Wrap-up on Eddy Current Effects in the NC RCS Vacuum Chamber

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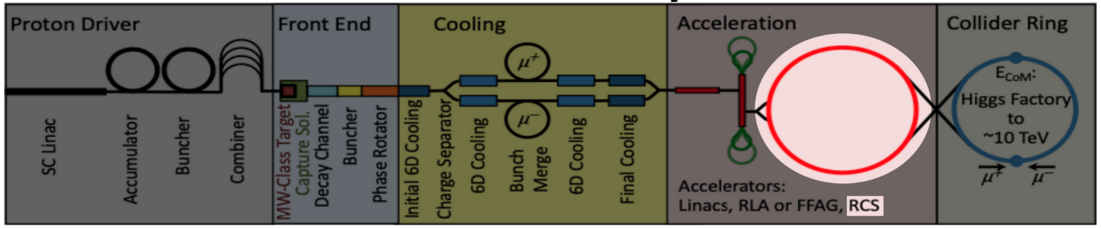
Overview

- Introduction
- Eddy Currents in Vacuum Chamber of Fast Ramping NC Magnets
- Impedance and Wakes
- XSuite stability simulations

Introduction

- The High energy complex of the Muon collider consists of a chain of **Rapid Cycling Synchrotrons** (RCS)
- **Goal:**
  - Accelerate muon **from 63 GeV to 5 TeV.**
  - This acceleration must occur within **approximately 10 ms** to ensure a muon **survival rate** of **at least 65%.**
- The magnetic field strength must ramp with the muons' energy, causing **rapid changes of the magnetic field.**
- These rapid changes induce Eddy currents within conductive materials, leading to both **field distortions** and **power losses**.
- This study aims to understand the **magnitude of the eddy currents** generated under extreme ramp conditions and **explore vacuum chamber designs** that both minimizes these undesirable effects while keeping beam coupling **impedance** low.

Schematic layout of Muon Collider complex



RCS	$\dot{B}$ (T/s)
1	4200
2	3282
3	1519
4	565

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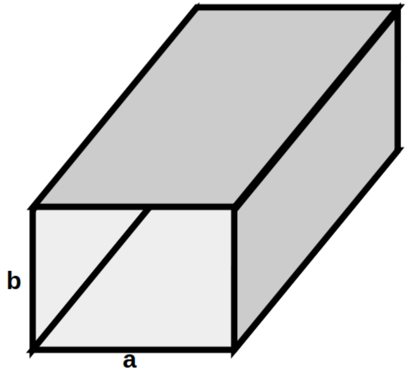
Eddy Currents in the NC Magnet's Vacuum Chamber

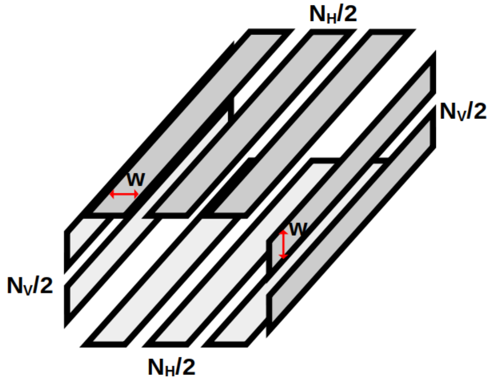
- The **ohmic loss per unit length** due to eddy currents in two different designs was investigated
- By assuming a uniform, time-varying magnetic field the ohmic loss per unit length can be derived analytically under certain additional conditions.

Rectangular vacuum chamber



$$P_{rectangular}/L = \frac{\dot{B}^2 a^2 d\sigma}{2}(\frac{a}{3} + b)$$

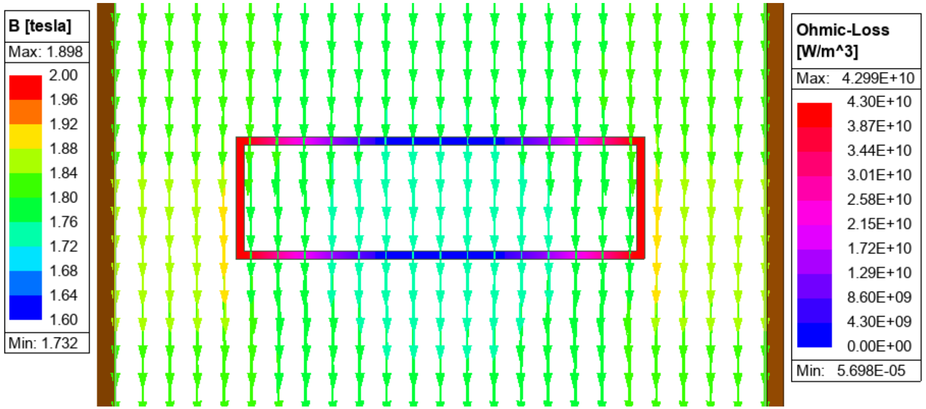
Longitudinally striped design



$$P_{striped}/L = \frac{\dot{B}^2 w d\sigma}{3}(\frac{N_H w^2}{4} + N_V d^2)$$

Electromagnetic simulation

- Uncertainties arise regarding the analytical formula's applicability due to the rapid ramp rates of the RCS.
- **Ansys Maxwell2D** was used to validate the analytical formula by comparing with **electromagnetic simulations** for conditions similar to the ones of the RCS.
- In these simulations a **uniform magnetic field** is created between two large conducting plates, excited by an alternating current with **frequency *f***. The field strength at any point is approximately given by:



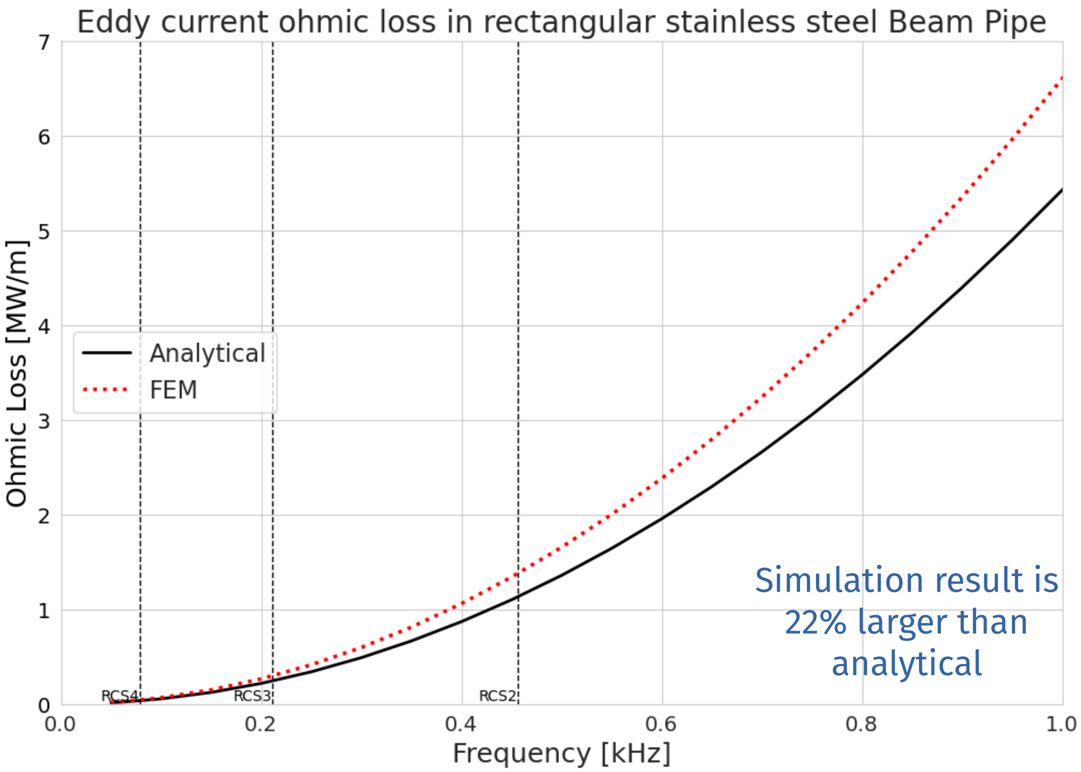
$$B(t) = B_0 cos(2\pi f \cdot t)$$

Stainless Steel Rectangular Vacuum Chamber

Stainless steel:

