Impedance and beam stability considerations

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Swiss Accelerator Research and Technology

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Contents

- Introduction
- Impact of RF cavities
- Impact of normal conducting magnets beam pipe
- Summary and relevant topics for impedance and transverse beam stability

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International
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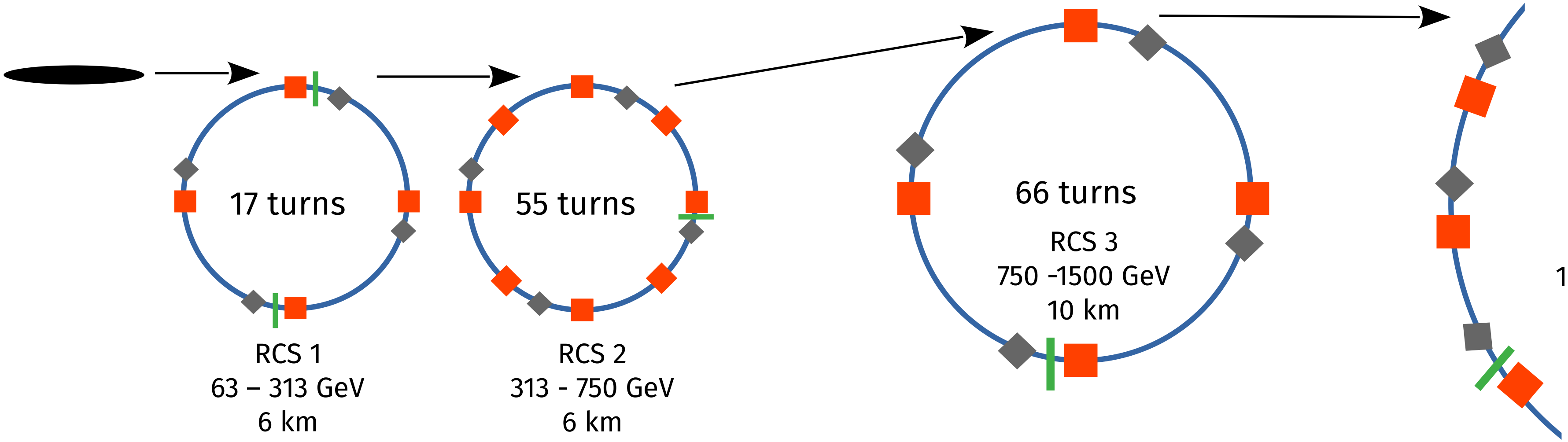
Simulation setup for transverse beam stability studies

- Bunch tracking through the RCS chain
- Check the transverse emittance at the end of the chain (ejection of RCS 4) versus at injection of RCS 1
- Can include impedance effects, transverse damper, chromaticity…



Beam and machine parameters for the RCS

Beam parameters	Unit	Value
Bunch length 1σ	**mm**	**5.7**
Bunch intensity	**Particles per bunch**	**2.7e12**
ε_x / ε_y	**µm rad**	**25**
# of macropaticles		400k
# of turns wakefield		5
# of slices wakefield		2000

Machine parameters	Unit	RCS 1	RCS 2	RCS 3	RCS 4
Circumference	m	5990	5990	10700	35000
NC magnet length	m	3655	2539	4366	20376
Bunch intensity	10^{12}	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
Rev. 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
Avg. beta x/y	m	50 / 50	50 / 50	50 / 50	50 / 50
Chromaticity Q'_x/Q'_y		scan	scan	scan	scan
Detuning from octupoles x/y	m^{-1}	0 / 0	0 / 0	0 / 0	0 / 0

