International MUON Collider Collaboration

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Start-to-end transverse beam dynamics simulations in the RCS chain: assessing TESLA cavity impact

DRAFT

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CHART Swiss Accelerator Research and Technology

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Contents

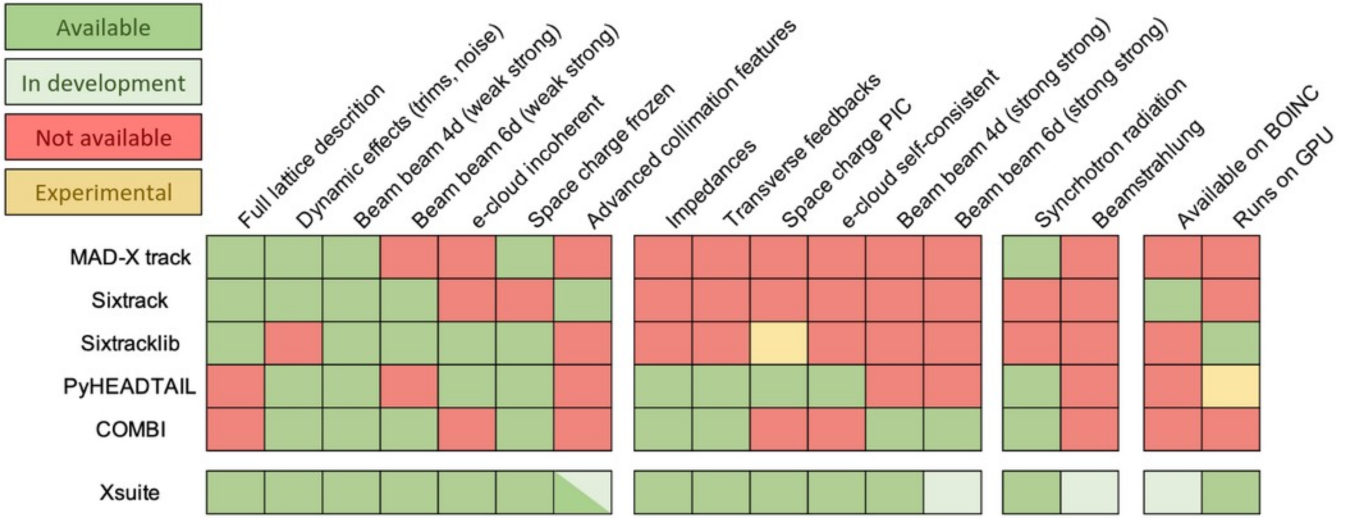
- XSuite presentation
- Simulation setup
- Example of start-to-end simulations and future work
- Evaluation of TESLA cavities impact on transverse stability, with 3 RCS
- Evaluation of TESLA cavities impact on transverse stability, with 4 RCS

XSuite presentation

Project launched to **rationalize and modernize software for multiparticle simulations**

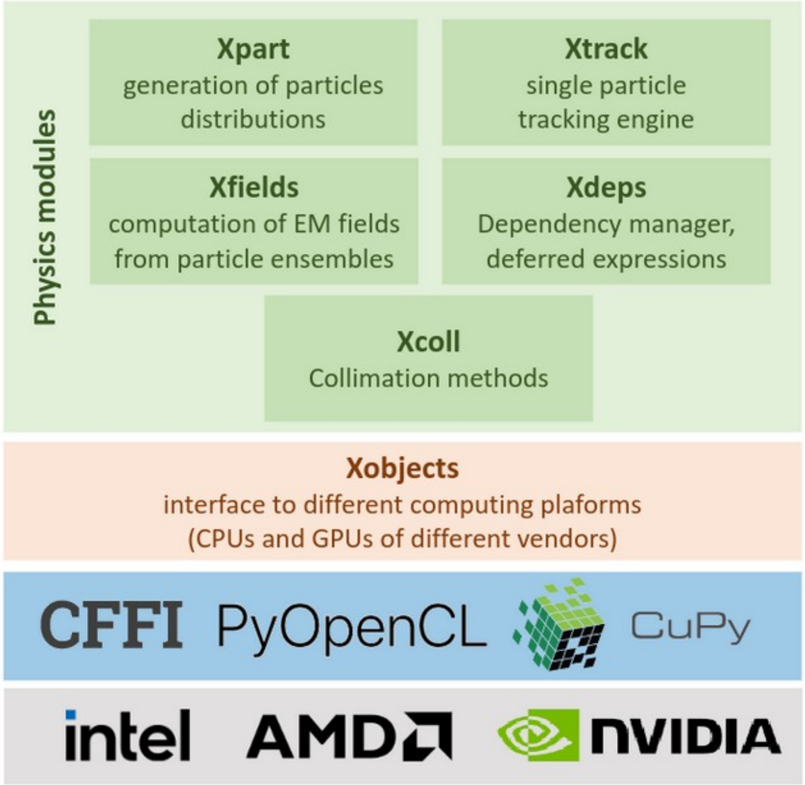
→ Moved **from a heterogenous range of programs** each with limited capabilities to an **integrated modular toolkit** (Xsuite)

- Covering with a single toolkit of **injectors, LHC, HL-LHC and design studies** (e.g. PBC, FCC hh & ee)
- Exploitation of **modern computing platforms** (e.g. GPUs) for a wide range of applications
- Strong **simplification** of development and maintenance process (removes several duplications)



G. Iadarola et al.,
Xsuite: An integrated beam physics simulation framework
CEI section meeting
03/11/2022

XSuite presentation



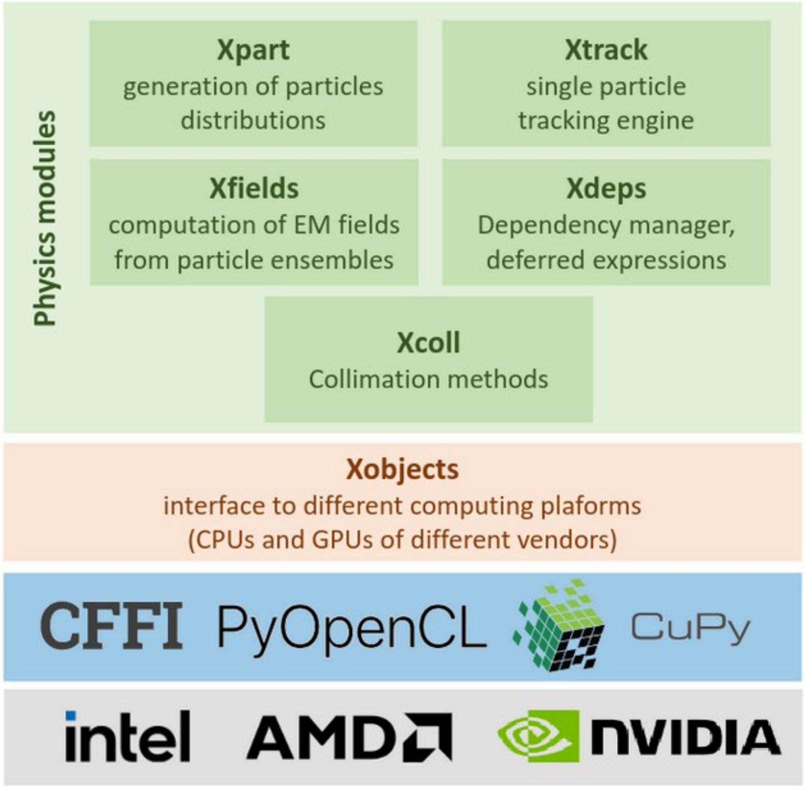
High level methods and objects, building blocks for the physics simulations