- Conductivity: 1.1×10^6 S/m
- Height and width: 30X100mm*
- Thickness: 0.3mm

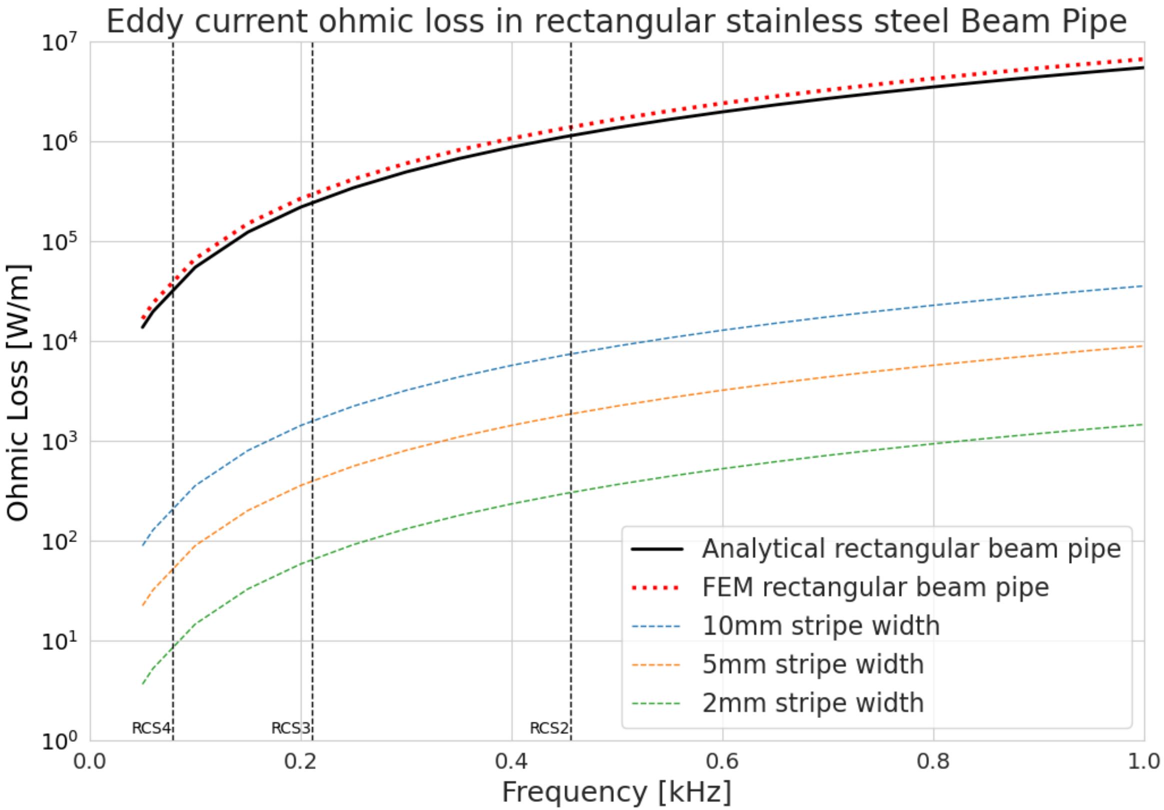
*(Tentative Parameter list for the IMCC)



Energy loss per cycle for rectangular beam pipe:

RCS:	2	3	4
Energy loss [J/cycle/m]	2462	1143	425

Longitudinal striped design



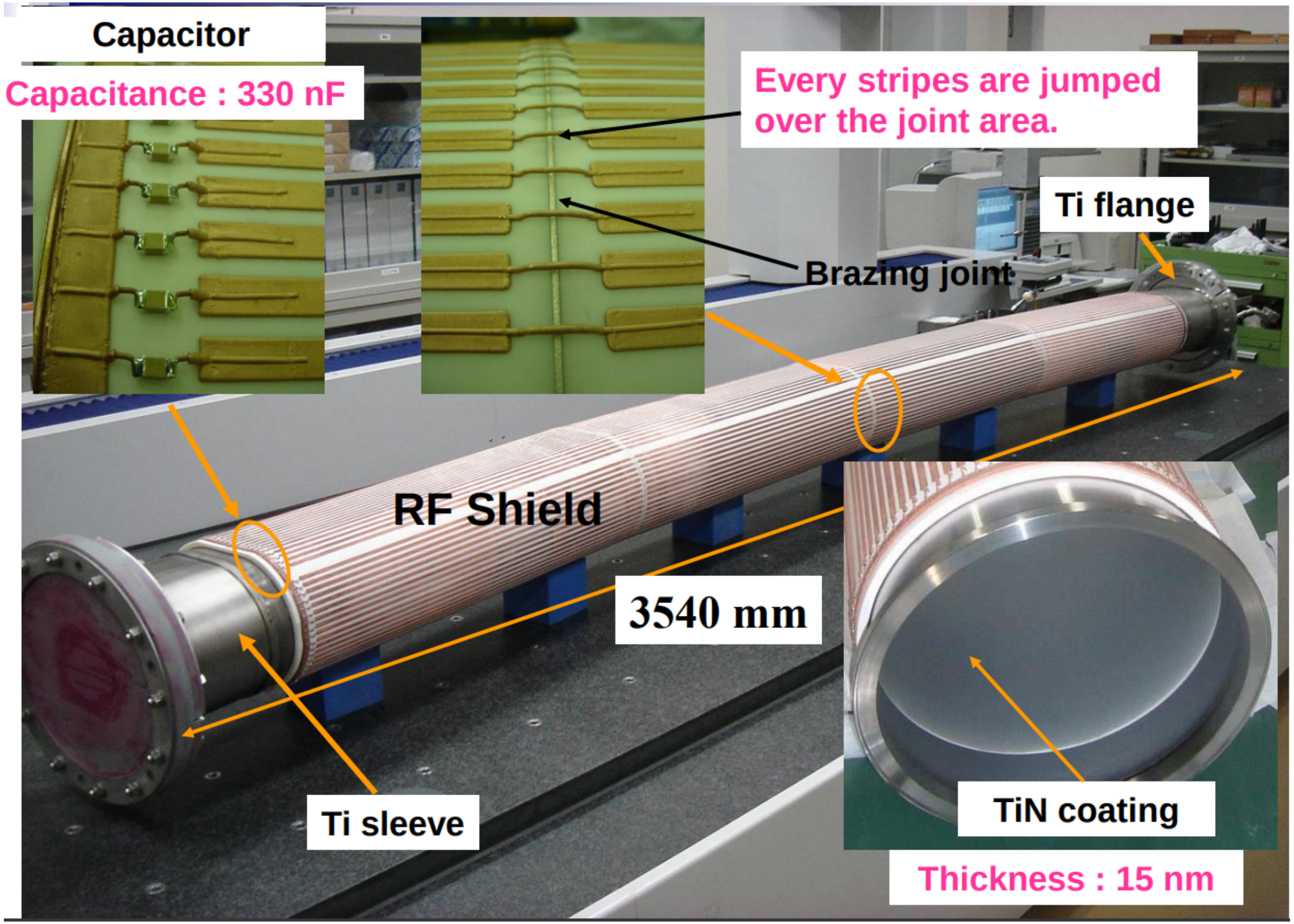
By changing to a striped design, while keeping the thickness unchanged, we see a reduction of ohmic loss of **2-3 orders of magnitude** depending on the width of the stripes.

This assumes the parallel stripes to be touching. In reality we would have some spacing between them. This will in turn reduce the number of stripes and thus the ohmic loss further.

Energy loss per cycle for the longitudinally striped design:

	RCS:	2	3	4
10 mm stripe width	Energy loss [J/cycle/m]	16.01	7.43	2.76
5 mm stripe width	Energy loss [J/cycle/m]	4.01	1.86	0.69
2 mm stripe width	Energy loss [J/cycle/m]	0.65	0.30	0.11

Example from J-PARC



(Michikazu Kinsho, 2005)

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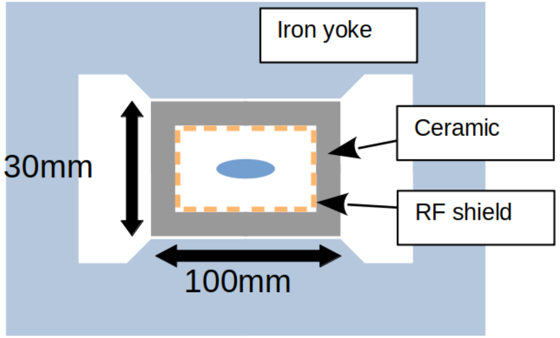
Vacuum Chamber Impedance

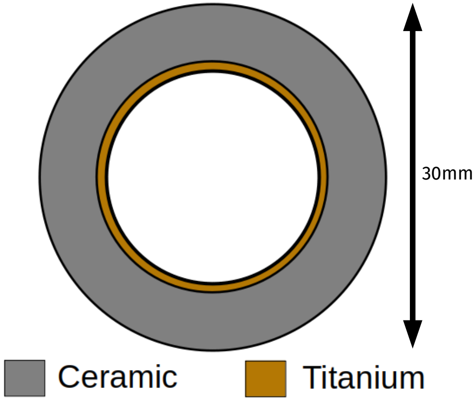
- The vacuum chamber is expected to be a **large contributor to the total impedance** of each RCS because …
  - The NC sections makes up between 41% and 61% of each RCS and
  - The magnet aperture is quite small at 30x100mm and it needs to house both the ceramic layer (~5mm) and RF shield.
- The impedance of two different simplified vacuum chambers was **computed using IW2D**.
- The vacuum chambers was assumed to be **circular** and the **RF shield was modeled as a uniform layer***.