Parameters from F. Batsch RCS tables

Example of start-to-end simulations

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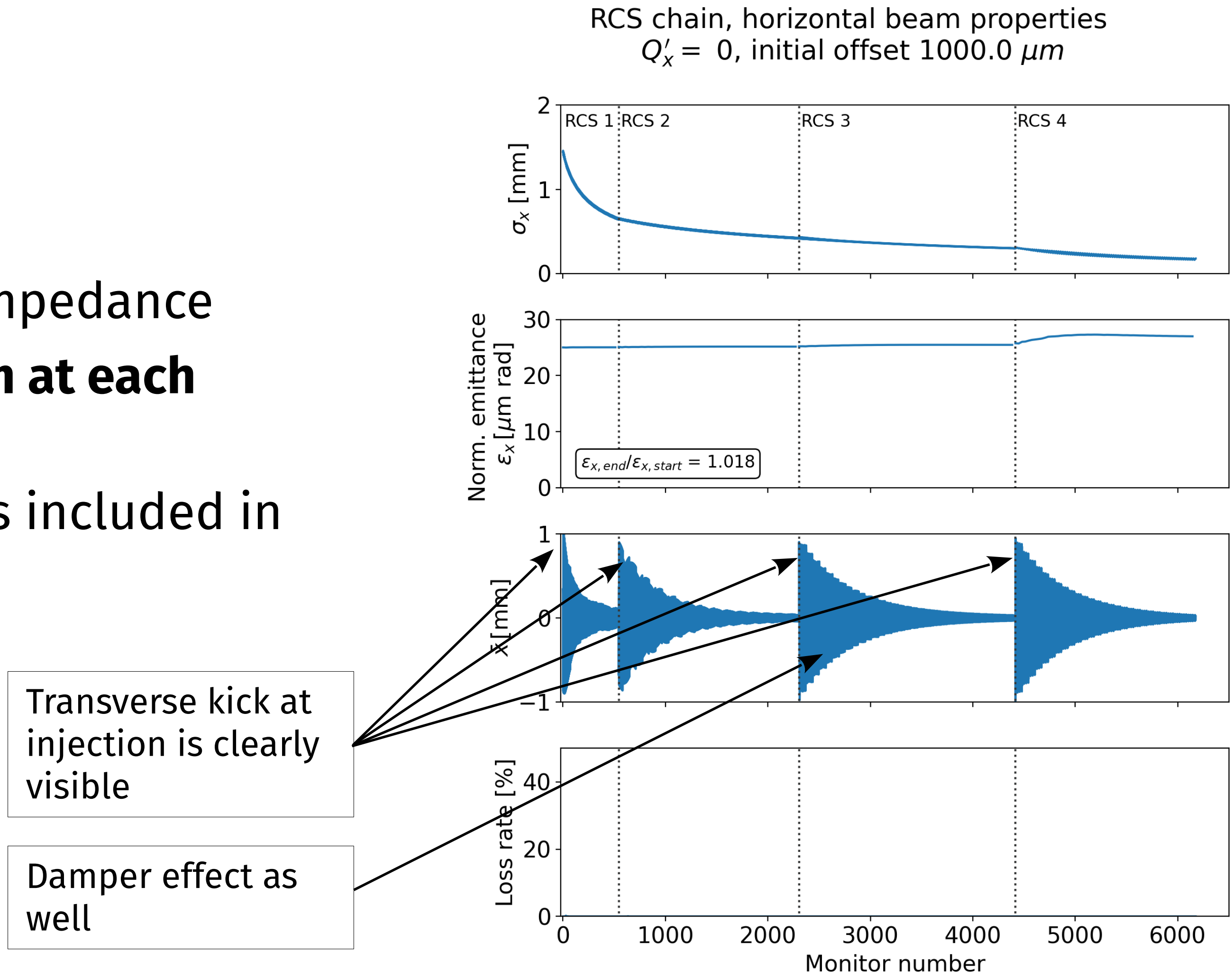
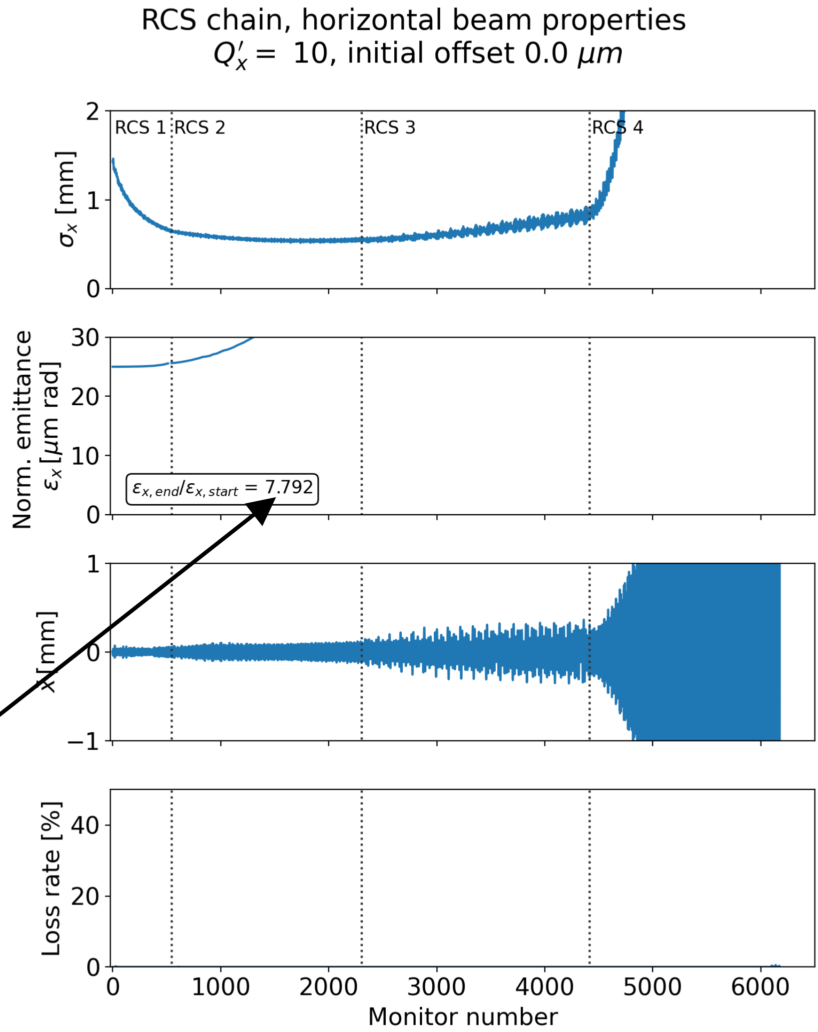
- Chromaticity **Q' = 0**, reduced impedance
- **Initial transverse offset = 1 mm at each machine injection**
- A 20-turn transverse damper is included in each ring (at station #9)



Example of start-to-end simulations

- Chromaticity **Q' = 10**, nominal cavities impedance
- No initial transverse offset
- A 20-turn transverse damper is included in each ring (at station #9)



We will look at the emittance growth ratio ε(end of RCS 4)/ε(start of RCS 1)

