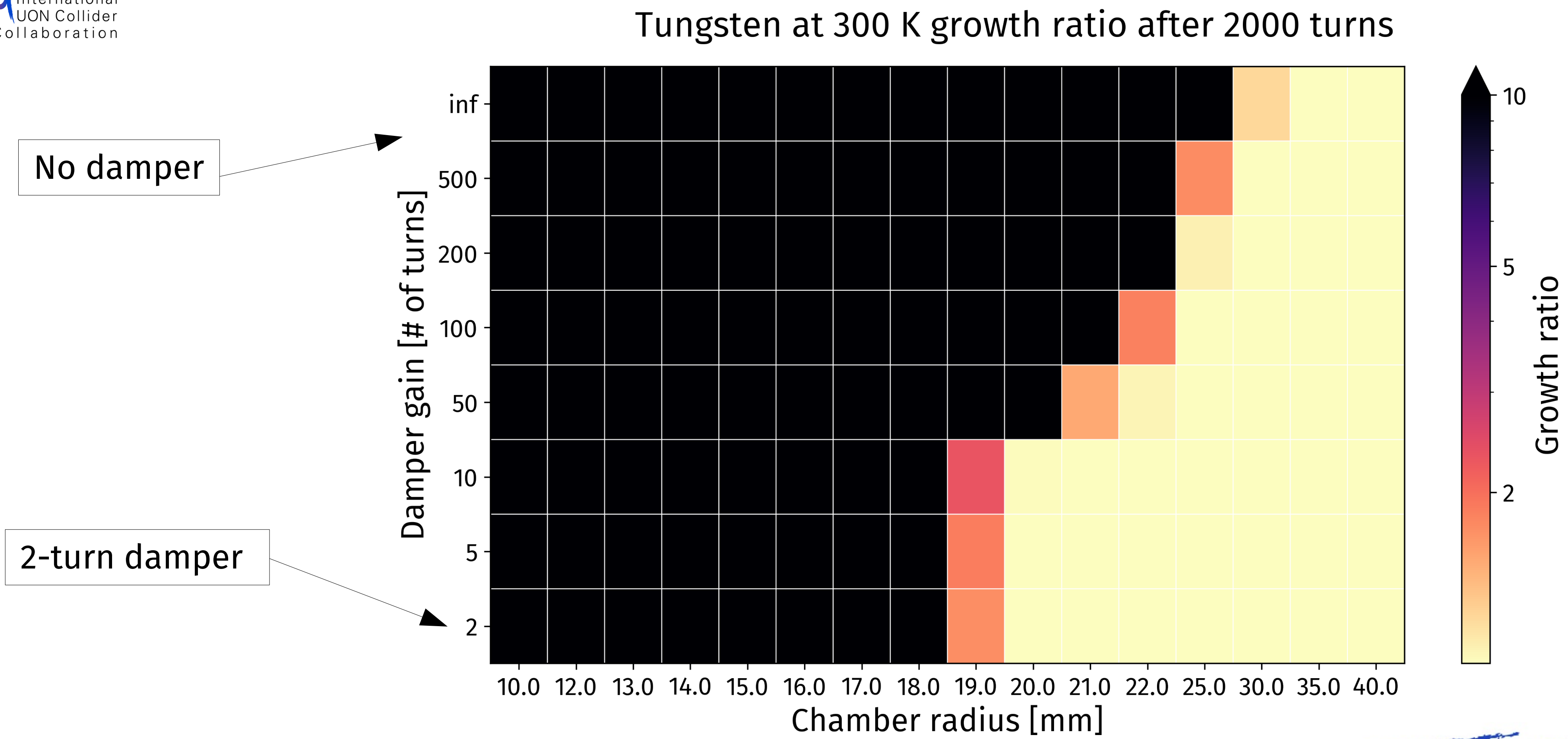
2-turn damper



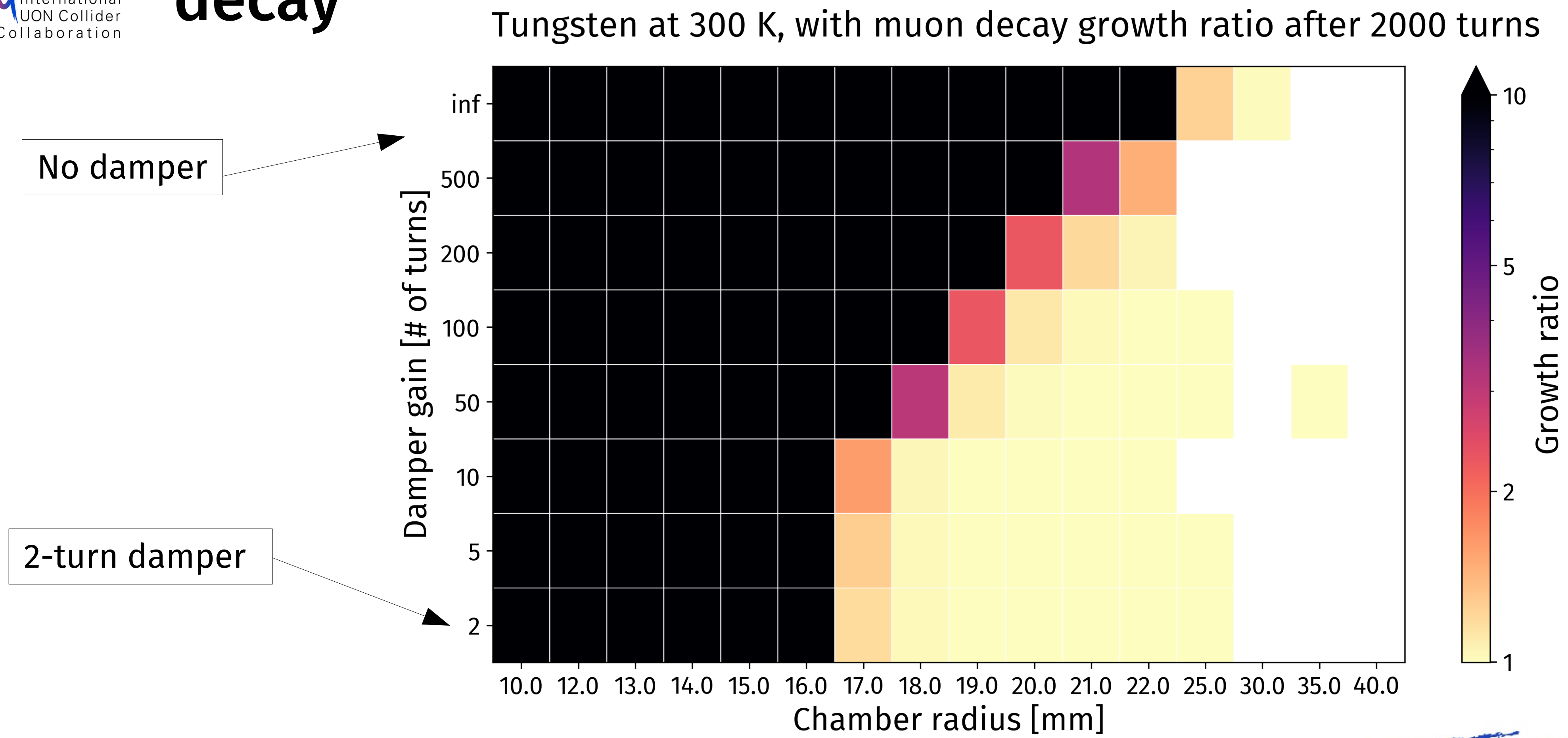
# Tungsten 80 K, after 2000 turns, with muon decay



# Tungsten 300 K, after 2000 turns



# Tungsten 300 K, after 2000 turns, with muon decay



# *Appendix: 10TeV collider*

# Impedance simulations parameters: materials

- Infinite thickness for all the chambers simulated

Copper at 80 K

| | Unit | Value |
|---|---|---|
| Magnetic field | T | 7 |
| Temperature | K | 80 |
| RRR | | 70 |
| DC resistivity | nOhm m | 2.35 |