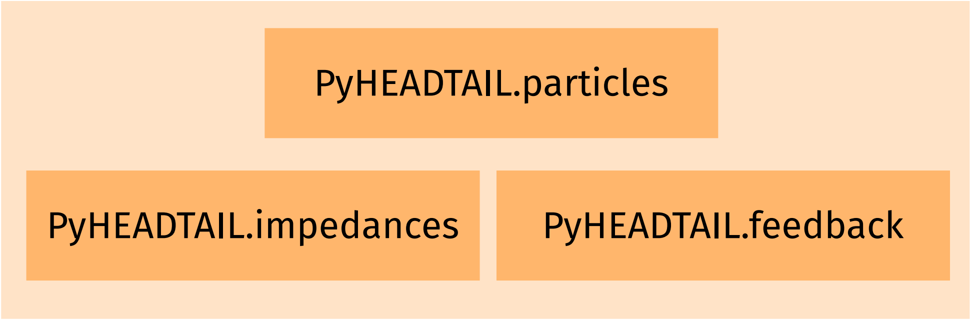
External libraries
(lower-level, interface with hardware)

Hardware

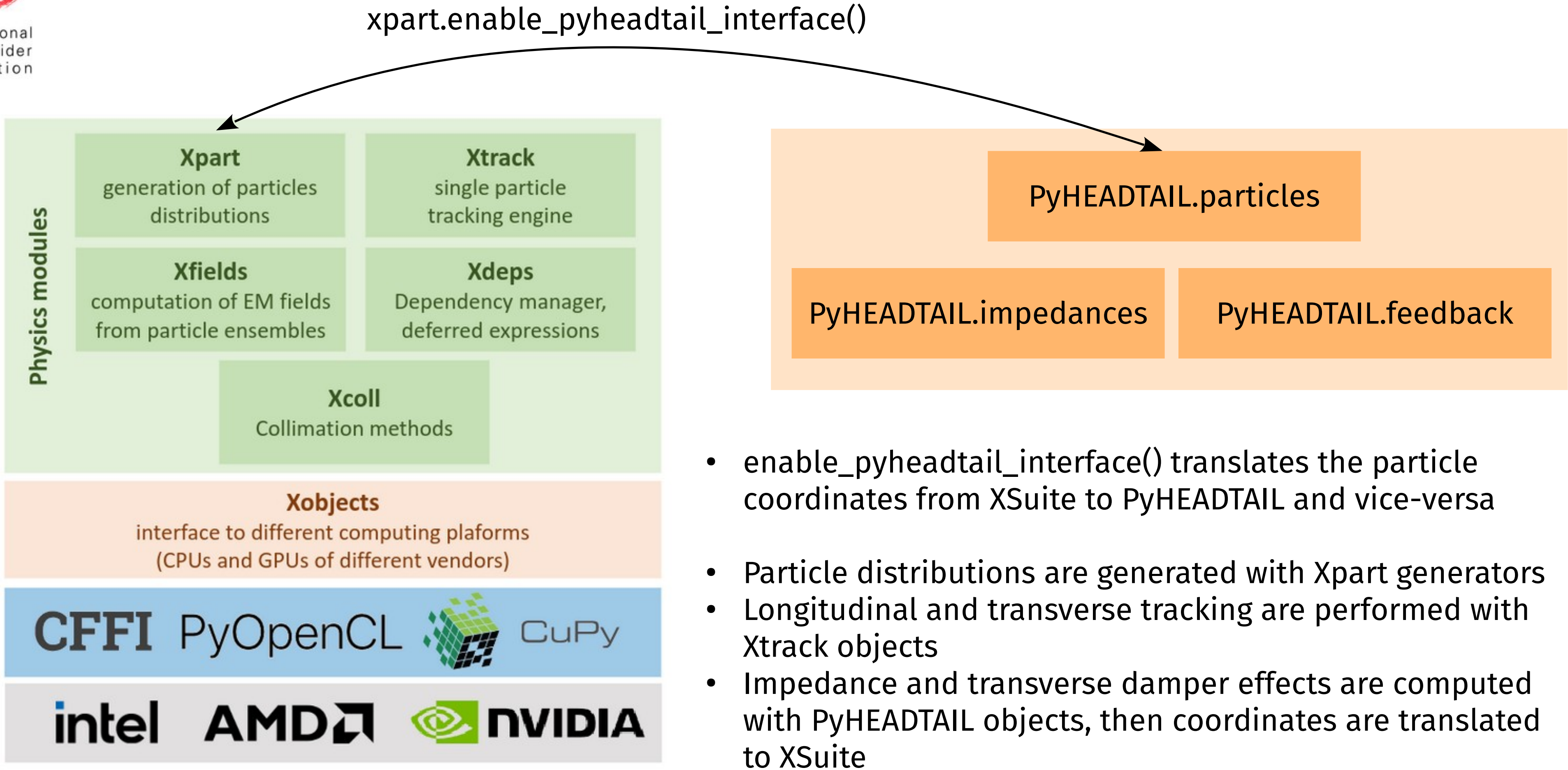
G. Iadarola et al., *ibid*

XSuite presentation





XSuite presentation



- enable_pyheadtail_interface() translates the particle coordinates from XSuite to PyHEADTAIL and vice-versa

- Particle distributions are generated with Xpart generators
- Longitudinal and transverse tracking are performed with Xtrack objects
- Impedance and transverse damper effects are computed with PyHEADTAIL objects, then coordinates are translated to XSuite

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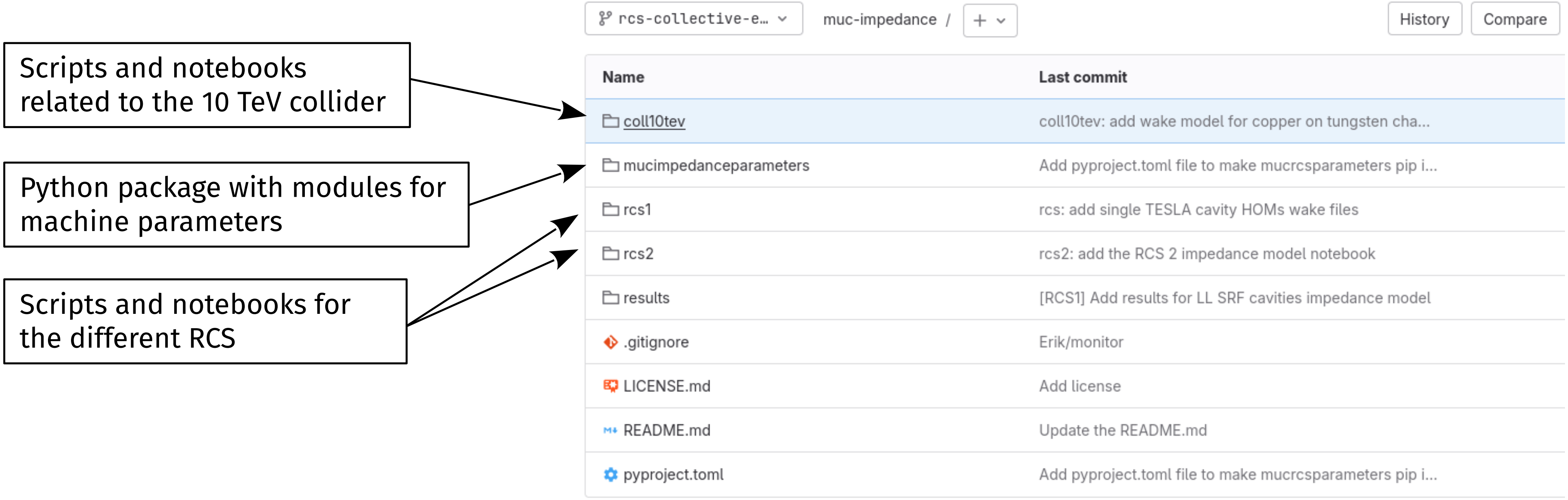
RCS parameters and beam dynamics scripts