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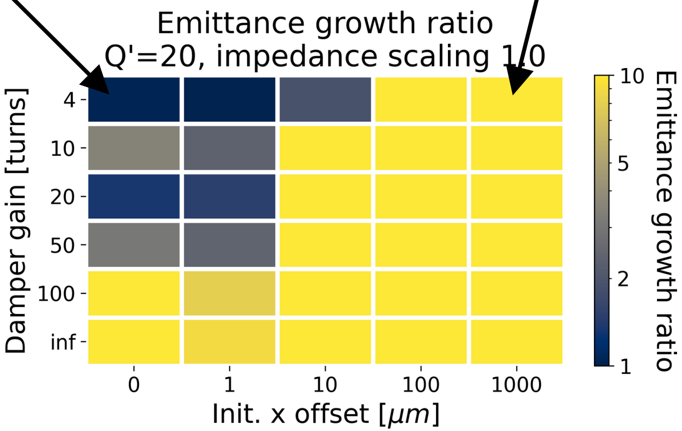
RCS parameters

- Impedance model **for this study: RF cavities High Order Modes (HOMs) only**
  - Single cavity: Low Loss TESLA type cavity, all transverse HOMs included. Assume all HOMs have $Q=10^5$. (see https://accelconf.web.cern.ch/p05/papers/tppt056.pdf)
  - Multiply by the number of cavities: there are (**700, 380, 540, 3000**) cavities in (**RCS1, RCS2, RCS3, RCS4**)
- Main assumptions for the RCS are
  - 32 RF stations in each machine
  - One transverse damper unit, located at RF station 9 (~¼ of the ring)
- Scan several parameters
  - Chromaticity Q' from Q'=-20 to Q'=+20
  - Damper gain from 4-turn to 100-turn + no damper
  - Initial transverse offset of the bunch (in each RCS), from 1 μm to 1 mm

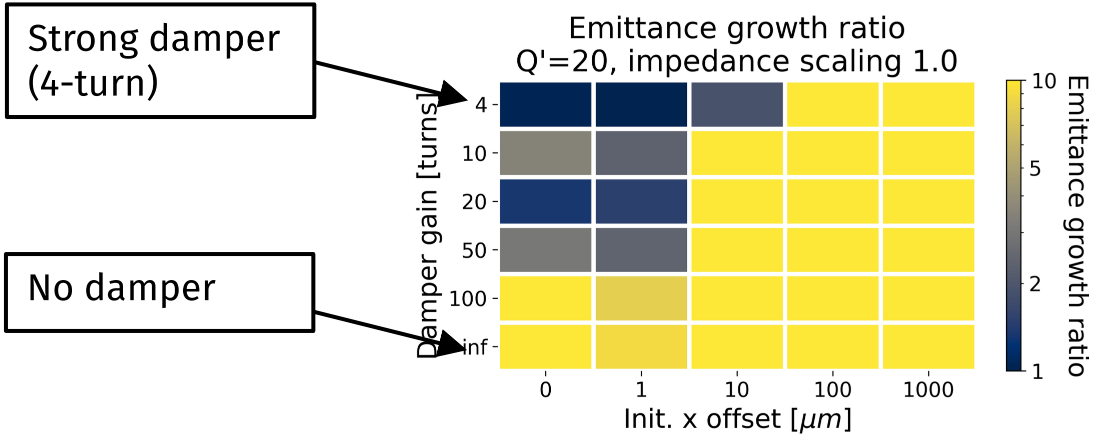
Results of scans versus positive chromaticity Chain of 4 RCS (up to 5 TeV)

No emittance growth (ratio=1)

Large emittance growth (ratio > 10)



Results of scans versus positive chromaticity
Chain of 4 RCS (up to 5 TeV)



Results of scans versus positive chromaticity
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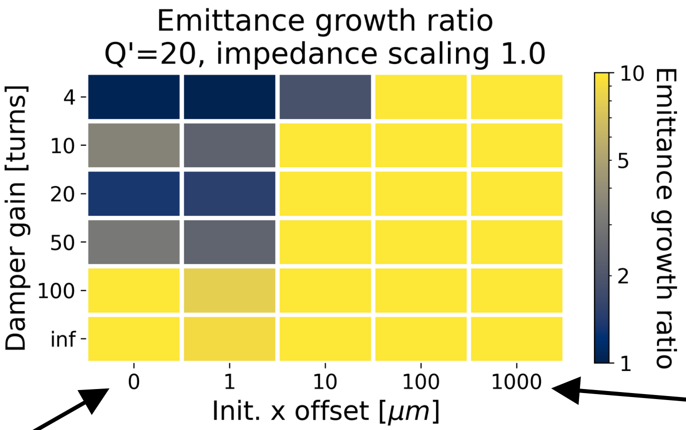
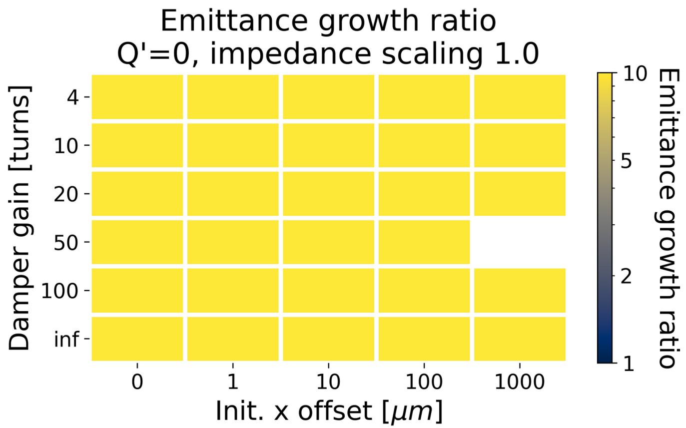
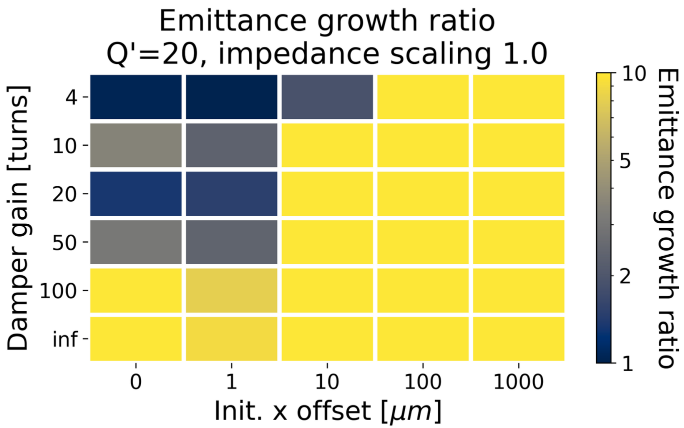