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 |

# Stability simulation parameters

International UON Collider Collaboration

## Machine parameters

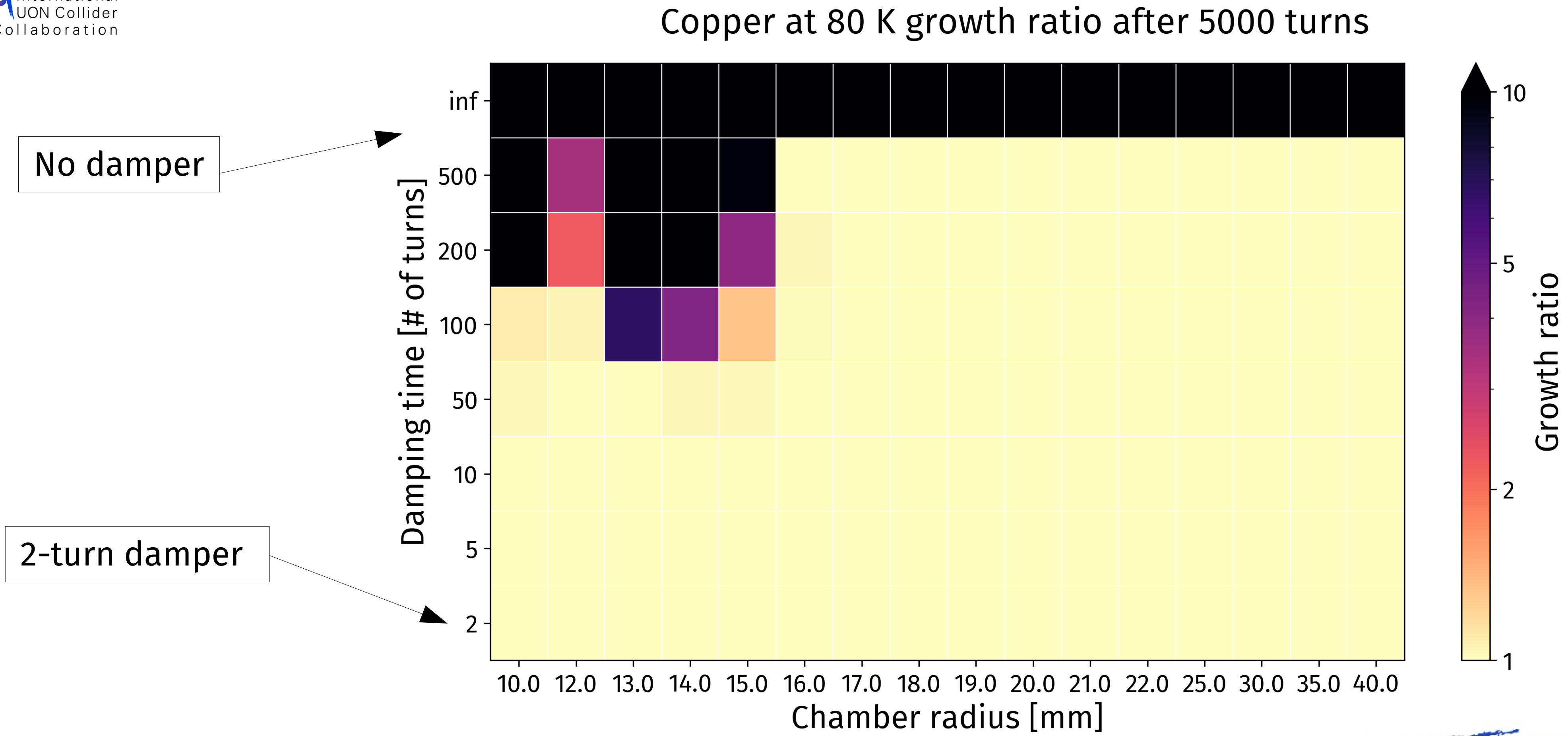
| | Unit | Value |
|---|---|---|
| Circumference | m | 10000 |
| Beam momentum | GeV/c | 5000 |
| Rev. frequency | kHz | 30 |
| RF frequency | MHz | 800 |
| Harmonic number | | 26685 |
| RF voltage | MV | 3200 |
| $\alpha_p$ | | -2.0e-6 |
| Avg. beta x/y | m | 85 / 51 |
| Chromaticity $Q'_x/Q'_y$ | | 0/ 0 |
| Detuning from octupoles x/y | $m^{-1}$ | 0 / 0 |

| | Unit | Value |
|---|---|---|
| Synchrotron tune $Q_s$ | | 0.00233 |
| Synchrotron period | turns | 429 |
| **Bunch length 1σ** | **mm** | **5** |
| **Bunch intensity** | **Particles per bunch** | **1.8e12** |
| **$\varepsilon_x$ / $\varepsilon_y$** | **µm rad** | **25** |
| # of macropaticles | | 20000 |