- Scripts and input data are collected in Gitlab repository https://gitlab.cern.ch/muon-collider-bd/muc-impedance



RCS parameters and beam dynamics scripts

- Scripts and input data are collected in Gitlab repository https://gitlab.cern.ch/muon-collider-bd/muc-impedance
- The mucimpedanceparameters folder is a python package and must be pip installed
  - Requires recent versions of pip and setuptools (tested with versions 23.2 and 68.1)
  - Provides modules particle_parameters.py and synchrotron.py

RCS parameters and beam dynamics scripts

- The synchrotron.py module provides a Synchrotron class
- This class requires a parameter file as input, with the main machine parameters
- Configuration files are present for RCS 1, 2, 3 and 4.
- Values are based on IMCC parameter report/Fabian's table

muc-impedance / mucimpedanceparameters / machine_configuration / RCS / RCS1_RF_1300MHz_posmuon.yaml

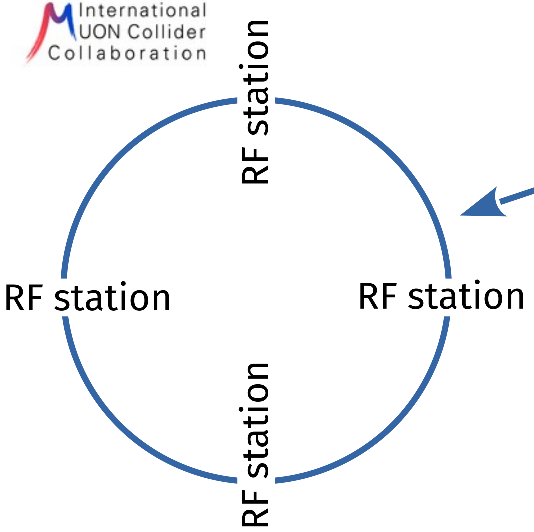
RCS1_RF_1300MHz_posmuon.yaml 790 B


```yaml
# Paramters file for the RCS1 at injection energy
# Reference for values: F. Batsch HEMAC parameters
#
# Bunch length 1 sigmaz = 23.1mm/4 = 5.775 mm
# RF cavity phase is given in degrees
# emit_z is the product sigma_z * sigma_E in eV s
Ring Parameters:
    name: RCS1
    year: 2022
    state: injection
    circumference: 5990
Beam Parameters:
    particle_name: PosMuon
    E_kinetic: 63.0e+09
    harmonic: 25917
    RF_voltage: 20.87e+09
    sigmaz: 5.775e-3
    emit_z: 0.025
    alphap: 2.4e-3
    synchrotron_phase: 45
    energy_gain_per_turn: 14755.0e+06
    number_of_rf_stations: 32
    number_of_bunches: 1
    initial_bunch_intensity: 2.7e+12
    Qx_frac: 0.26
    Qy_frac: 0.26
    average_beta_x: 50
    average_beta_y: 50
    norm_emit_x: 25.0e-06
    norm_emit_y: 25.0e-06
```

Simulation setup

- XSuite uses Line objects (part of Xtrack) to model a ring
  - A line can contain all kind of elements defined in Xtrack: bends, quadrupoles, multipoles, RF cavities, electron lenses…
  - For our studies, we use **LineSegmentMap** elements (analog to the TransverseMap and LongitudinalMap objects of PyHEADTAIL)

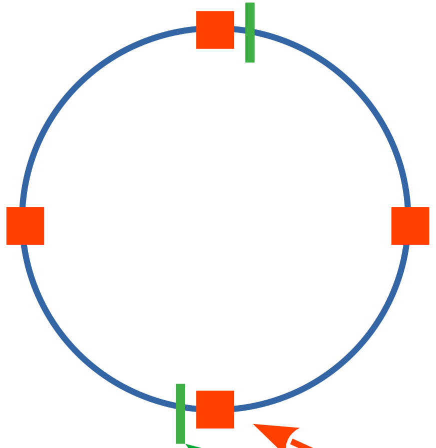
Simulation setup




```
for ii_rf_station in range(0, number_of_rf_stations):
    elements_list.append(xt.LineSegmentMap(length=accelerator_parameters.circumference/number_of_rf_stations,
                                            qx=average_Qx/number_of_rf_stations, qy=average_Qy/number_of_rf_stations,
                                            betx=beta_x, bety=beta_y, alfx=alpha_x, alfy=alpha_y,
                                            dx=0., dpx=0., dy=0., dpy=0.,
                                            x_ref=0.0, px_ref=0.0, y_ref=0.0, py_ref=0.0,
                                            longitudinal_mode=rf_longitudinal_mode,
                                            qs=None, bets=None,
                                            momentum_compaction_factor=momentum_compaction_factor,
                                            slippage_length=None,
                                            voltage_rf=rf_voltage/number_of_rf_stations,
                                            frequency_rf=rf_frequency, lag_rf=rf_lag_degrees,
                                            dqx=chroma_x, dqy=chroma_y,
                                            detx_x=0.0, detx_y=0.0, dety_y=0.0, dety_x=0.0,
                                            energy_increment=0,
                                            energy_ref_increment=energy_increment_per_turn/number_of_rf_stations,
                                            damping_rate_x = 0.0, damping_rate_y = 0.0, damping_rate_s = 0.0,
                                            equ_emit_x = 0.0, equ_emit_y = 0.0, equ_emit_s = 0.0,
                                            gauss_noise_ampl_x=0.0,gauss_noise_ampl_px=0.0,
                                            gauss_noise_ampl_y=0.0,gauss_noise_ampl_py=0.0,
                                            gauss_noise_ampl_zeta=0.0,gauss_noise_ampl_delta=0.0,))
    elements_names_list.append(f'arc_{ii_rf_station}_{ii_rf_station+1}')
```