No initial transverse offset

1 mm initial offset in each RCS

Results of scans versus positive chromaticity Chain of 4 RCS (up to 5 TeV)



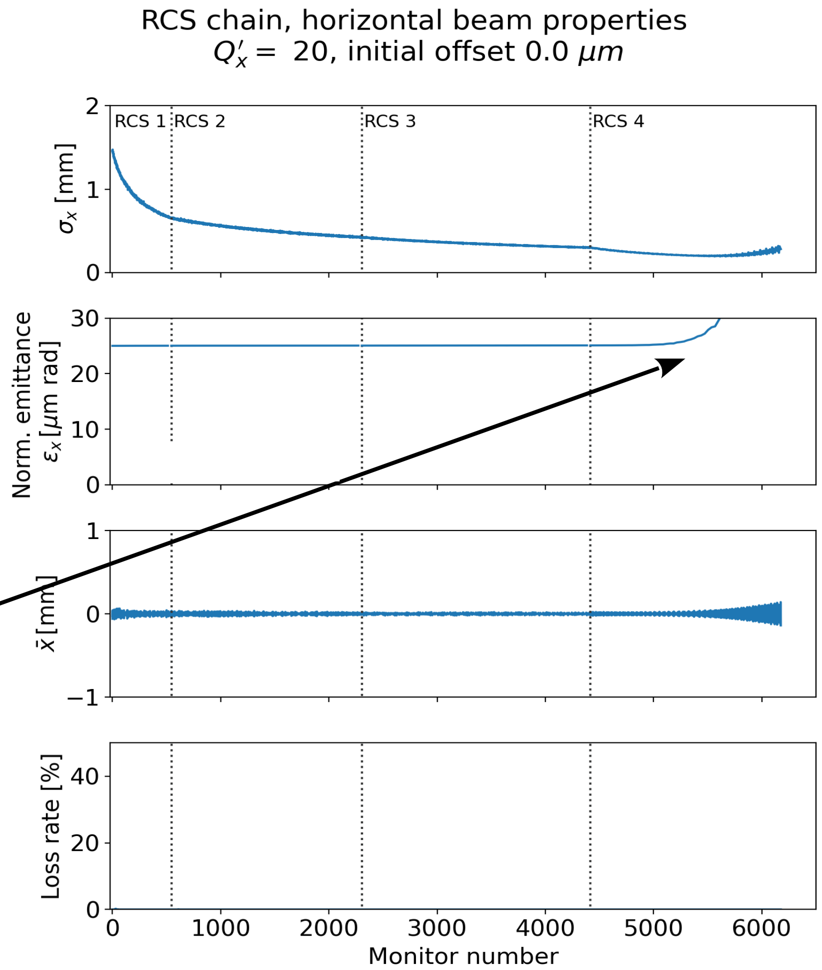


- Withe the nominal HOMs, a **strong damper**, 4-turn to 10-turn range, combined with **chromaticity Q'=20**, are required to stabilize the beam
- The admissible offset is reduced to **1 µm level**

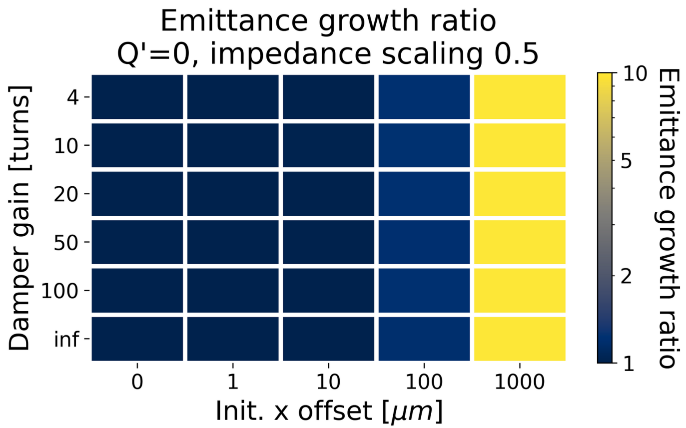
Example of start-to-end simulation with RCS 4

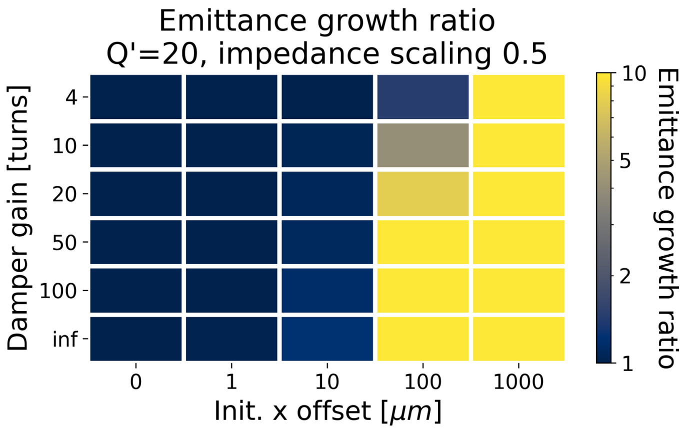
- Chromaticity **Q' = 20**
- **No initial transverse offset**
- A **50-turn transverse damper** is included in each ring (at station #9)