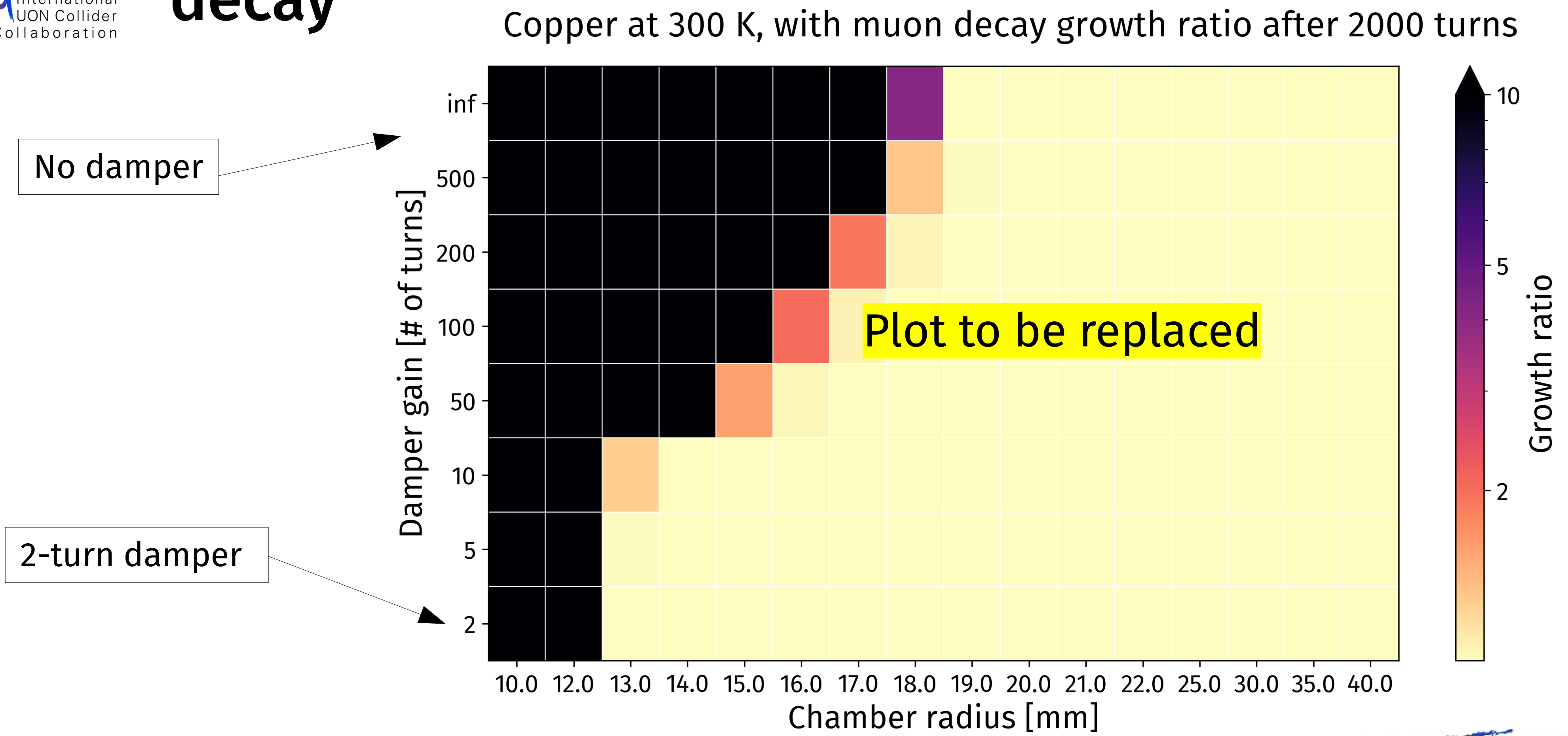
## Scanned parameters

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