Machine	RCS1	RCS2	RCS3	RCS4
Cicumference (m)	5990	5990	10700	35000
NC Section (m)	3655	2539	4366	20376
SC Section (m)	0	1115	2358	4257

NC magnet and beam pipe cross section



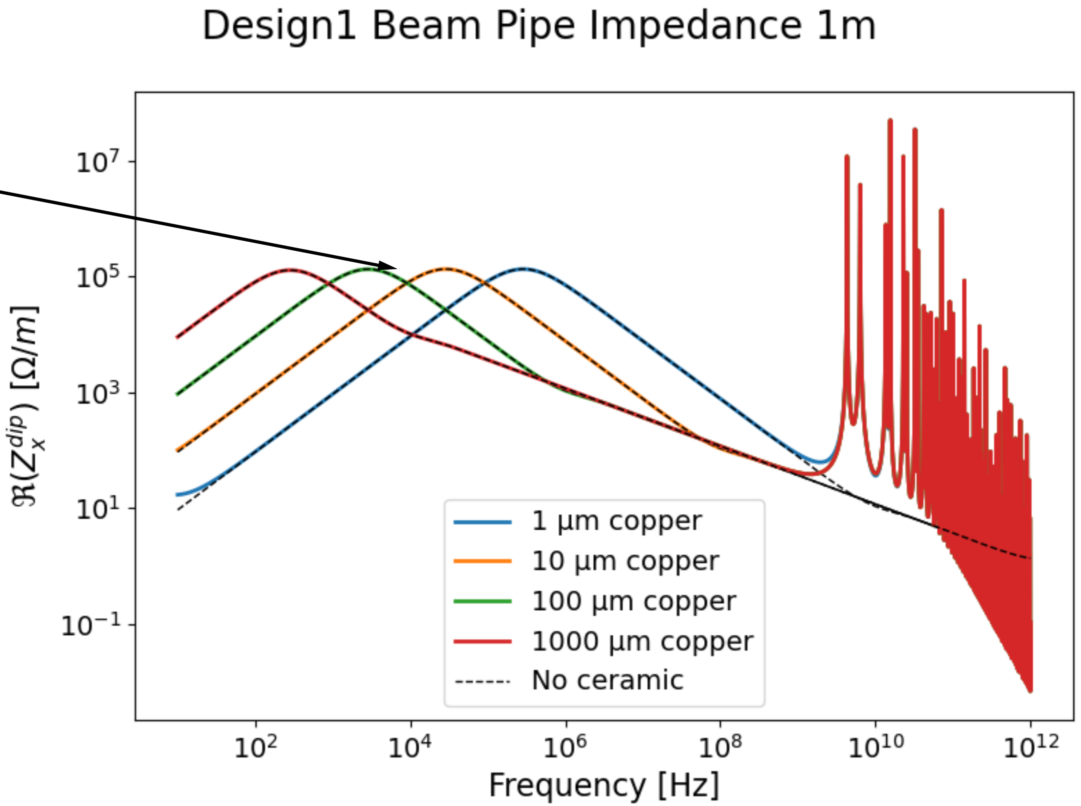
Simplified Vacuum Chamber Cross Section



*Y. Shobuda et al.

RF-Shield Outside Ceramic

- Changing the copper thickness has an impact on the lower frequency region of the impedance.
- However there are resonances caused by the ceramic that remains unaffected by the change in copper thickness.
- The impedance of these resonances are orders of magnitudes larger than the resistive-wall impedance we get without the ceramic layer.



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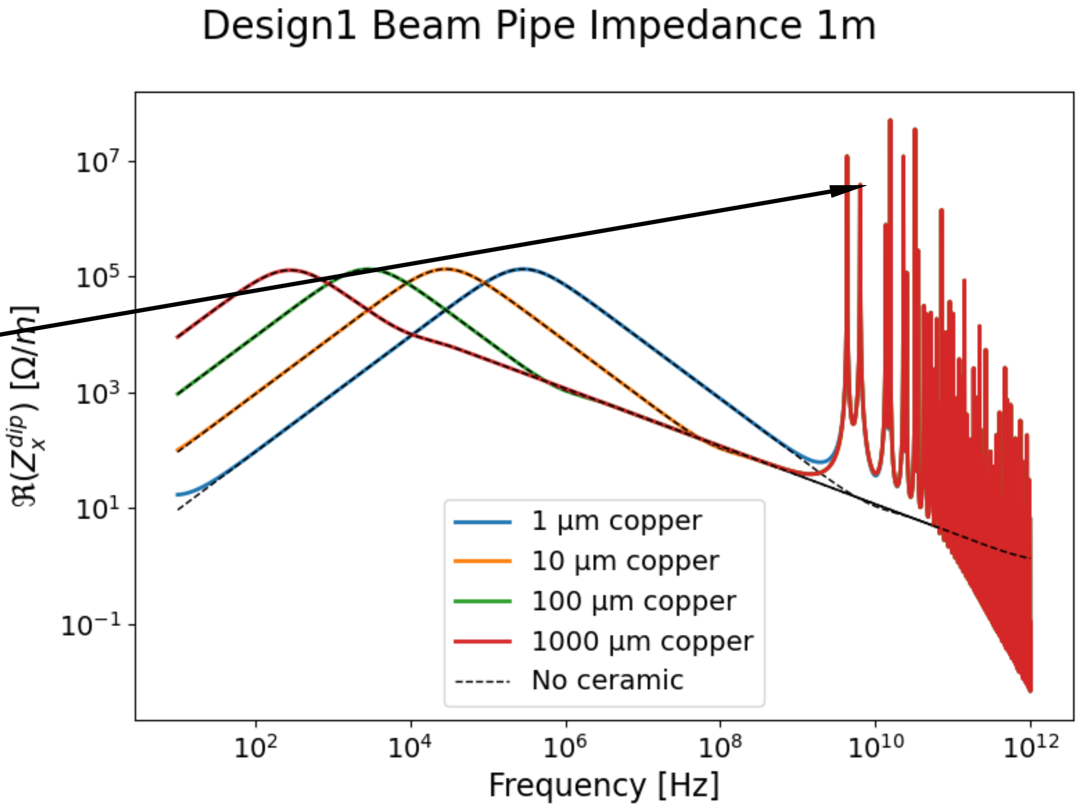