The instability clearly starts in RCS4



Reducing the R/Q of the modes





- Here the full impedance model is scaled by a factor 0.5 → like dividing the R/Q of every mode by 2
- We recover transverse coherent stability with larger offset

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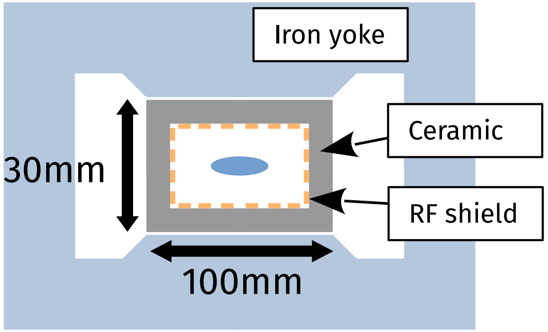
Normal conducting magnets beam pipe

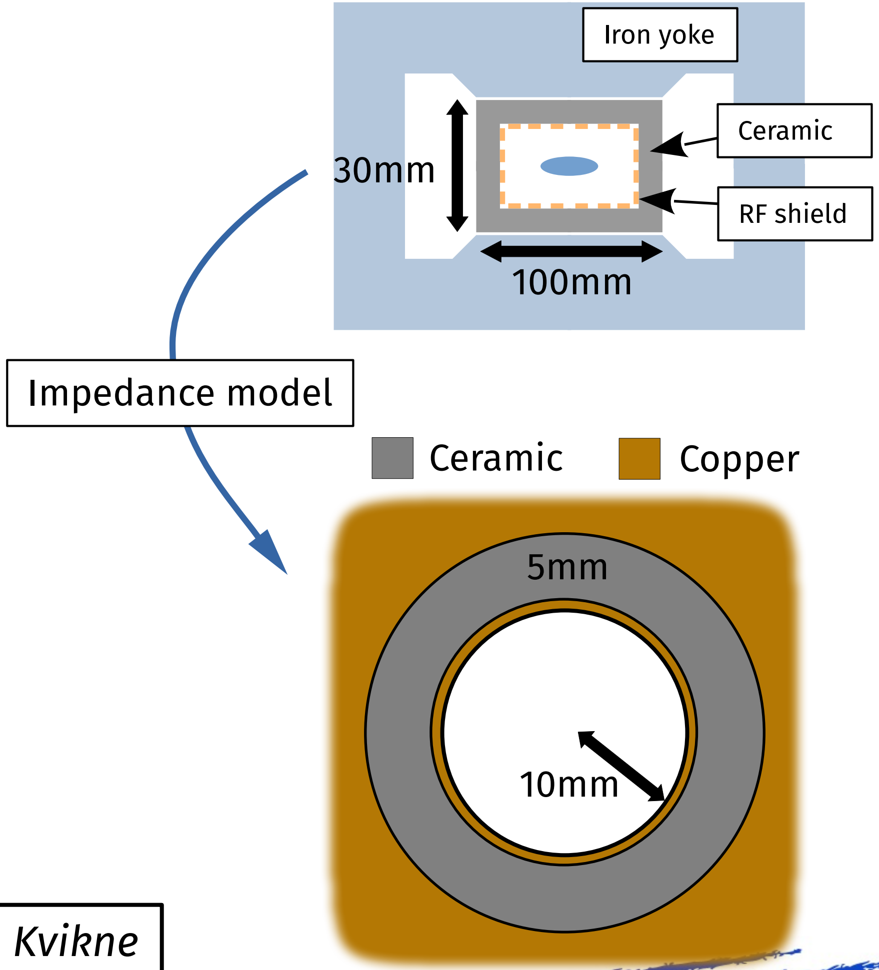


- Normal conducting magnets have a very high ramp rate **O(4.2 kT/s)**
- Power loss from eddy currents scales as $P \propto \dot{B}^2 a^3$
  - $\dot{B}$ the ramp rate, a the chamber thickness
- In a continuous metallic pipe, large eddy current losses would be induced (see E. Kvikne presentation)
- Possible solution is to use a **striped design for the RF shielding**, with an insulating substrate

Study and slides by E. Kvikne

RF-Shield on the Inside of Insulating substrate

- Copper stripes modeled as a **thin cylindrical layer**.
- For simplicity, the magnet is modeled as an infinitely thick layer of copper.
- We use IW2D to compute the impedance and **scan over different copper thicknesses** to find the amount of copper needed to provide the beam with sufficient RF-shielding.
- The inner radius is kept constant at **10mm** while the ceramic thickness is set to **5mm**.