LineSegmentMap
Longitudinal map
(including acceleration)
+ Transverse map

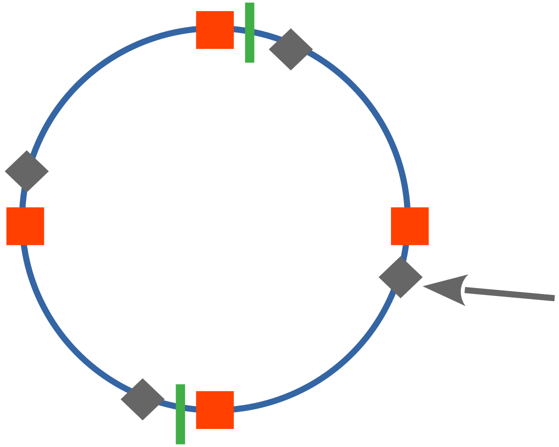
Simulation setup



Wakefield
Damper
PyHEADTAIL objects

```
for ii_rf_station in range(0, number_of_rf_stations):
    elements_list.append(xt.LineSegmentMap(length=accelerator_parameters.circumference/number_of_rf_stations,
                                          qx=average_Qx/number_of_rf_stations, qy=average_Qy/number_of_rf_stations,
                                          betx=beta_x, bety=beta_y, alfx=alpha_x, alfy=alpha_y,
                                          dx=0., dpx=0., dy=0., dpy=0.,
                                          x_ref=0.0, px_ref=0.0, y_ref=0.0, py_ref=0.0,
                                          longitudinal_mode=rf_longitudinal_mode,
                                          qs=None, bets=None,
                                          momentum_compaction_factor=momentum_compaction_factor,
                                          slippage_length=None,
                                          voltage_rf=rf_voltage/number_of_rf_stations,
                                          frequency_rf=rf_frequency, lag_rf=rf_lag_degrees,
                                          dqx=chroma_x, dqy=chroma_y,
                                          detx_x=0.0, detx_y=0.0, dety_y=0.0, dety_x=0.0,
                                          energy_increment=0,
                                          energy_ref_increment=energy_increment_per_turn/number_of_rf_stations,
                                          damping_rate_x = 0.0, damping_rate_y = 0.0, damping_rate_s = 0.0,
                                          equ_emit_x = 0.0, equ_emit_y = 0.0, equ_emit_s = 0.0,
                                          gauss_noise_ampl_x=0.0,gauss_noise_ampl_px=0.0,
                                          gauss_noise_ampl_y=0.0,gauss_noise_ampl_py=0.0,
                                          gauss_noise_ampl_zeta=0.0,gauss_noise_ampl_delta=0.0,))
    elements_names_list.append(f'arc_{ii_rf_station}_{ii_rf_station+1}')

    elements_list.append(wake_field)
    elements_names_list.append(f'wakefield_{ii_rf_station+1}')

    # Add the transverse damper at the given location in the ring
    if ii_rf_station in damper_location_index_list:
        elements_list.append(TransverseDamper(dampingrate_x=damper_strength,
                                              dampingrate_y=damper_strength))
        elements_names_list.append(f'damper_{ii_rf_station+1}')
```

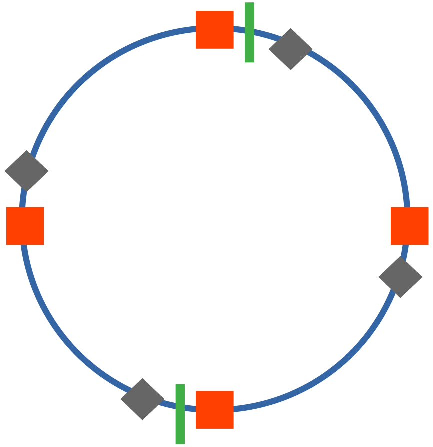
Simulation setup



ParticleMonitor
Longitudinal and Transverse apertures

```
# Add a particle monitor at each RF station
elements_list.append(xt.ParticlesMonitor(start_at_turn=n_turns_scan_cumsum[ii_rcs_to_study],
                                         stop_at_turn=n_turns_scan_cumsum[ii_rcs_to_study+1],
                                         num_particles=n_macroparticles_monitored))
elements_names_list.append(f'monitor_{ii_rf_station+1}')

# Add a Longitudinal aperture to remove uncaptured particles (in longitudinal)
elements_list.append(xt.LongitudinalLimitRect(min_zeta=-0.1, max_zeta=0.1))
elements_names_list.append(f'longitudinal_aperture_{ii_rf_station+1}')

# Add a Transverse aperture to remove unstable particles
elements_list.append(xt.LimitRect(min_x=-100e-3, max_x=100e-3, min_y=-100e-3, max_y=100e-3))
elements_names_list.append(f'transverse_rectangular_aperture_{ii_rf_station+1}')


line = xt.Line(elements=elements_list, element_names=elements_names_list)
```

Simulation setup

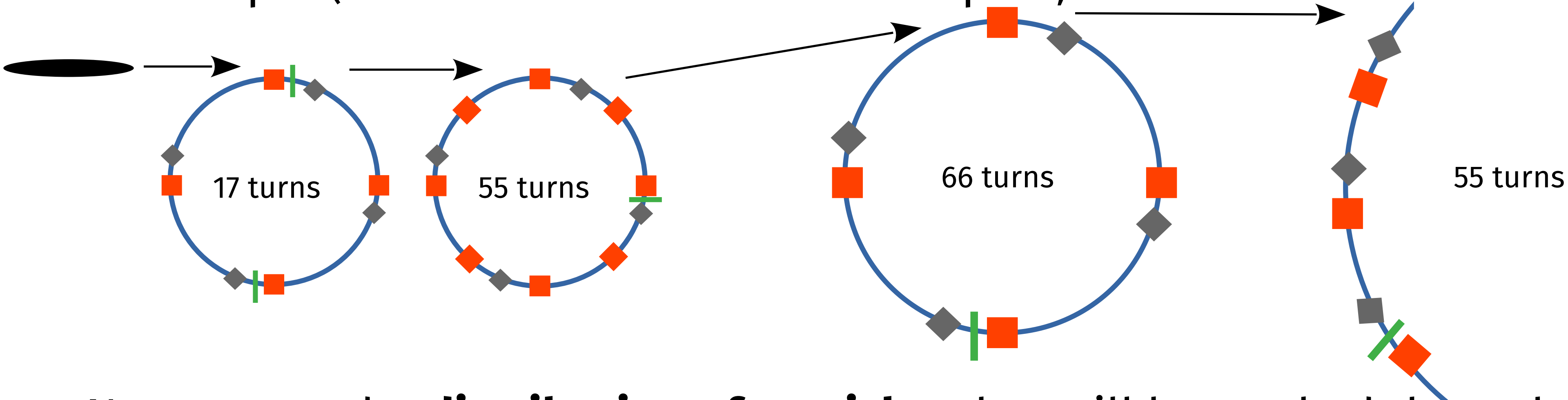


```python
    # Add a particle monitor at each RF station
    elements_list.append(xt.ParticlesMonitor(start_at_turn=n_turns_scan_cumsum[ii_rcs_to_study],
                                             stop_at_turn=n_turns_scan_cumsum[ii_rcs_to_study+1],
                                             num_particles=n_macroparticles_monitored))
    elements_names_list.append(f'monitor_{ii_rf_station+1}')

    # Add a Longitudinal aperture to remove uncaptured particles (in longitudinal)
    elements_list.append(xt.LongitudinalLimitRect(min_zeta=-0.1, max_zeta=0.1))
    elements_names_list.append(f'longitudinal_aperture_{ii_rf_station+1}')

    # Add a Transverse aperture to remove unstable particles
    elements_list.append(xt.LimitRect(min_x=-100e-3, max_x=100e-3, min_y=-100e-3, max_y=100e-3))
    elements_names_list.append(f'transverse_rectangular_aperture_{ii_rf_station+1}')


line = xt.Line(elements=elements_list, element_names=elements_names_list)
```

Create the XSuite line used for tracking

Simulation setup

- This process is repeated for all RCS we want to study
- Each RCS parameter can be set with the configuration file + inputs inside the scripts (number and location of dampers, wakefield model to use…)



- Now we need a **distribution of particles** that will be tracked through the different lines

Simulation setup

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If we are currently studying the first RCS in the chain, we must generate the particle distribution beforehand.
Otherwise we use the distribution that comes out of the previous line.

Longitudinal bunch matching.
Xsuite routines are the same as PyHEADTAIL's.