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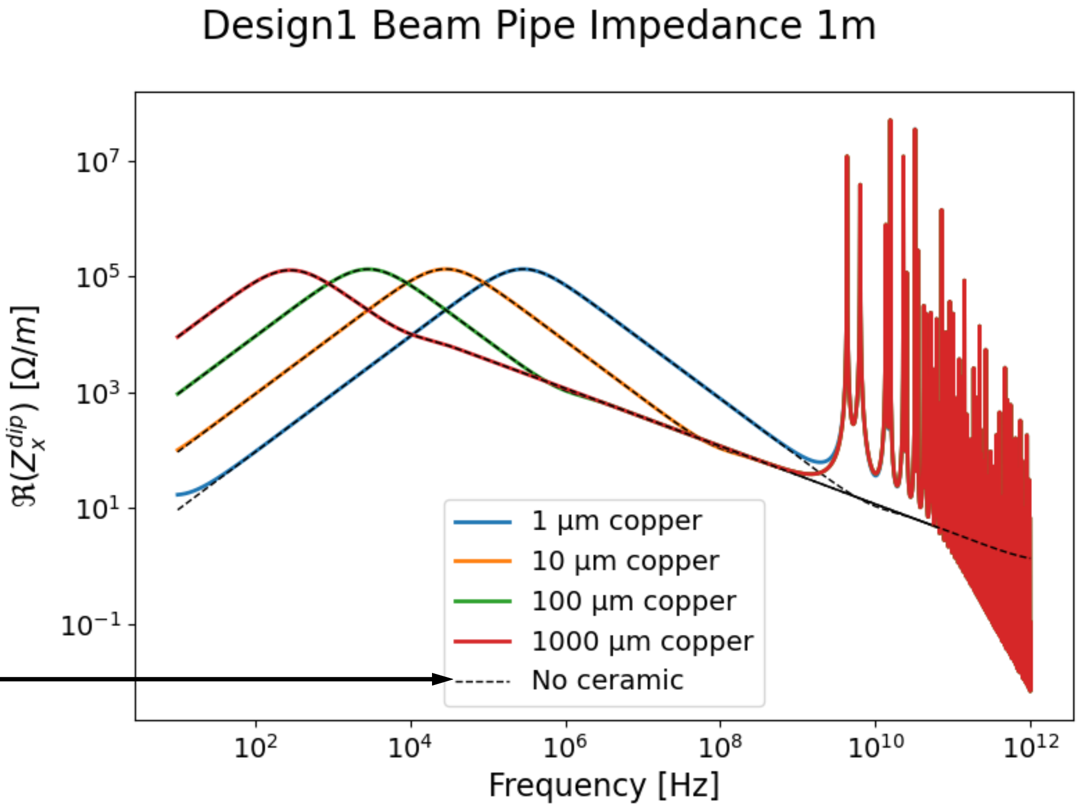
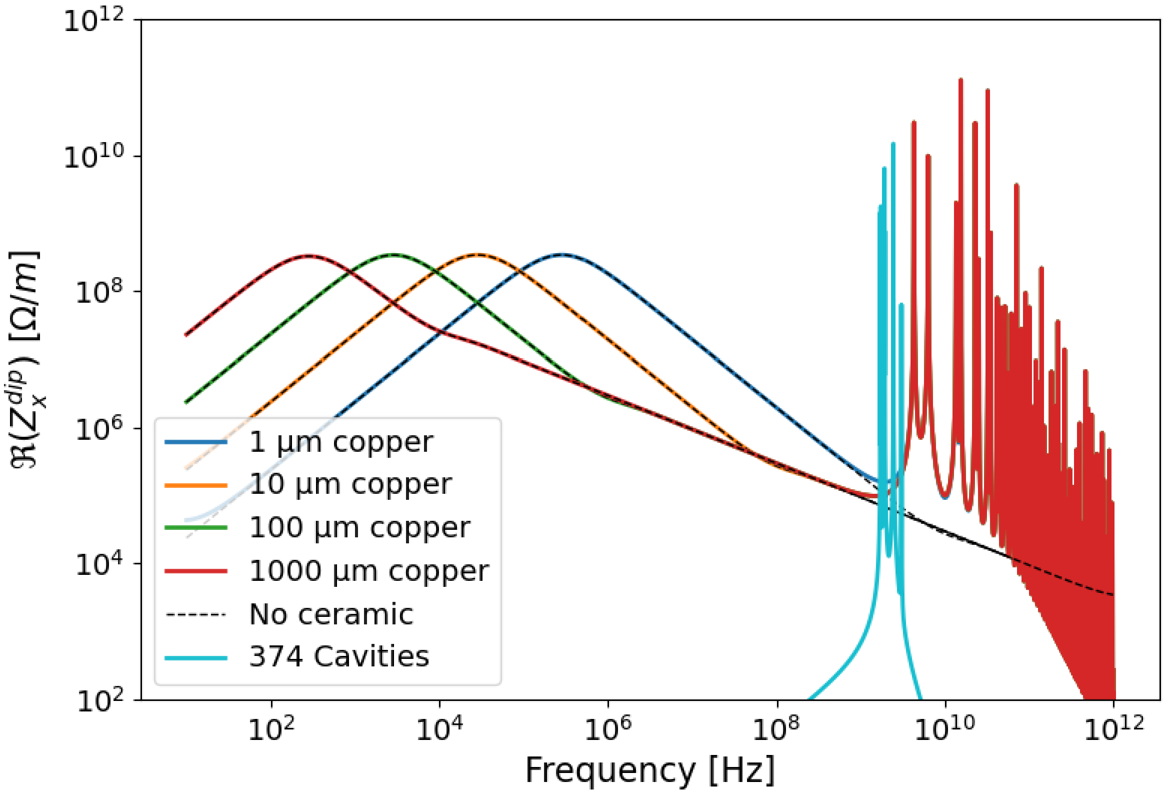


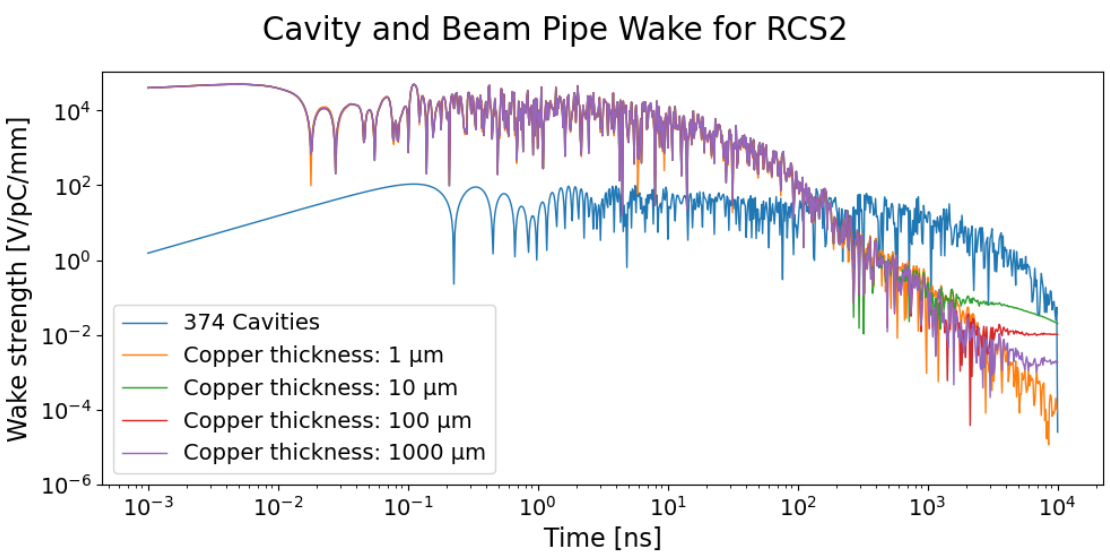
Comparison of Beam Pipe and Cavity Impedance for RCS2

- **RCS2 Specifications:**
  - Beam pipe length: **2539 m** (NC magnet length)
  - Number of cavities: **374**
- The resonances caused by the ceramic are **significantly larger** than the ones from the cavities.
- David has shown that the impedance from the cavities is already close to **the instability threshold** in the 4 RCS chain simulation.
- Given that the resonances from the beam pipe are ~10x greater than those from the cavities, **a stable beam is not achievable with this design.**



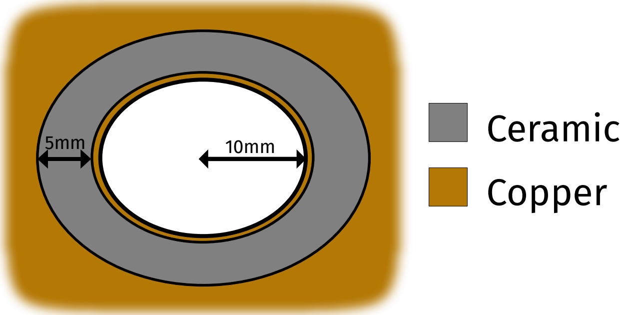
RCS2 Cavity and Beam Pipe Wake

- The **wake** was computed from the impedance in order to run XSuite simulations.
- As expected from the impedance plot, the beam pipe wake is **significantly larger** than the cavity wake.
- Changes in the **copper thickness have little impact on the beam pipe wake** due to the dominance of the ceramic resonances.
- The full RCS chain XSuite simulations showed, consistent with our expectations, that **all the particles were lost within the first two RCS**.

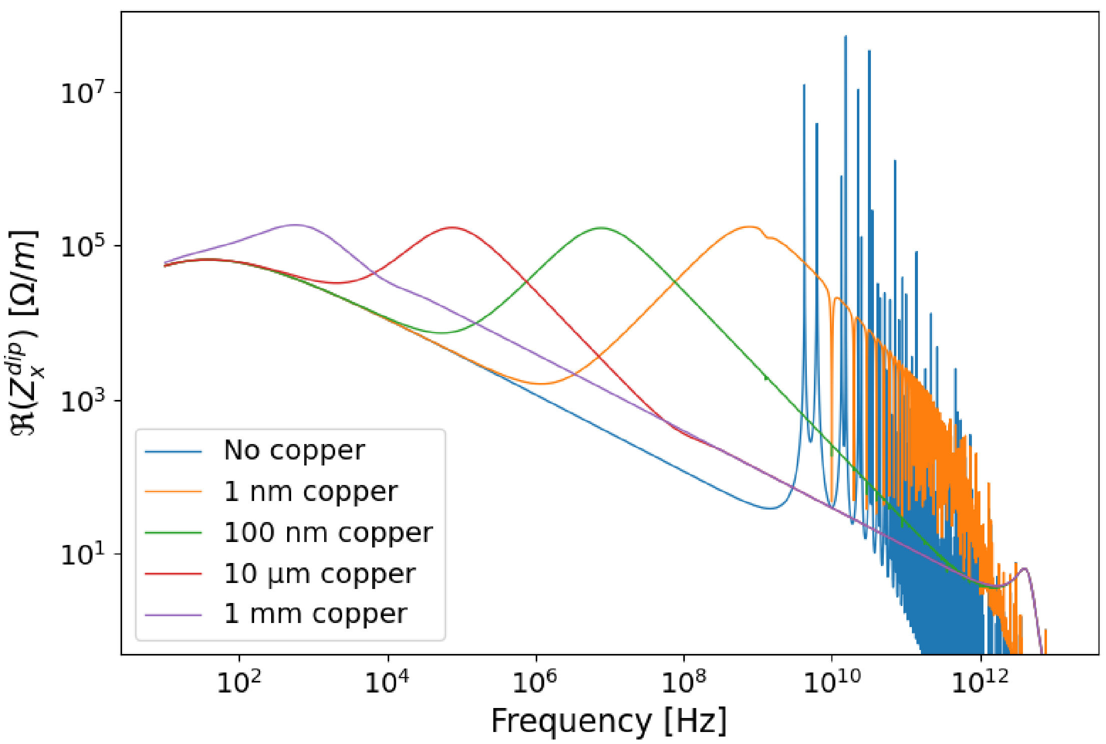


RF-Shield Inside Ceramic

- Even with a very thin (~nm) layer of copper we are able to **suppress the resonances** we saw in Design 1.
  - This effect is explained by Zotter on page 168 in "Impedances and Wakes in High Energy Particle Accelerators"
- Increasing the thickness of the copper layer can significantly **reduce the impedance at higher frequencies**.