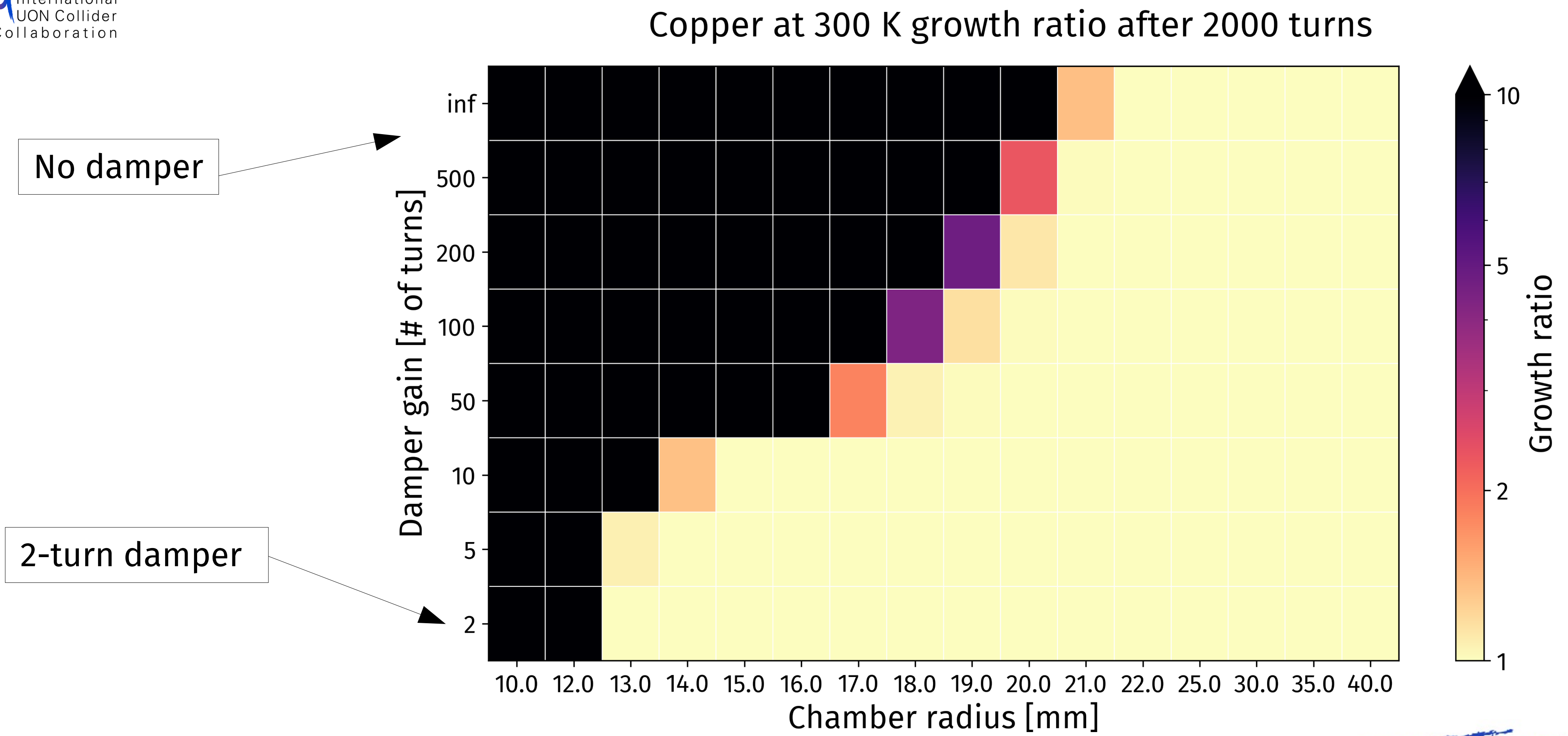
# Copper 80 K, after 2000 turns



# Copper 80 K, after 2000 turns, with muon decay



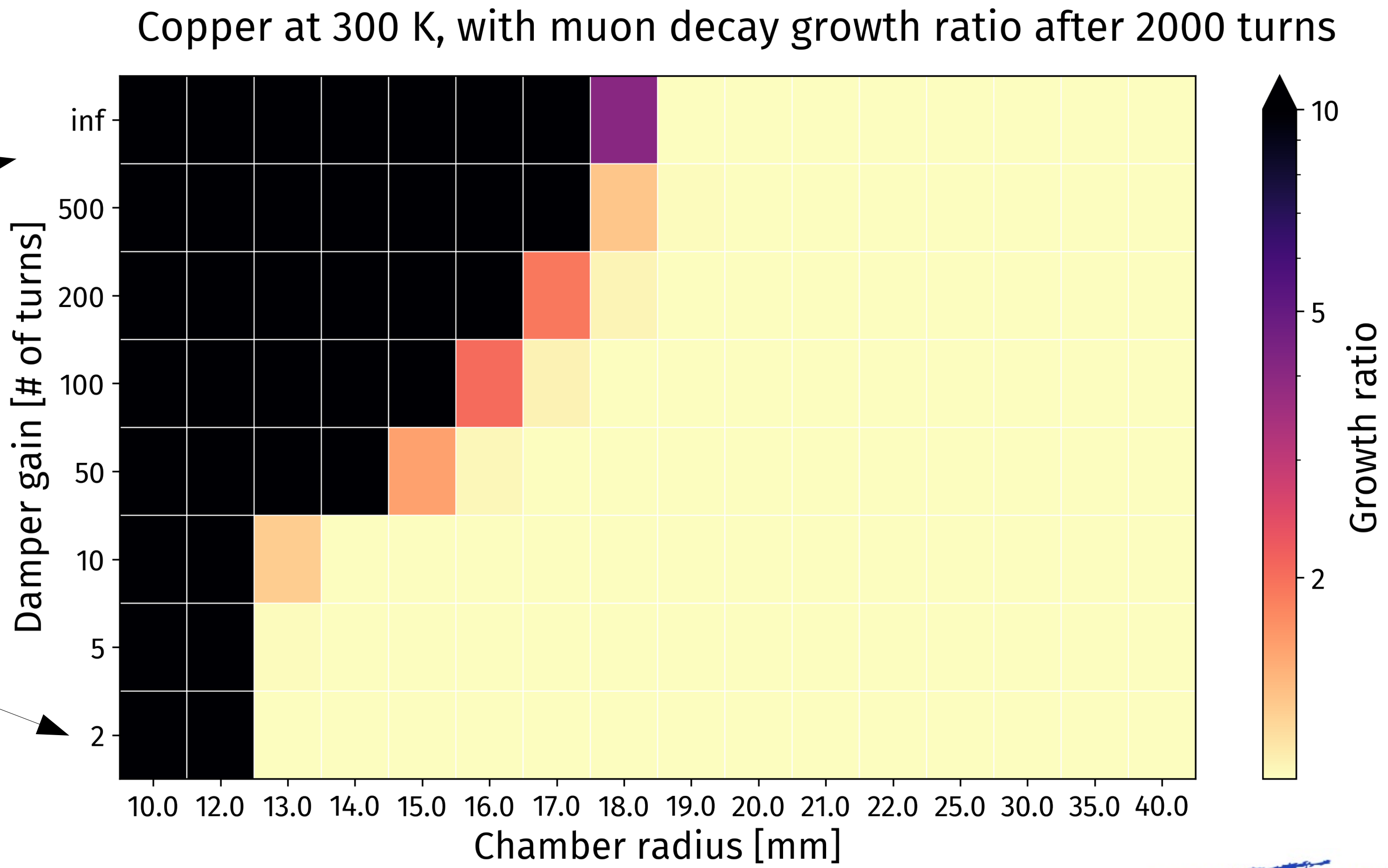