Given:
- the RF bucket parameters
- and the target longitudinal emittance

The matcher will try generate the longitudinal distribution

Transverse coordinates generation

A particle distribution is then created, and will be tracked through the different lines

```
    # We generate the particle distribution only if we are looking at the first RCS simulated
    if rcs_to_study == 'RCS1':

        # Define the reference particle for the simulations using the parameters specified beforehand
        particle_ref = xp.Particles(p0c=particle_p0c, mass0=particle_mass_eV,
                                    q0=particle_charge_number, x=0 , y=0, zeta=0)

        p_increment = energy_increment_per_turn * e / c

        rfbucket = RFBucket(circumference=accelerator_parameters.circumference,
                            gamma=gamma,
                            mass_kg=particle_mass_kg,
                            charge_coulomb=particle_charge,
                            alpha_array=np.atleast_1d(momentum_compaction_factor),
                            # alpha_array=np.atleast_1d(1.6e-4),
                            harmonic_list=np.atleast_1d(rf_harmonic_number),
                            voltage_list=np.atleast_1d(rf_voltage),
                            phi_offset_list=np.atleast_1d((rf_lag_degrees)*np.pi/180),
                            p_increment=p_increment)

        matcher = RFBucketMatcher(rfbucket=rfbucket,
                                  distribution_type=ThermalDistribution,
                                  #   sigma_z=None,
                                  epsn_z=4*np.pi*emit_z)

        z_particles, delta_particles,   = matcher.generate(macroparticlenumber=n_macroparticles)

        line.particle_ref = particle_ref.copy()
        line.particle_ref.zeta = 0

        x_in_sigmas, px_in_sigmas = xp.generate_2D_gaussian(n_macroparticles)
        y_in_sigmas, py_in_sigmas = xp.generate_2D_gaussian(n_macroparticles)

        particles = line.build_particles(
                    zeta=z_particles-rfbucket.z_sfp,
                    # zeta=z_particles,
                    delta=delta_particles,
                    x_norm=x_in_sigmas, px_norm=px_in_sigmas,
                    y_norm=y_in_sigmas, py_norm=py_in_sigmas,
                    nemitt_x=norm_emit_x, nemitt_y=norm_emit_y,
                    weight=initial_bunch_intensity/n_macroparticles)
        particles.circumference = accelerator_parameters.circumference
```

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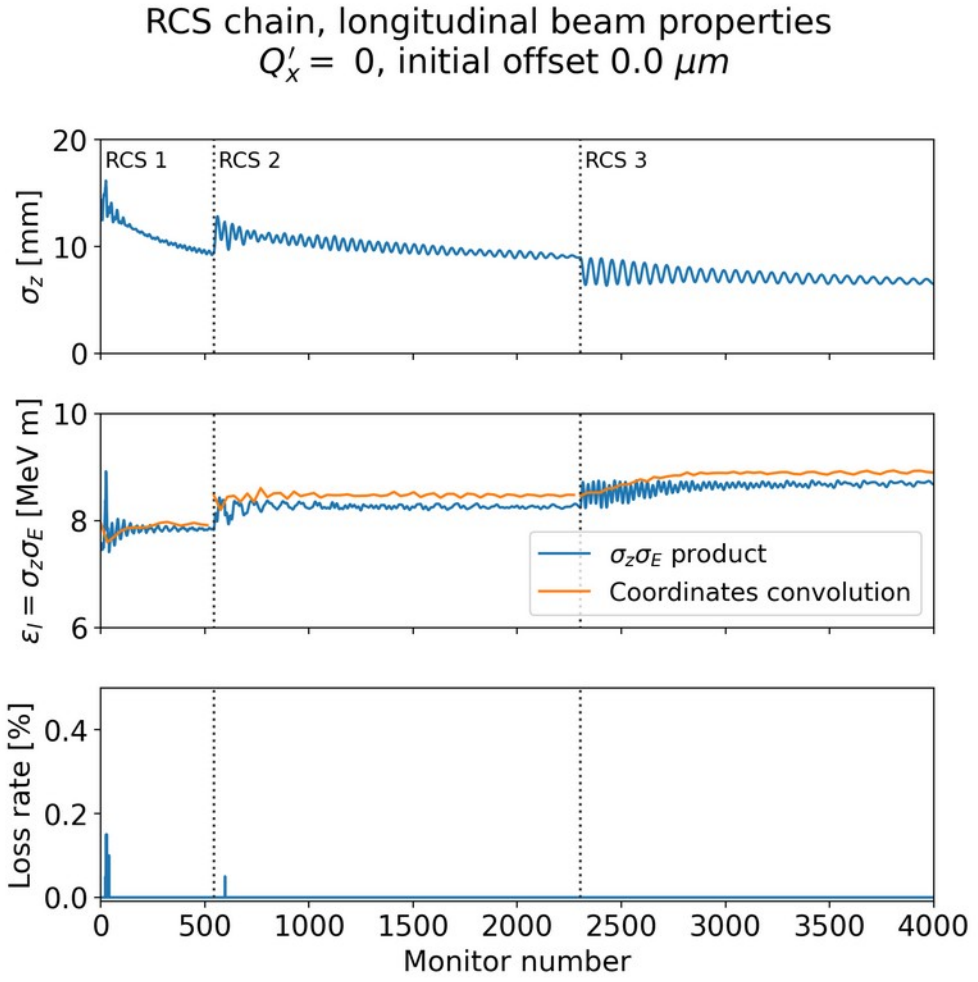
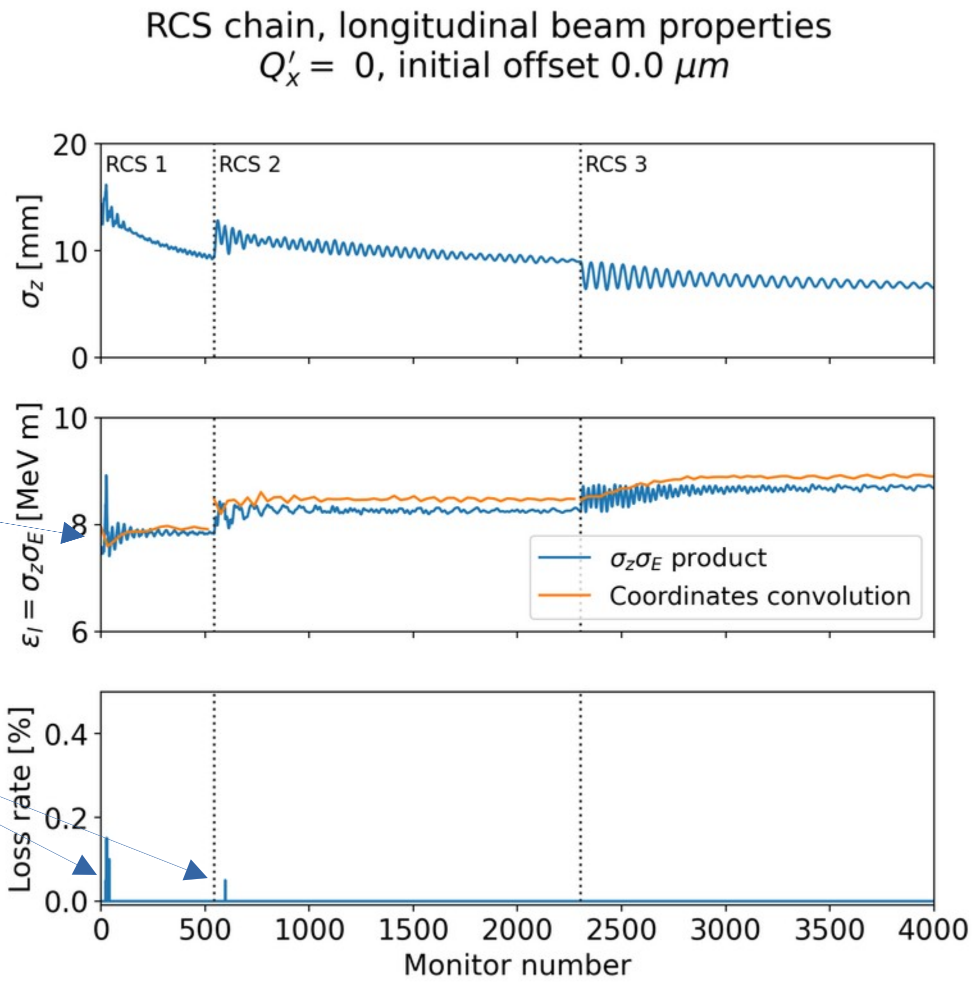
Example of start-to-end simulations