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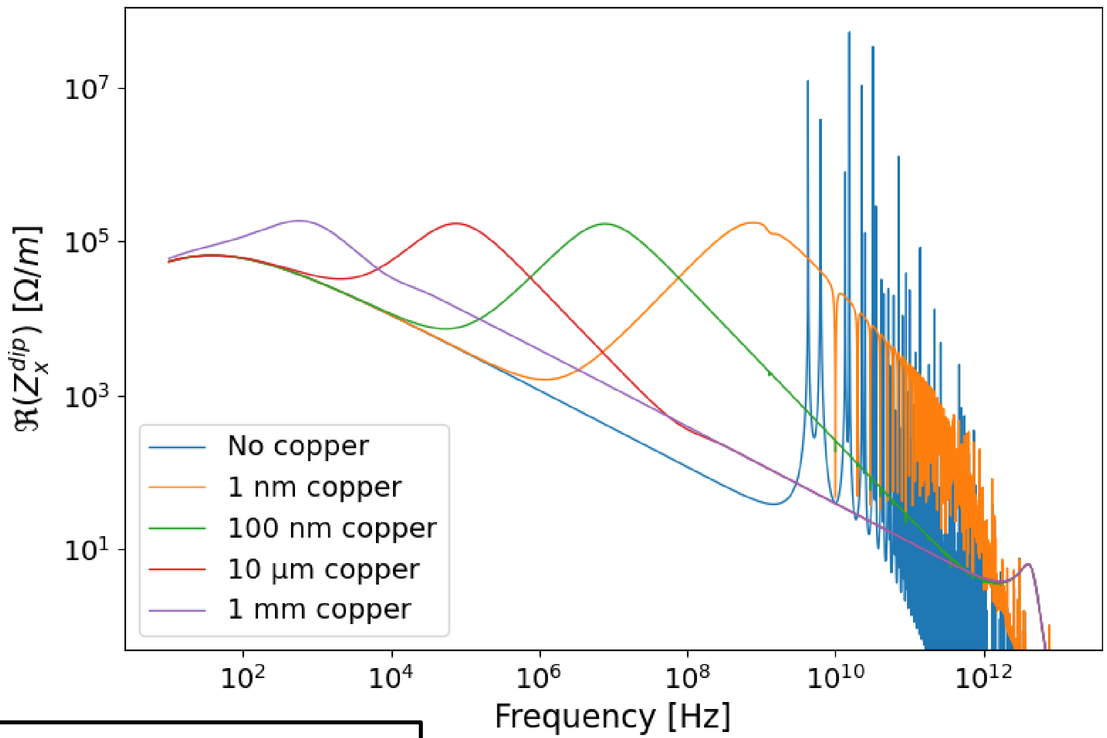
Beam Coupling Impedance

- In presence of a dielectric, large resonances appear in the impedance, at ~2 GHz and above
- A very thin (~nm) **layer of copper** can **reduce these resonances**
  - 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 to **10 μm** can **suppress these high frequencies resonances.**

Transverse dipolar impedance of 1m of beam pipe



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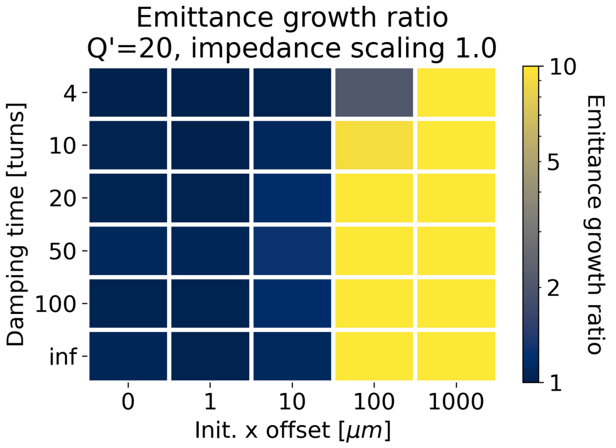
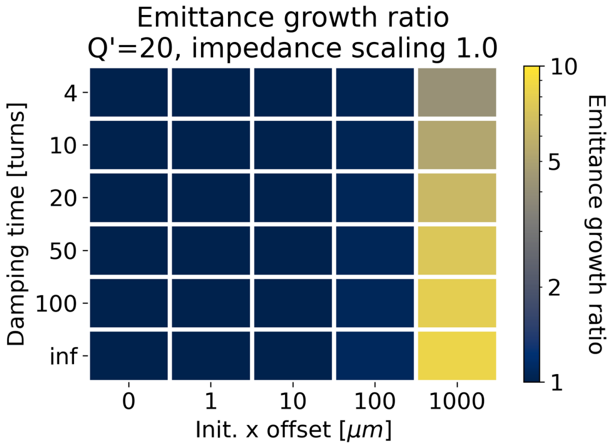
Stability simulation results up to RCS 4

- Impedance model: normal conducting beam pipe only
- A copper thickness of **10 µm is sufficient to keep the beam stable** for all chromaticities (Q' ranging from -20 to 20), as long as the initial offset at the entrance of each RCS is less than 1mm.
- Additionally, this implies that **any copper shield thicker than 10 µm will also provide sufficient RF-shielding**.

100 nm copper thickness



10 um copper thickness



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RF cavities: summary and relevant topics for impedance

- Studies assume the Low Losses TESLA cavities.
- The HOMs have a strong impact on transverse beam stability, in particular in RCS 4
  - Mitigation measures are required, such as chromaticty + transverse damper, or HOMs shunt impedance reduction (a factor 2 at least)
- The list of HOMs can evolve and be updated in the model

- Relevant topics for impedance
  - Integration of RF in the machine: **number of RF stations, transition design**
  - RF cavity and HOM coupler design: **R/Q and Q factor of HOMs, number of cavities**

Magnets: summary and relevant topics for impedance

- Normal conducting magnets
  - Around 2/3 of the total magnet length → can be a large impedance source
  - This is a first iteration on the vacuum chamber design considering eddy current and impedance effects
  - Relevant topics for impedance
    - Beam pipe **geometry and materials**
    - **RF shielding** for impedance effects
    - Continuity of the RF shielding: **transitions** between **NC and SC magnets, aperture changes**
- Superconducting magnets
  - Not yet included in the impedance model
  - Relevant topics
    - Beam pipe **geometry and materials, operating temperature**
    - **Muon decay shielding**

Thank you !