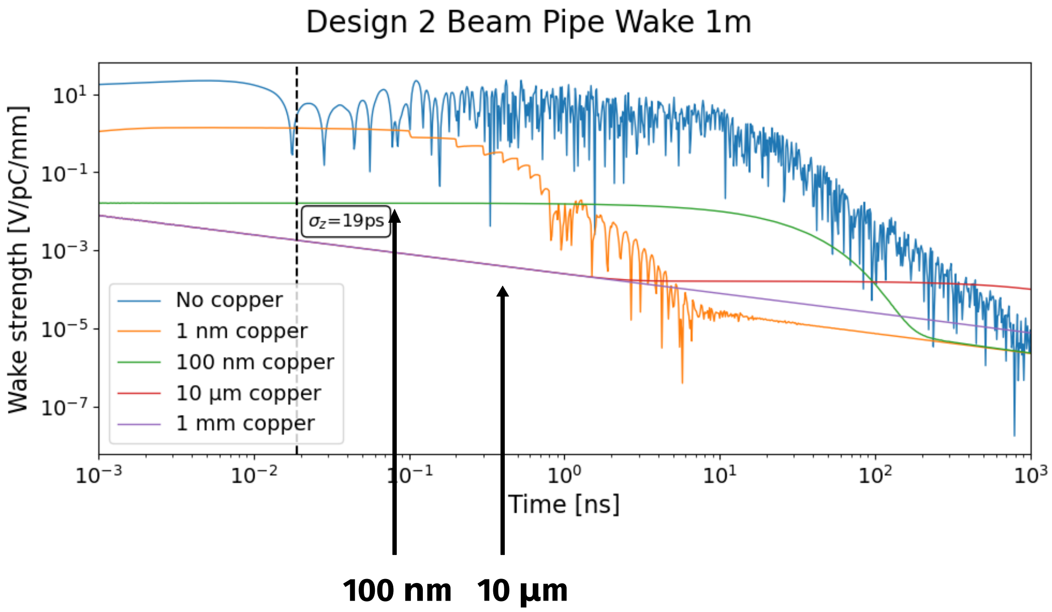


Design 2 Beam Pipe Impedance 1m



RF-Shield Inside Ceramic

- The wake has a **strong dependence on the thickness** of the copper layer. By decreasing the copper thickness, we see an increase in the wake magnitude.
- By setting the copper thickness to zero, we are essentially left with Design 1 with an infinitely thick copper layer.
- To determine the thickness of copper needed to provide sufficient RF-shielding to the beam, we will conduct full **RCS chain simulations** using XSuite.



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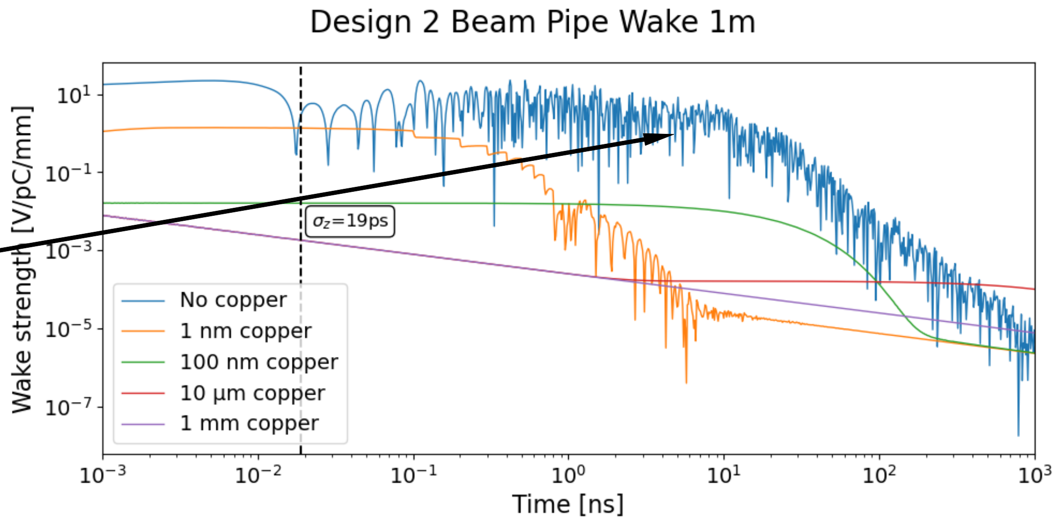

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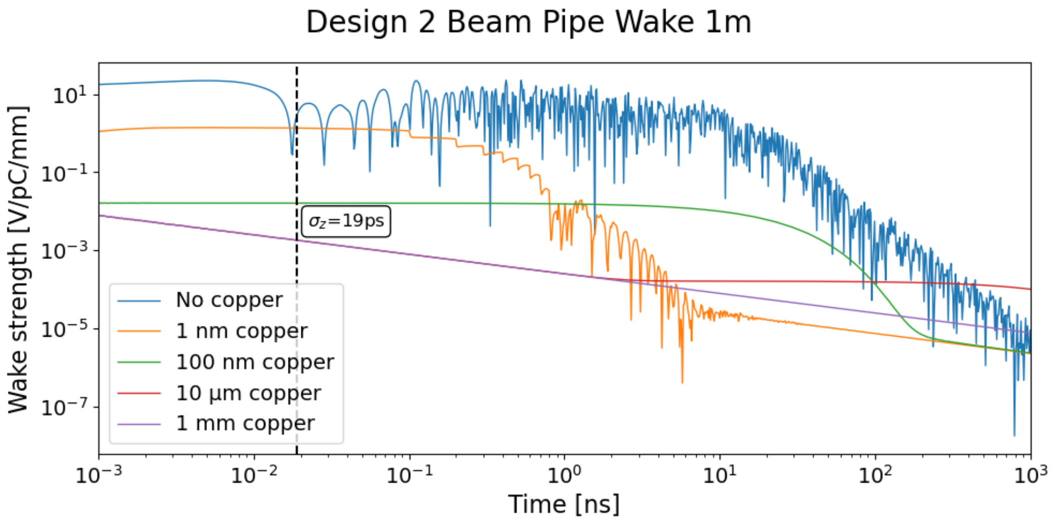
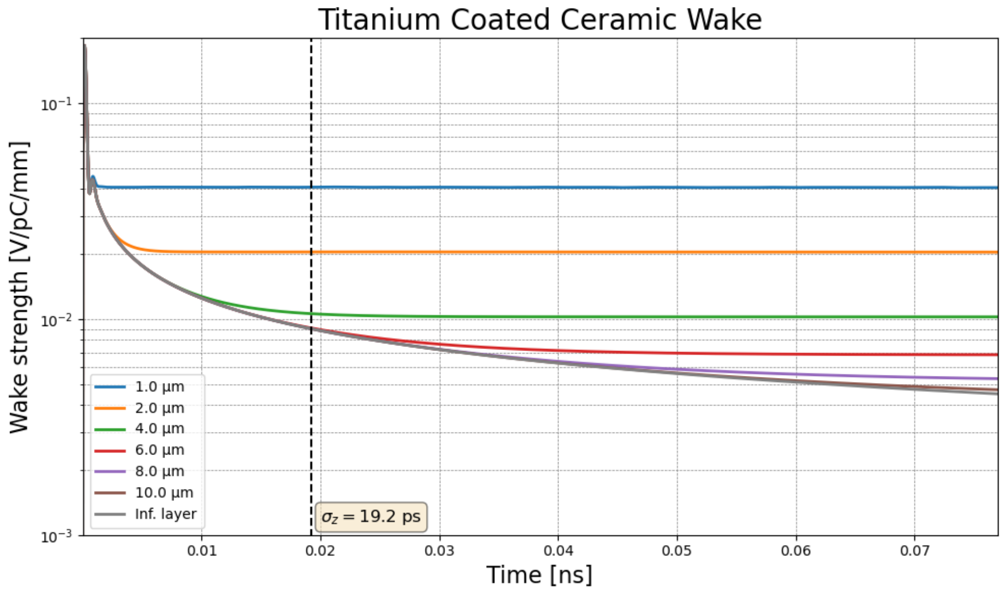