# Copper 300 K, after 2000 turns



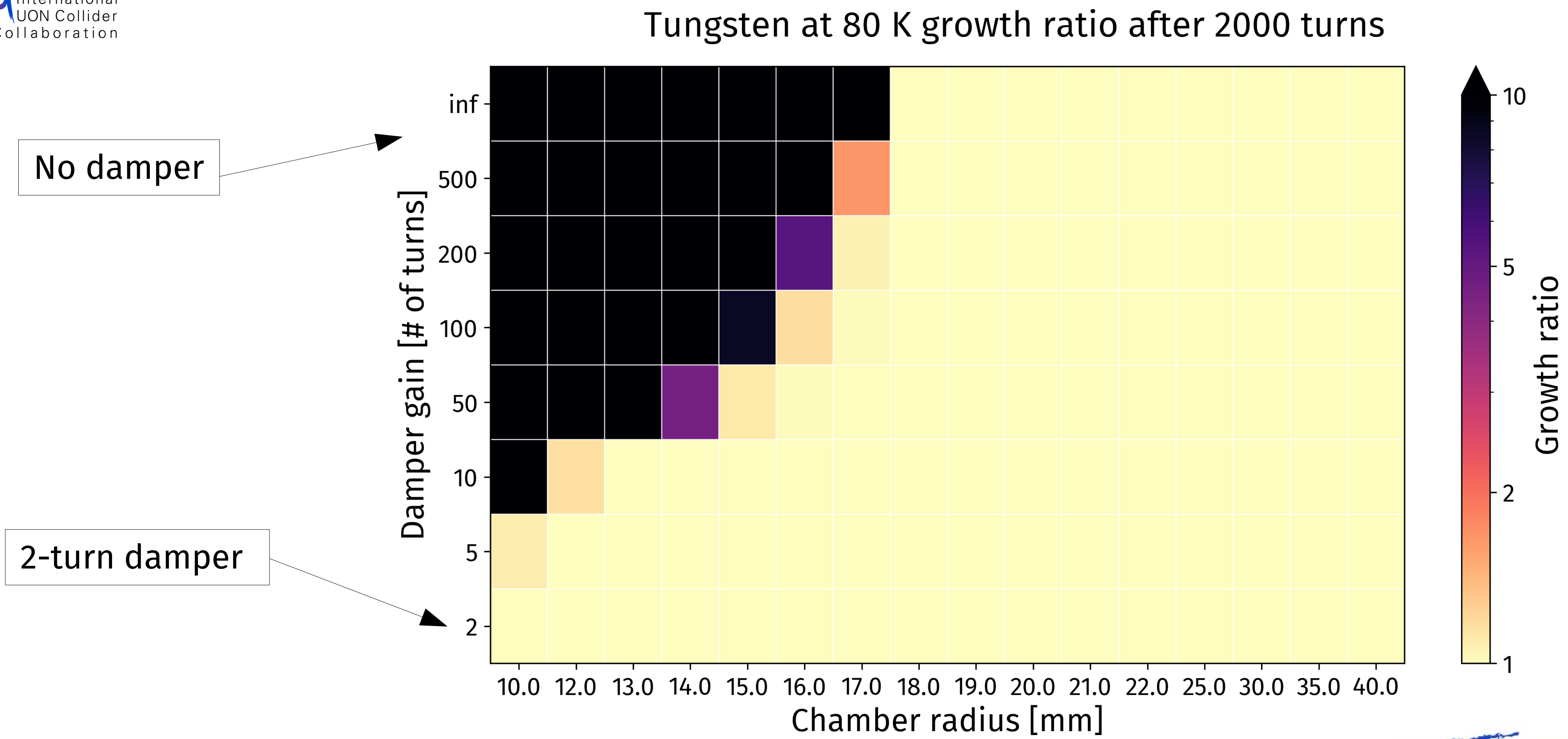
# Copper 300 K, after 2000 turns, with muon decay