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References

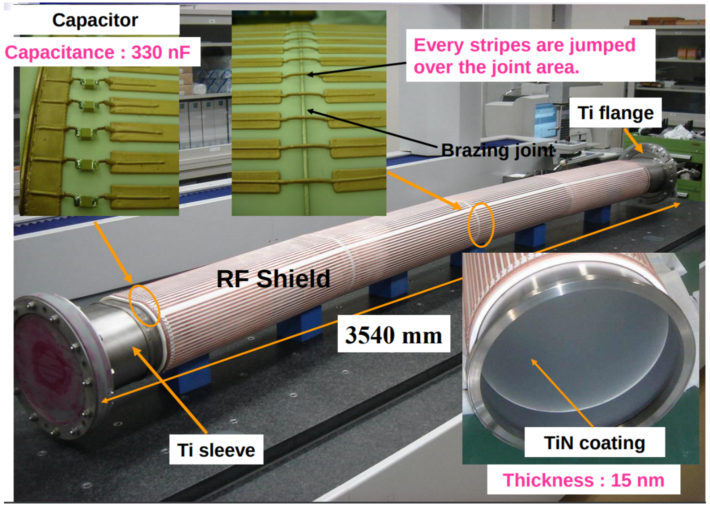
- D. Amorim, Collective effects and start-to-end simulations, IMCC and MuCol annual meeting 2024
- D. Amorim, Stability thresholds of first RCS stage for resonator wakefield, 9th HEMAC meeting
- E. Kvikne, Impedance Study of the RCS Normal Conducting Beam Pipe, to be presented at design meeting
- E. Kvikne, Eddy currents, IMCC and MuCol annual meeting 2024
- F. Boattini et al., Resistive magnets design and analysis baseline, IMCC and MuCol annual meeting 2024
- L. Thiele, RF parameters in the high energy acceleration chain, IMCC and MuCol annual meeting 2024
- M. Gast, Magnet and power converter optimization, IMCC and MuCol annual meeting 2024

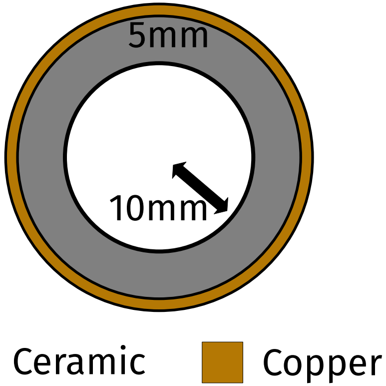
Normal conducting magnets chamber impedance

Ceramic pipe with RF-shield on the outside

- As per the Tentative parameter report the NC magnet aperture is **30x100mm.**
- Beam pipe design for impedance computation:
  - Inner radius of 10 mm
  - Ceramic thickness of 5 mm
  - Varying thickness of copper used in calculations

Design 1: Ceramic pipe with RF-shield (M. Kinsho)





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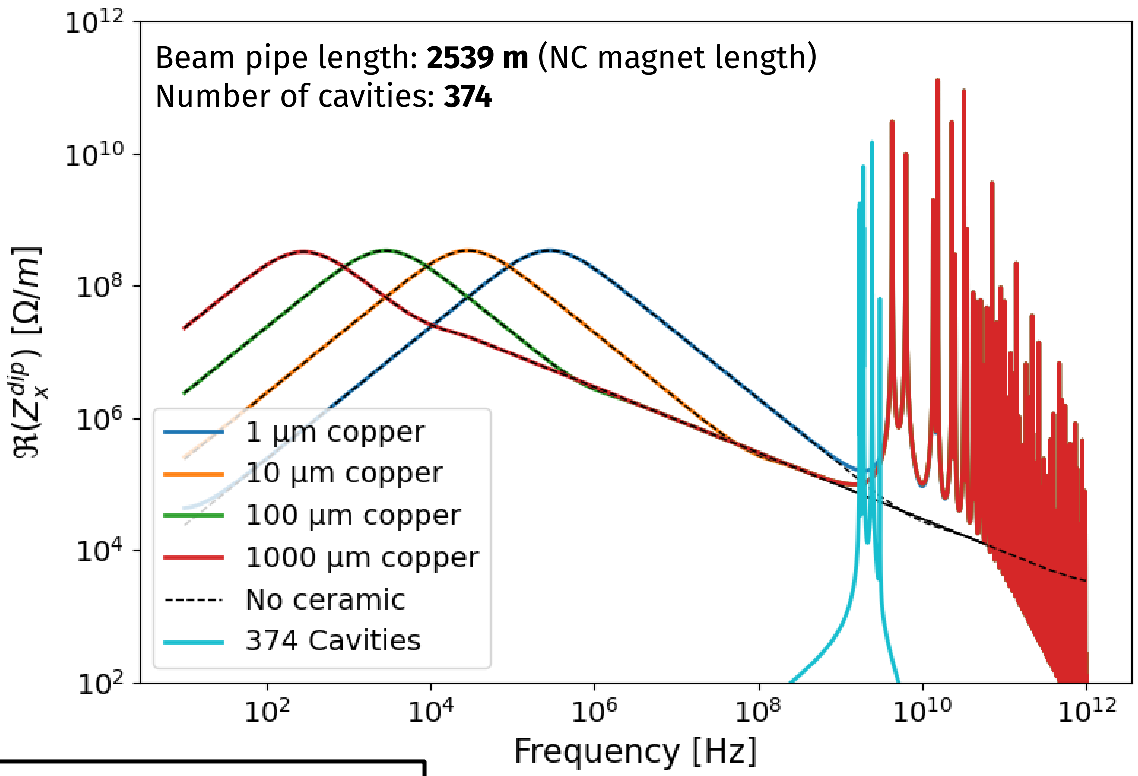
Comparison of Beam Pipe and Cavity Impedance for RCS2