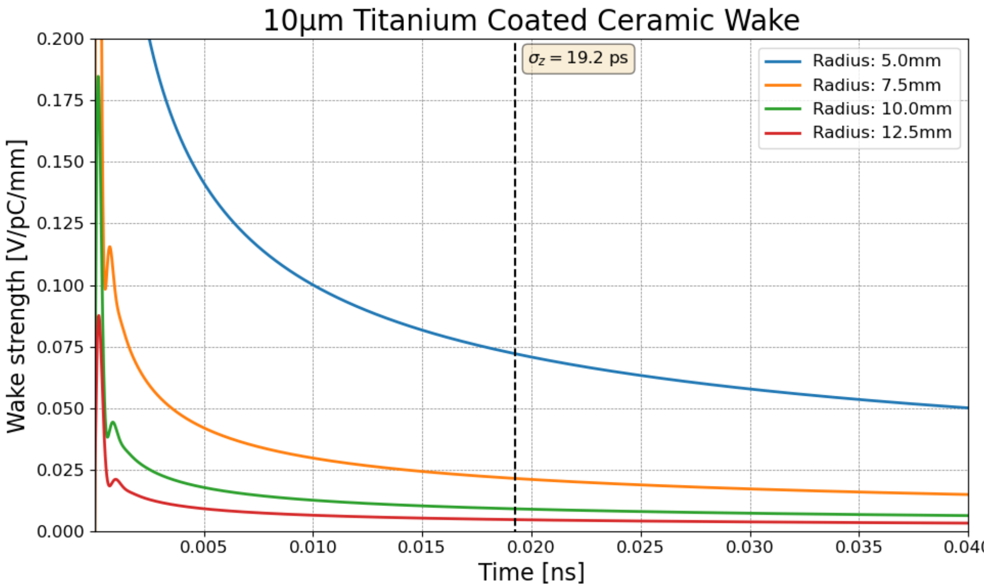
Radius and Thickness scan

- The impedance was also computed for a number of **different inner radii and RF shield thicknesses**, which was later used to study **beam dynamic with XSuite**.

Titanium Thickness Scan



Inner Radius Scan



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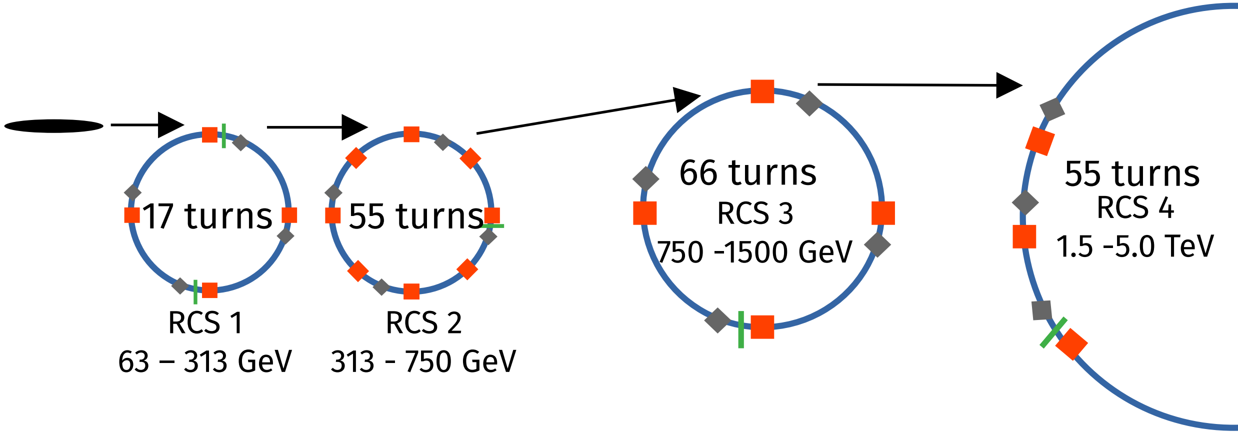
XSuite Simulation Parameters and Setup

- D.Amorim's presentation at the 2024 IMCC and MuCol Annual Meeting details the **general setup** for start-to-end XSuite simulation of the RCS chain.

- Simulations were conducted scanning over different **chromaticities**, **horizontal damper strengths** and initial **offsets** at the entrance of an RCS, focusing on analyzing the wake effects of the Design 2 beam pipe at **different copper thicknesses**.

XSuite Simulation Parameters

- **Copper thickness:**
  - 0 nm , 1 nm, 100 nm, 10 μm, 1mm
- **Chromaticity:**
  - -20, -15, -10, -5, 0, 5, 10, 15, 20
- **Damping time (# of turns):**
  - 4, 10, 20, 50, 100, ∞
- **Initial offset:**
  - 0, 1 μm, 10 μm, 100 μm, 1000 μm



Courtesy D. Amorim

Beam and machine parameters

International
MUON Collider
Collaboration

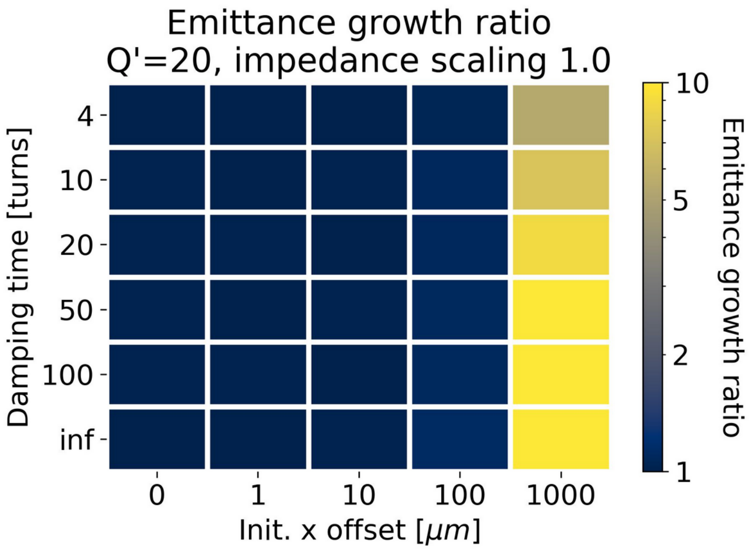
Machine Parameters	Unit	RCS1	RCS2	RCS3	RCS4
Circumference	m	5990	5990	10700	35000
Bunch Intensity	10^{12} particles	2.7	2.7	2.7	2.7
Beam Momentum	GeV/c	63	313.8	750	1500
Energy Increase per Turn	GeV	14.7	7.9	11.3	63.6
Revolution Frequency	kHz	50	50	28	8.6
RF Frequency	MHz	1300	1300	1300	1300
Harmonic Number		25957	25957	46295	151433
RF Voltage	GV	20.9	11.22	16.1	90.0
α_p		0.0024	0.0024	0.001	0.001
Average β_x/β_y	m	50/50	50/50	50/50	50/50
Chromaticity Q'_x/Q'_y		Scan	Scan	Scan	Scan
Detuning from Octupoles	m^{-1}	0/0	0/0	0/0	0/0
Length of NC Section	m	3655	2539	4366	20376
Number of Turns		17	55	66	55

Beam Parameters	Unit	Value
Bunch length $1\sigma_z$	mm	5.7
Bunch intensity	Particles per bunch	2.7×10^{12}
ϵ_x/ϵ_y	μm rad	25
Number of macroparticles		50
Number of turns wakefield		1
Number of slices		2000

Parameters from F. Batsch RCS tables

Result Plots of XSuite Simulation

- The result of the simulations are presented as heat maps
- The color intensity on these maps represents the normalized horizontal emittance growth between the beginning of RCS1 and end of RCS4.
- The x-axis represents the initial transverse offset at the entrance of each RCS
- The y-axis indicates the damping time, measured in number of turns.
- The plot title includes the chromaticity and an impedance scaling factor.