No damper

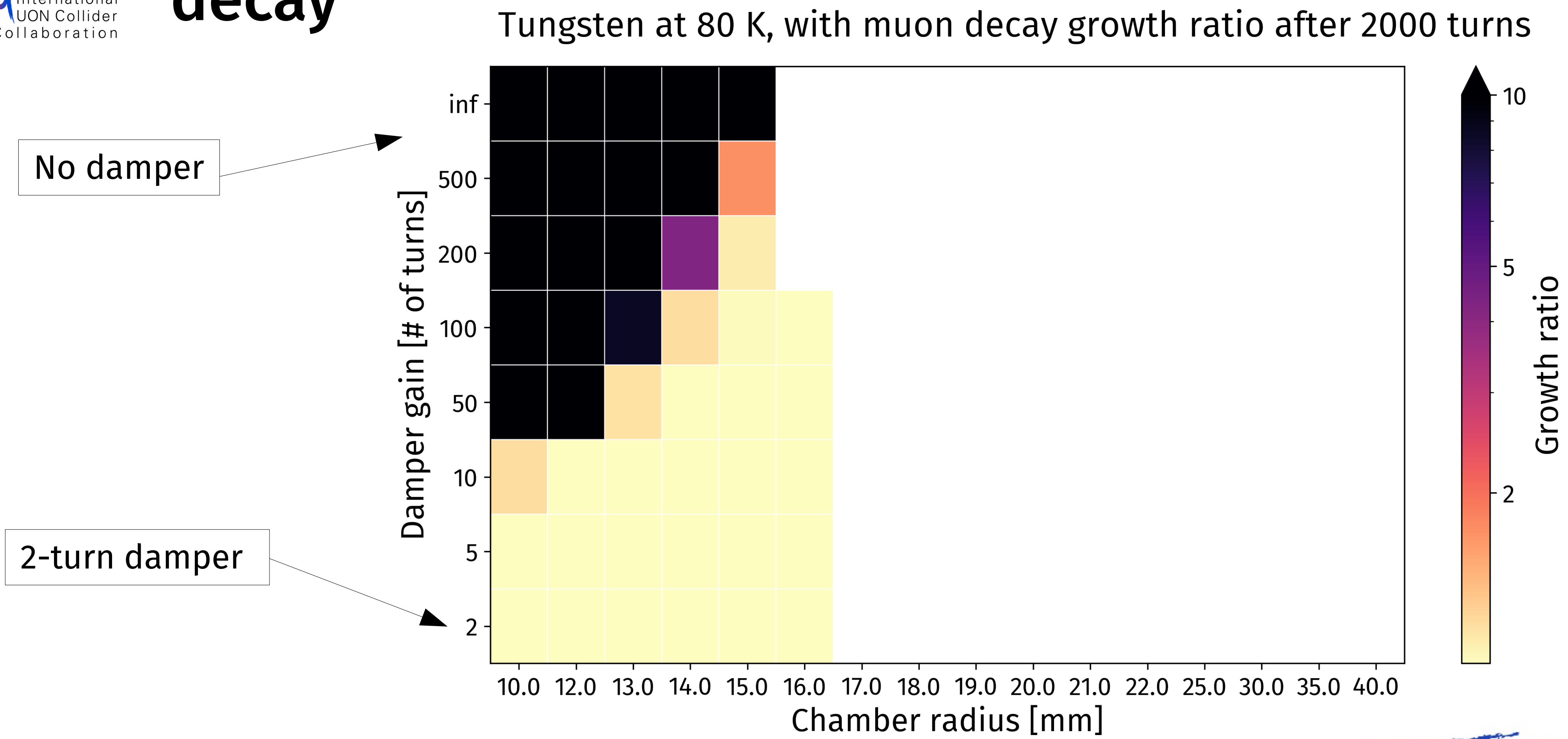
2-turn damper



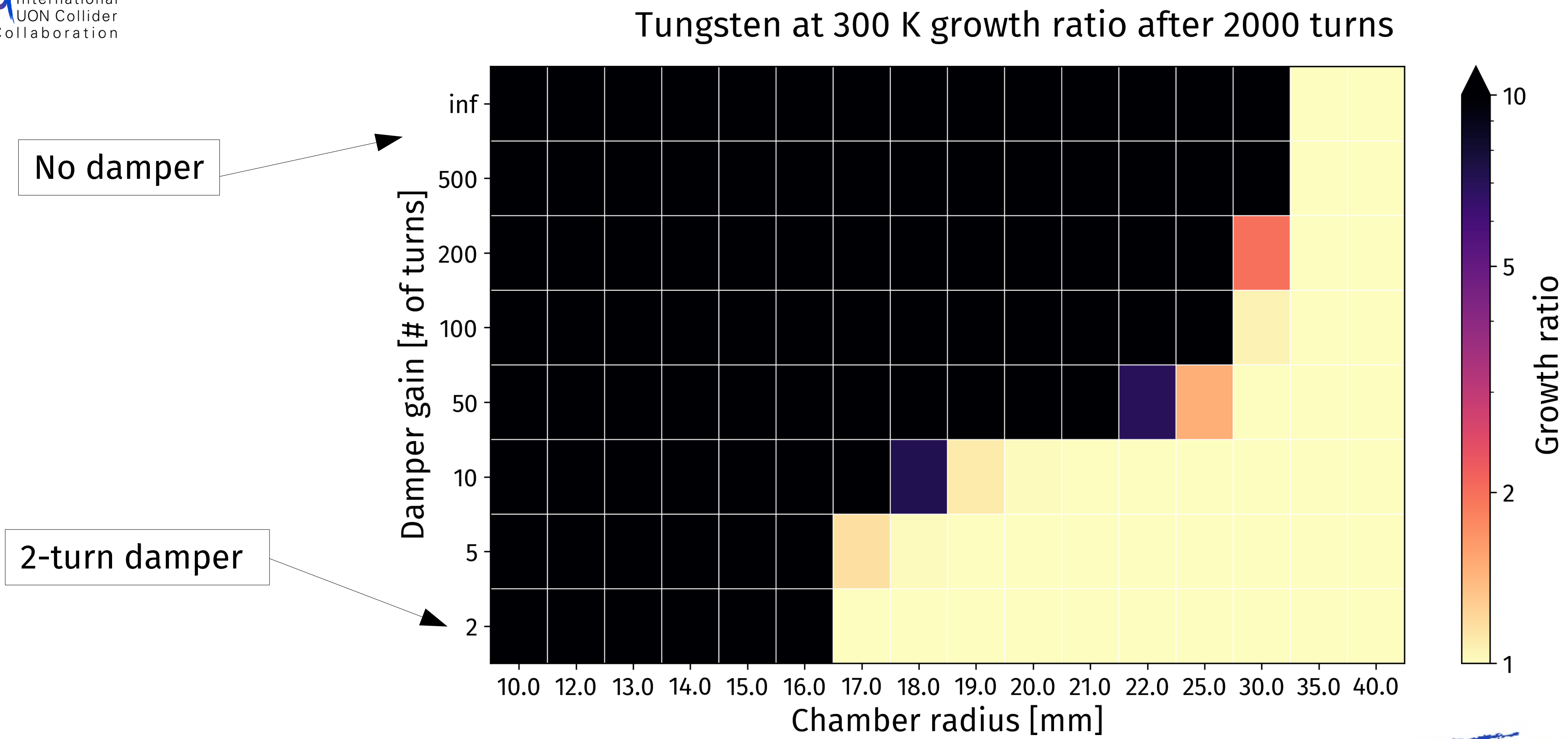
# Tungsten 80 K, after 2000 turns



# Tungsten 80 K, after 2000 turns, with muon decay



# Tungsten 300 K, after 2000 turns



# Tungsten 300 K, after 2000 turns, with muon decay