- Example of a simulation in RCS 1, RCS 2 and RCS 3 chain
  - 17/55/66 turns of acceleration in RCS1/2/3
  - 32 RF stations in each RCS
  - Chromaticity Q’ = 0, no impedance, no initial transverse offset
- There is a beam monitor at each RF station
  - Total of (17+55+66) * 32 = **4416 measurement points**



Example of start-to-end simulations



Bunch is matched longitudinally at injection into RCS 1

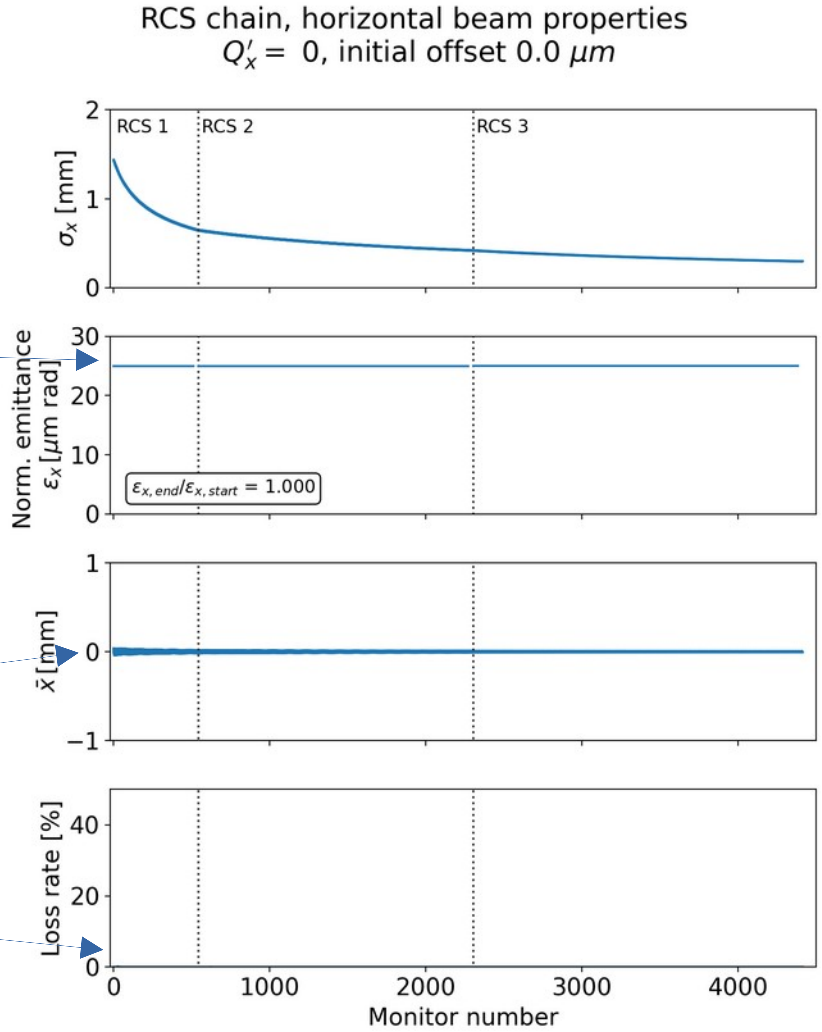
Some particles are lost in the first turns after injection

Example of start-to-end simulations

Bunch is matched transversely at injection into RCS 1

Bunch centroid motion is stable

The losses are only longitudinal (not visible on this scale)



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RCS parameters and beam dynamics scripts

- Goal of the study
  - **Check** that the superconducting, 1.3 GHz, **TESLA type cavities** are compatible with transverse coherent effect limitations
  - **Check** the admissible **transverse offset** in the cavities with respect to impedance effects
  - If there are limitations, provide **mitigation** options such as **transverse damper** strength, **chromaticity** strength

RCS parameters and beam dynamics scripts

- Impedance model
  - 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) cavities in (RCS1, RCS2, RCS3)
- Main assumptions for the RCS:
  - 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

Beam and machine parameters for the RCS

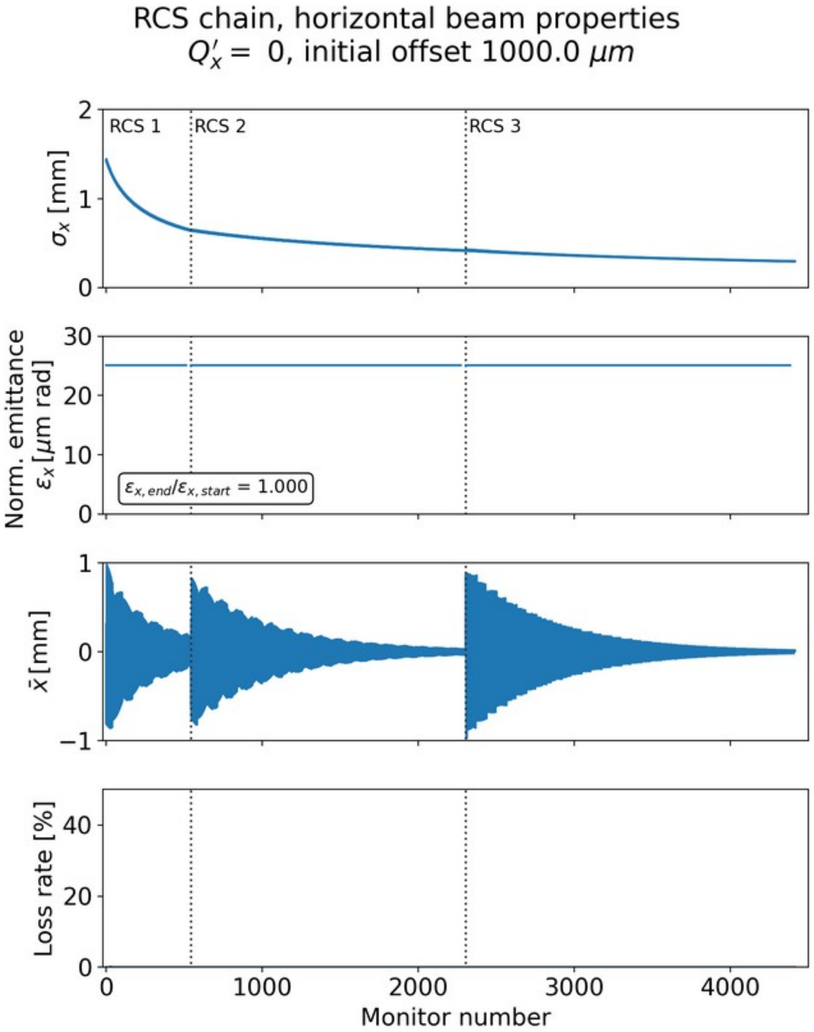
Beam parameters	Unit	Value
Bunch length 1σ	**mm**	**5.7**
Bunch intensity	**Particles per bunch**	**2.7e12**
ε_x / ε_y	**µm rad**	**25**
# of macropaticles		**400k**
# of turns wakefield		**5**
# of slices wakefield		**2000**

Machine parameters	Unit	RCS 1	RCS 2	RCS 3
Circumference	m	5990	5990	10700
Bunch intensity	10^{12}	2.7	2.7	2.7
Beam momentum	GeV/c	63	313.8	750
Energy increase per turn	GeV	14.7	7.9	11.3
Rev. frequency	kHz	50	50	28
RF frequency	MHz	1300	1300	1300
Harmonic number		25957	25957	46295
RF voltage	GV	20.9	11.22	16.1
α_p		0.0024	0.0024	0.001
Avg. beta x/y	m	50 / 50	50 / 50	50 / 50
Chromaticity Q'_x/Q'_y		scan	scan	scan
Detuning from octupoles x/y	m^{-1}	0 / 0	0 / 0	0 / 0