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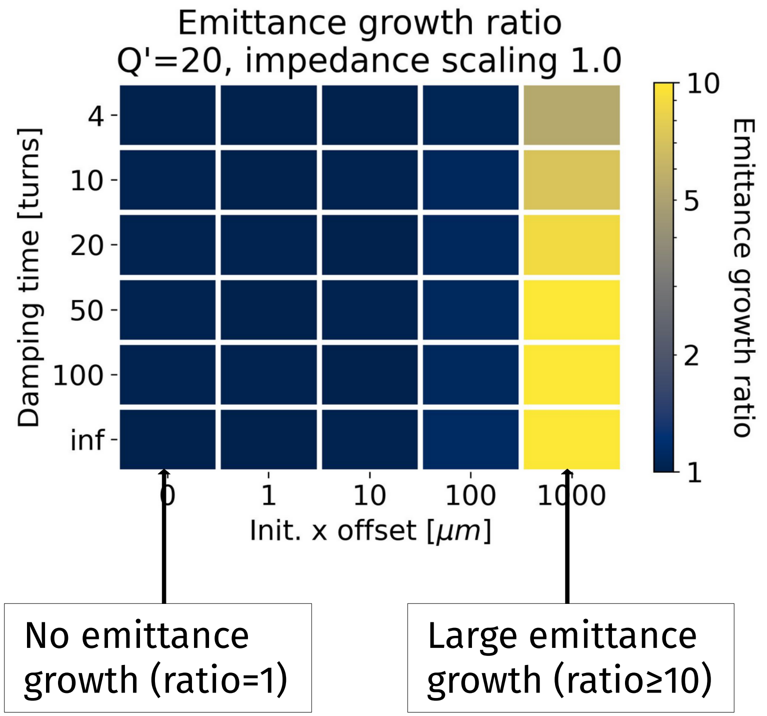

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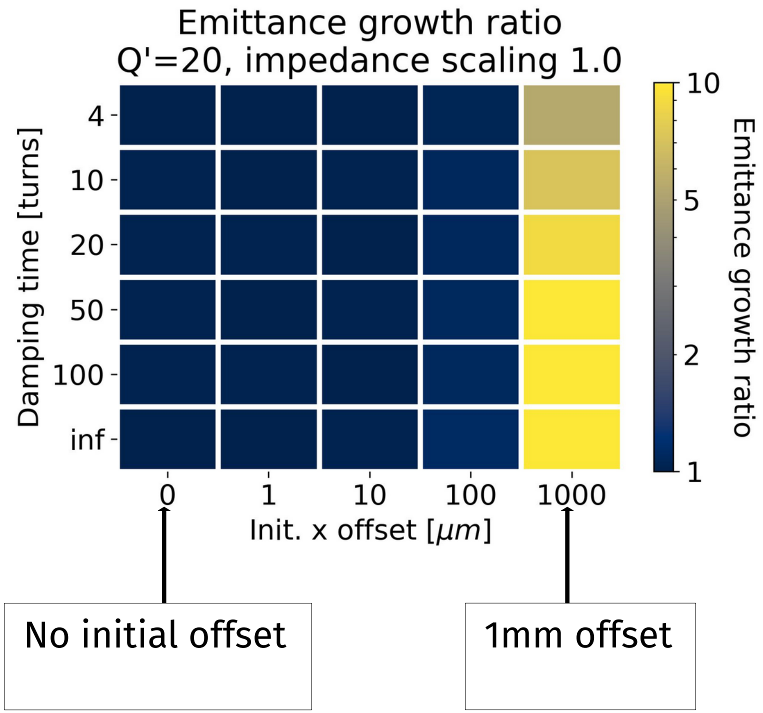

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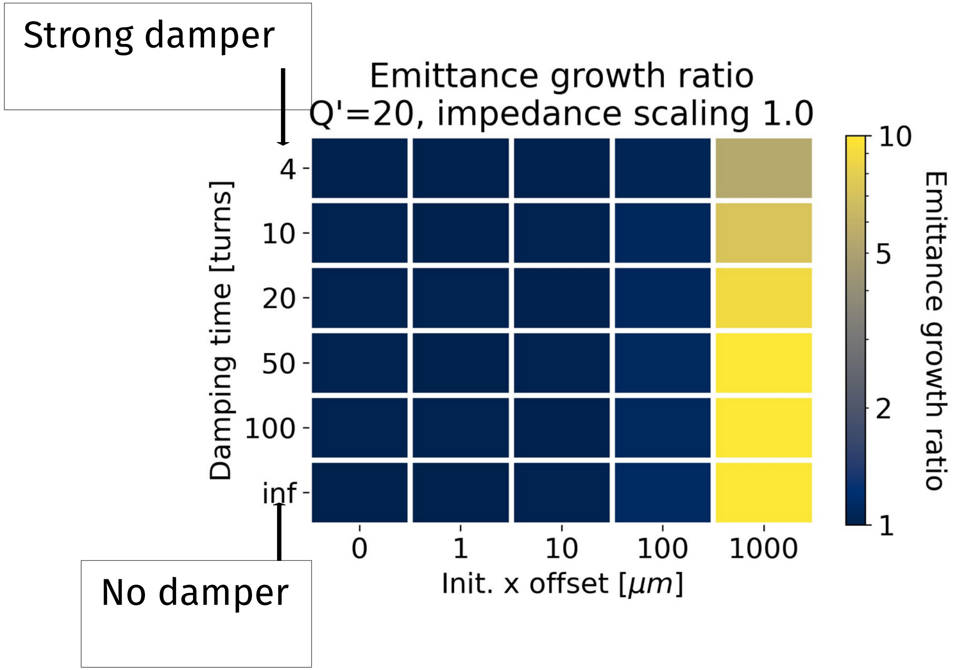

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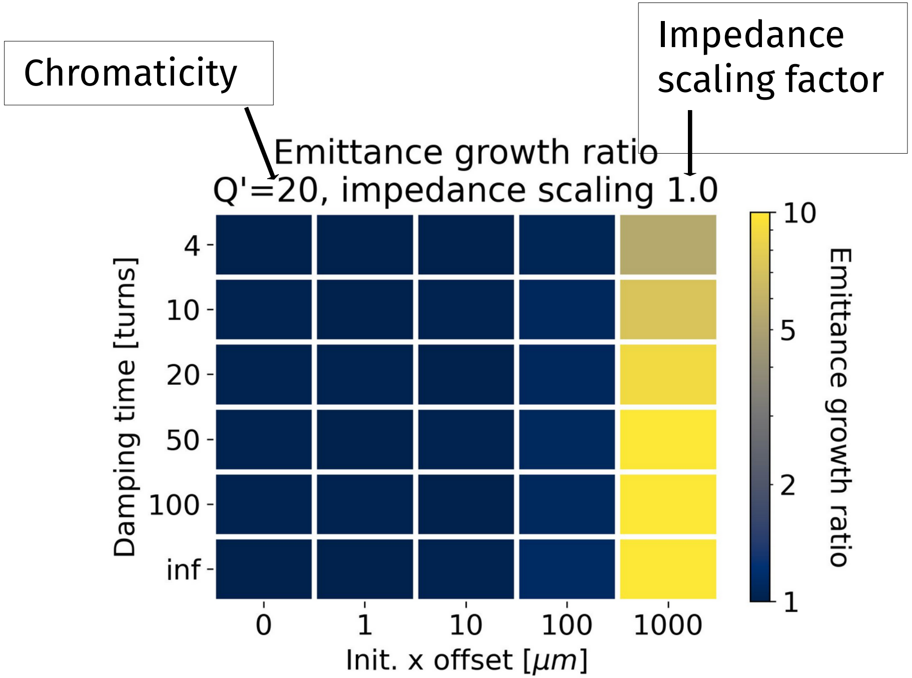
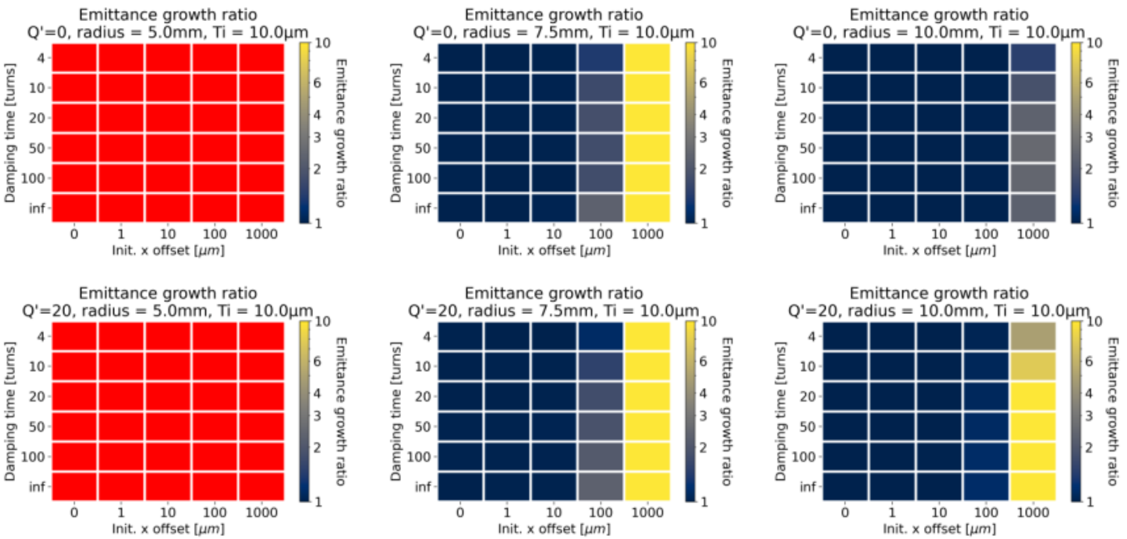


Bunch Stability at Varying Inner Radius

- The stability at different inner radii was investigated with a **10µm titanium layer and 5 mm ceramic layer**.
- Simulations where the **particle loss was larger than 10% are marked in red**, showing that stable beam is not achievable with a inner radius of 5mm.
- At 7.5mm we see no emittance growth at an initial offset of 10µm or less.
- While we allow for a larger offset with an inner radius of 10mm.