- The resonances caused by the ceramic are **significantly larger** than the ones from the cavities.
- 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.**



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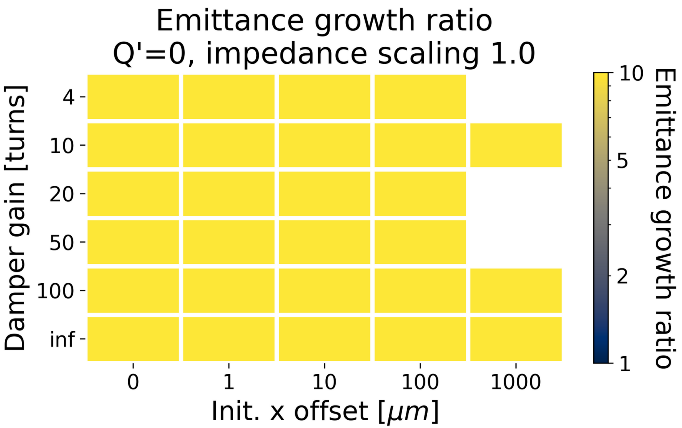
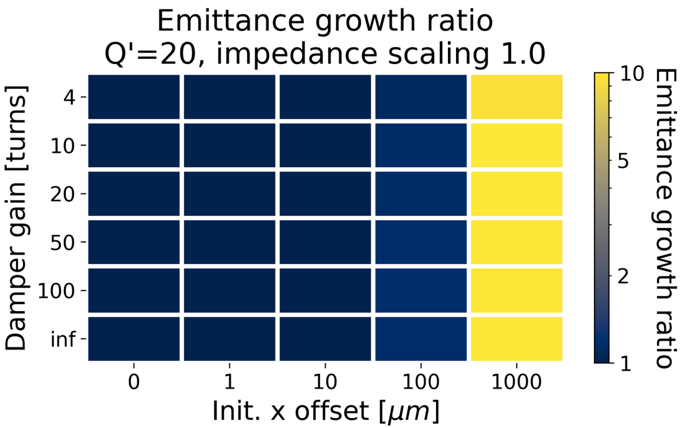
Impact of TESLA cavities, with 3 RCS (63 GeV to 1.5 TeV chain)

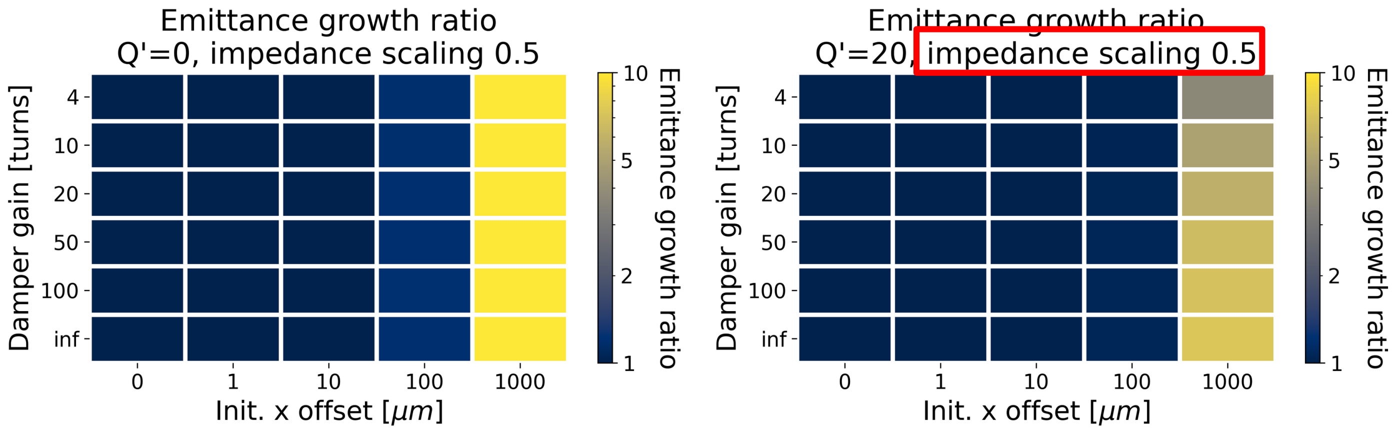
Results of scans versus chromaticity





- Positive chromaticity is required to stabilize the beam, at least Q'=+15
- The transverse damper is not required for high chromaticities
- An initial transverse offset can be tolerated, up to 10-100 μm

Reducing the R/Q of the modes



- Here the full impedance model is scaled by a factor 0.5 → like dividing the R/Q of every mode by 2
- More relaxed situation: chromaticity can be reduced to Q' > ~0
- An initial transverse offset can be tolerated, up to 10-100 μm

Summary for three RCS

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	Positive Q’	Negative Q’
Nominal R/Q of the HOMs	Q’>15 + any damper offset up to 100 μm	Always unstable
Half R/Q of the HOMs	Q’>0 + any damper Offset up to 100 μm	Q’< -15 + 4-turn damper Offset up to 100 μm

Summary for four RCS

	Positive Q'	**Negative Q'**
Nominal R/Q of the HOMs	Q'>15 + 10-turn damper offset up to 1 μm	Always unstable
Half R/Q of the HOMs	Q'>0 + any damper Offset up to 100 μm	Q'< -15 + 4-turn damper Offset up to 100 μm