Parameters from F. Batsch RCS tables

Example of start-to-end simulations

- Chromaticity Q' = 0
- No impedance
- **Initial transverse offset = 1 mm at each machine injection**
- A **20-turn transverse damper** is included in each ring (at station #9)

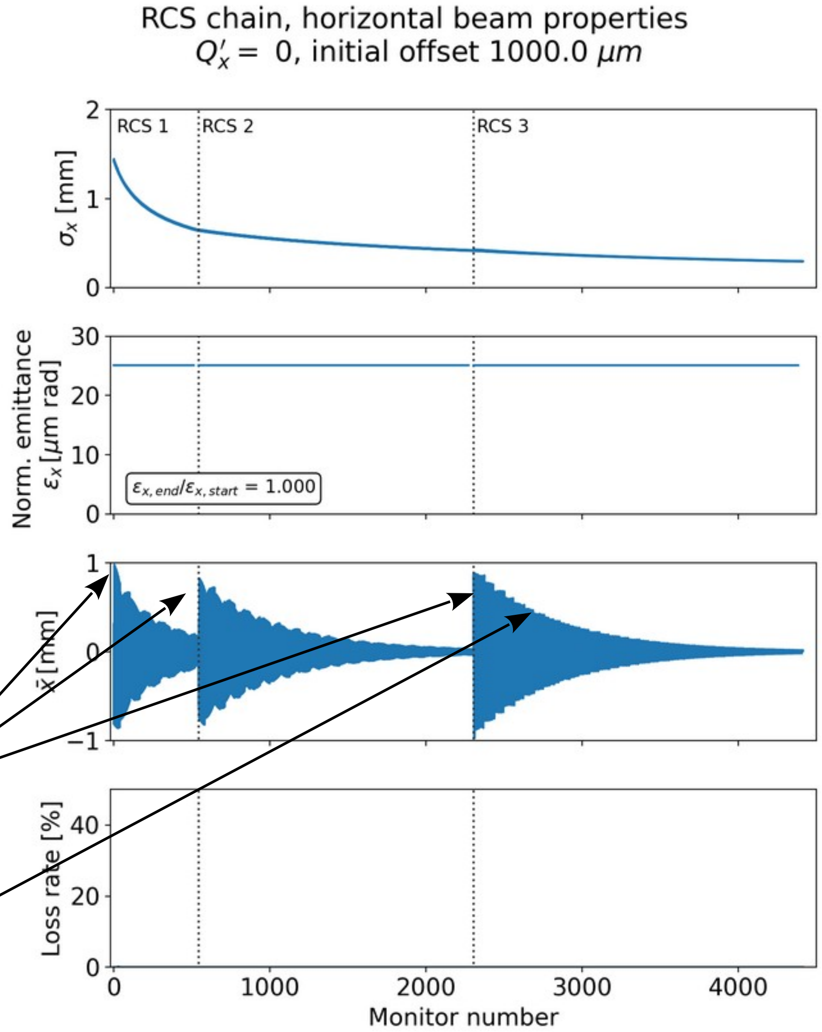


Example of start-to-end simulations

- Chromaticity Q' = 0
- No impedance
- **Initial transverse offset = 1 mm at each machine injection**
- A **20-turn transverse damper** is included in each ring (at station #9)

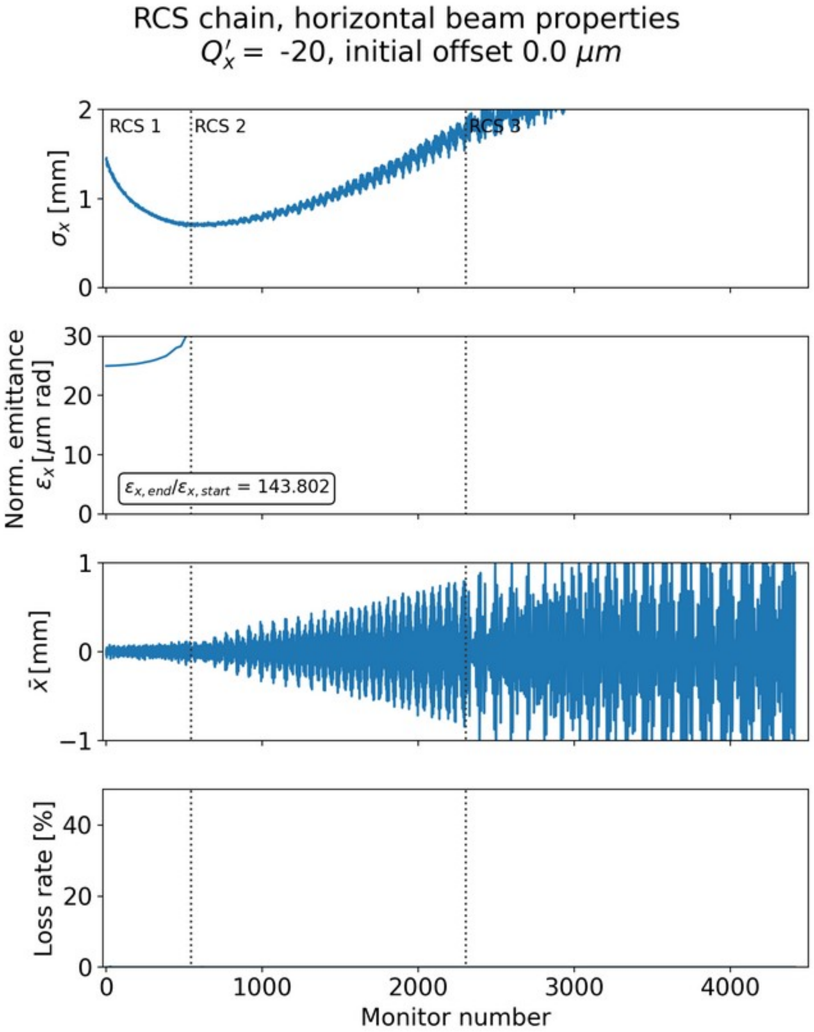
Transverse kick at injection is clearly visible

Damper effect as well



Example of start-to-end simulations

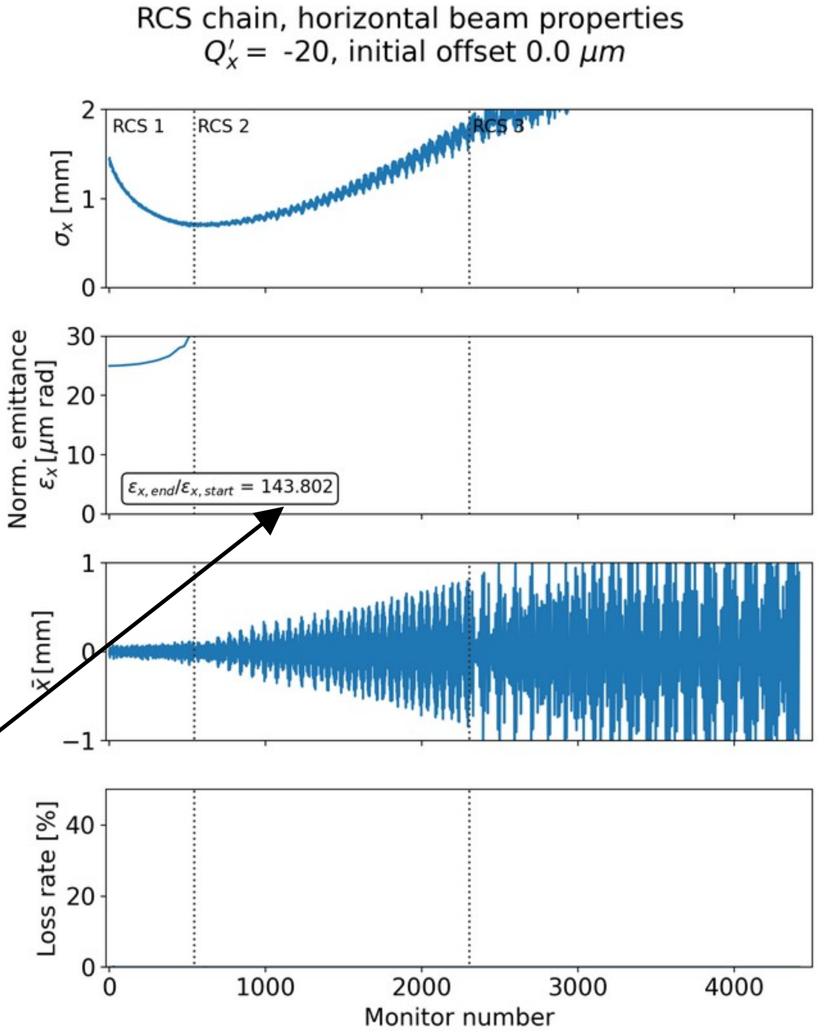
- Chromaticity **Q’ = -20** (natural chromaticity)
- **TESLA cavities impedance model is included**
- No initial transverse offset
- A 20-turn transverse damper is included in each ring (at station #9)