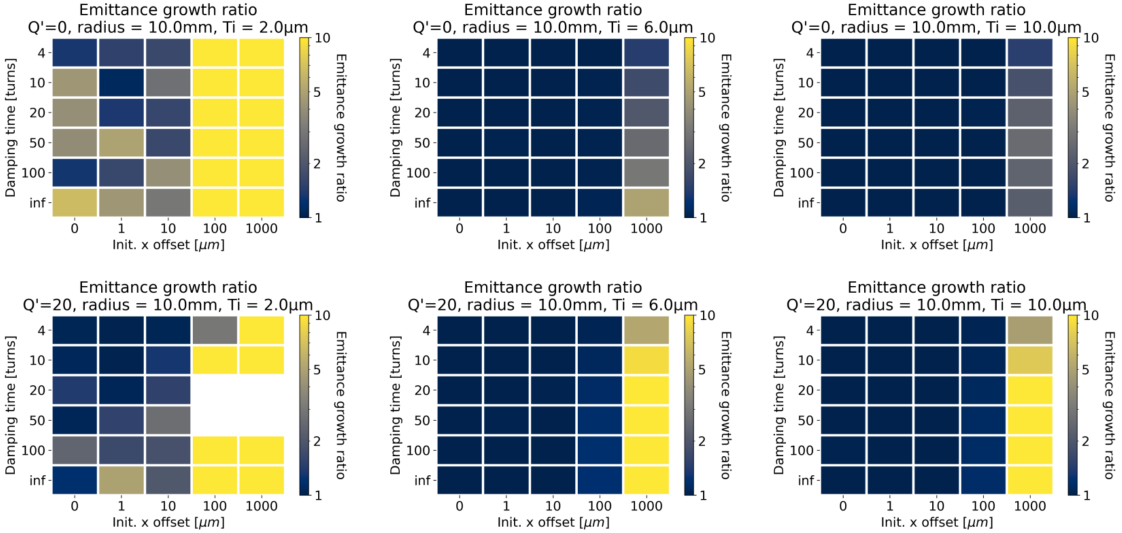
Inner radius dependence



Bunch Stability at Varying Titanium Thickness

- With a **6µm Titanium layer** the beam is stable for all non-negative Q', as long as the offset is smaller than 1000µm.
- A slight improvement can be observed when increasing the Titanium thickness to 10µm.
- **After 10µm we see no additional improvements of the stability**.

Titanium thickness dependence



Instabilities in RCS4

- Many of the observed **instabilities develop in RCS4**, primarily due to its longer sections of NC magnets.

- Having a **thicker layer of shielding within RCS4** could help mitigate some of these instabilities.

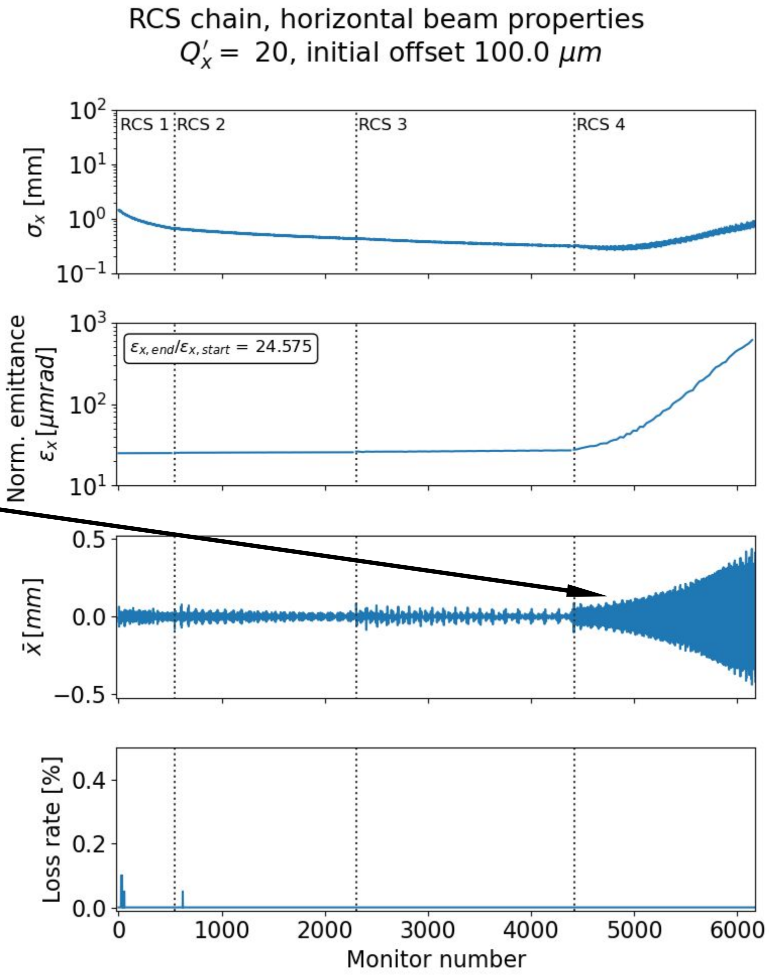


Fig: 100 nm copper, horizontal damping time 50 turns.

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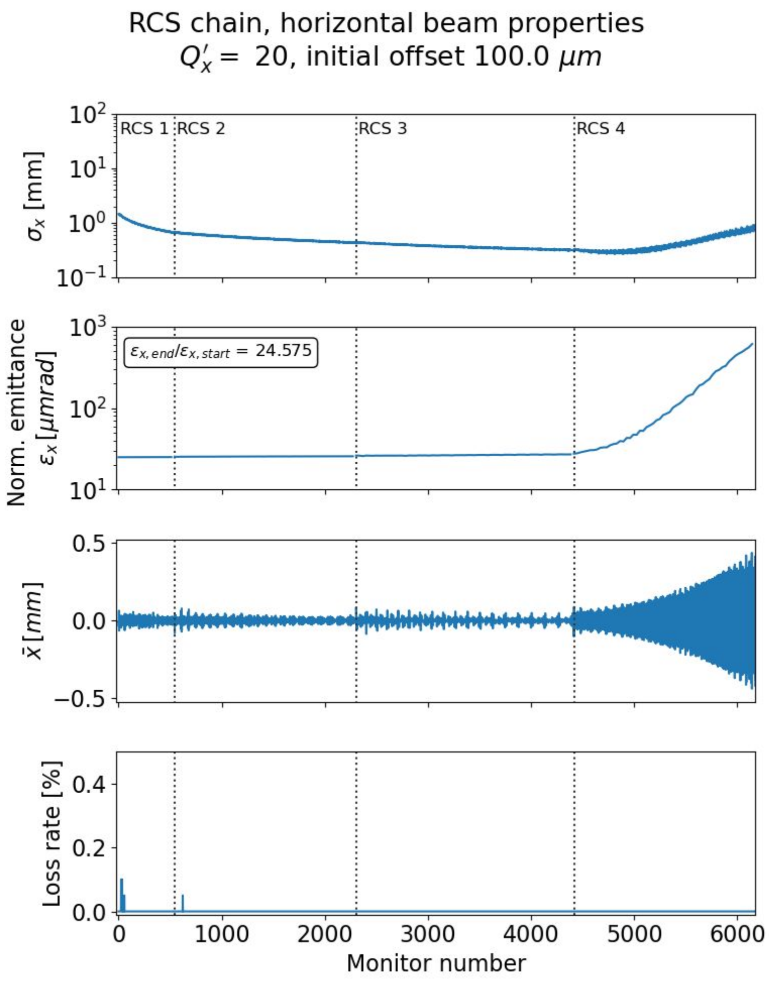

Fig: 100 nm copper, horizontal damping time 50 turns.

Conclusion (1/2)

- **Minimize Conductive Materials:**
  - The RCS vacuum chamber should limit conductive material to reduce eddy current flow.
- **Ceramic With Metallic Stripes:**
  - Ceramic is effective but requires conductive stripes to maintain low impedance.
  - Segmenting metal into thin longitudinal stripes significantly lowers eddy currents.
  - The stripes should be placed internally to suppress resonances seen with external coatings.
- **Further study:**
  - Further investigation needed on the dimensions and spacing of stripes to manage heat effectively.

Conclusion (2/2)

Titanium Ceramic Chamber:

- **Inner Radius Challenges:**
  - For a ceramic vacuum chamber with titanium coating a 7.5mm radius allows for stable beam.
  - With a radius of 10mm we see stability over a broader range of offsets and damper strengths.
- **Titanium Layer thickness:**
  - Critical for stability.
  - 6 μm sufficient for stable beam across various settings.
  - No stability improvement with thickness beyond 10 μm.
- **Further study:**
  - Combine impedance from vacuum chamber with other impedance sources into a unified RCS impedance model.

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