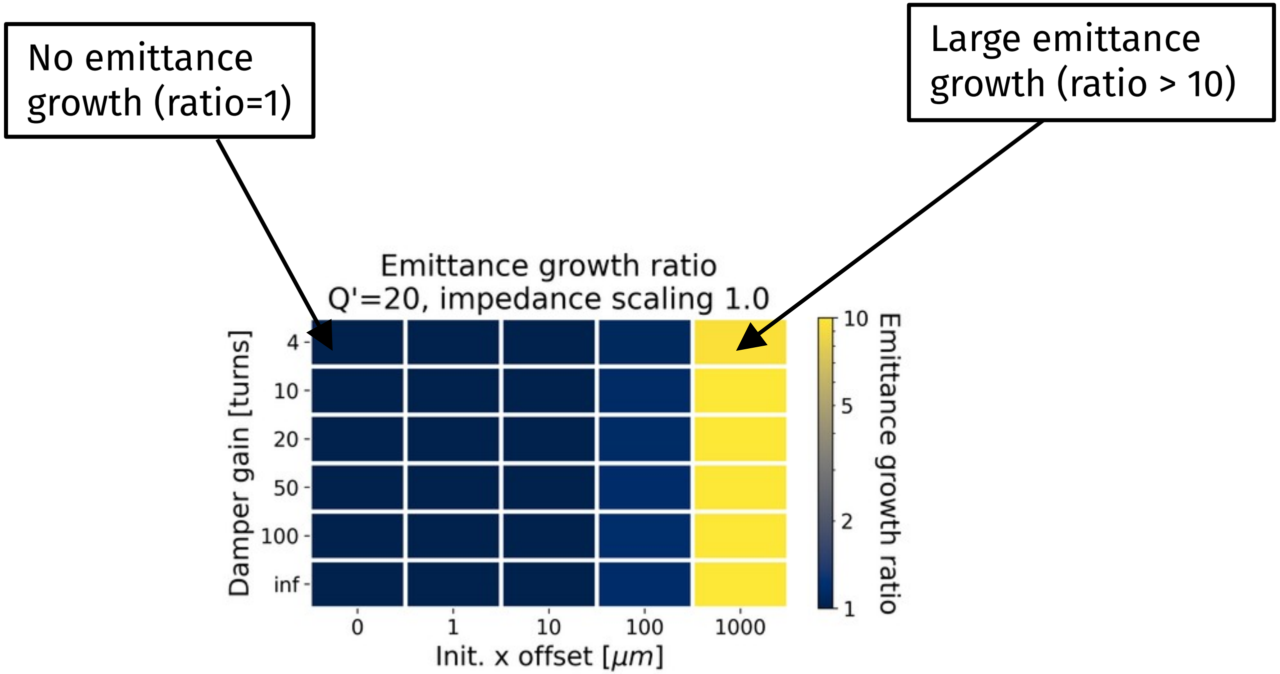
Example of start-to-end simulations

- Chromaticity **Q' = -20** (natural chromaticity)
- **TESLA cavities impedance model is included**
- 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 3)/ε_(start of RCS 1)



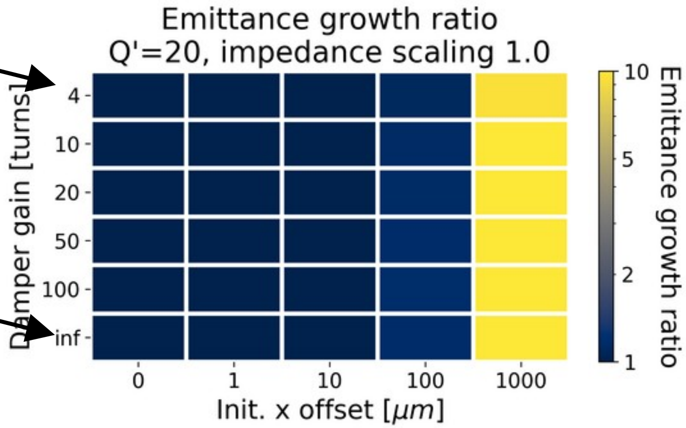
Results of scans versus (positive) chromaticity



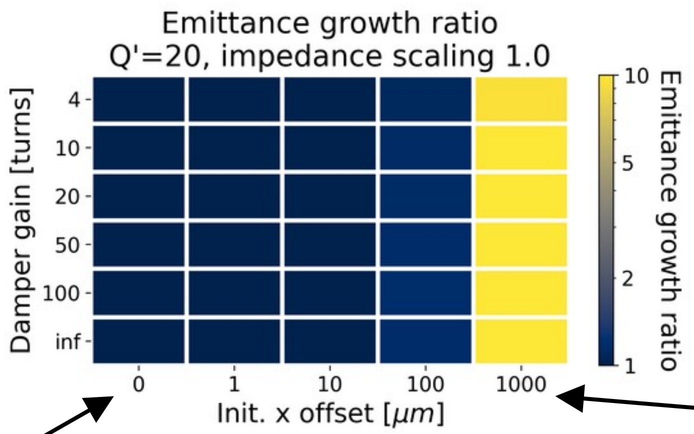
Results of scans versus (positive) chromaticity

Strong damper (4-turn)

No damper



Results of scans versus (positive) chromaticity



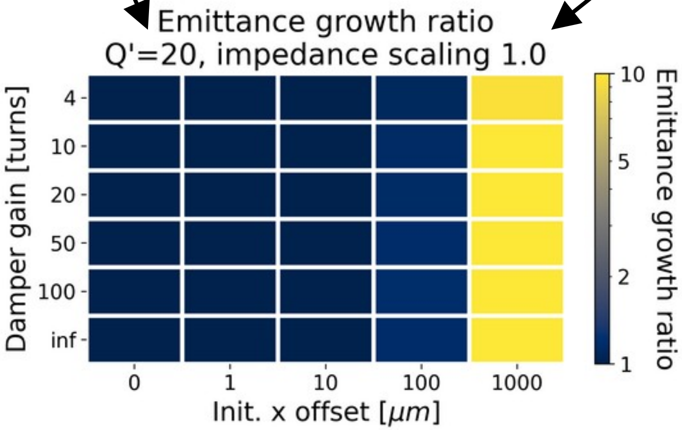
No initial transverse offset

1 mm initial offset in each RCS

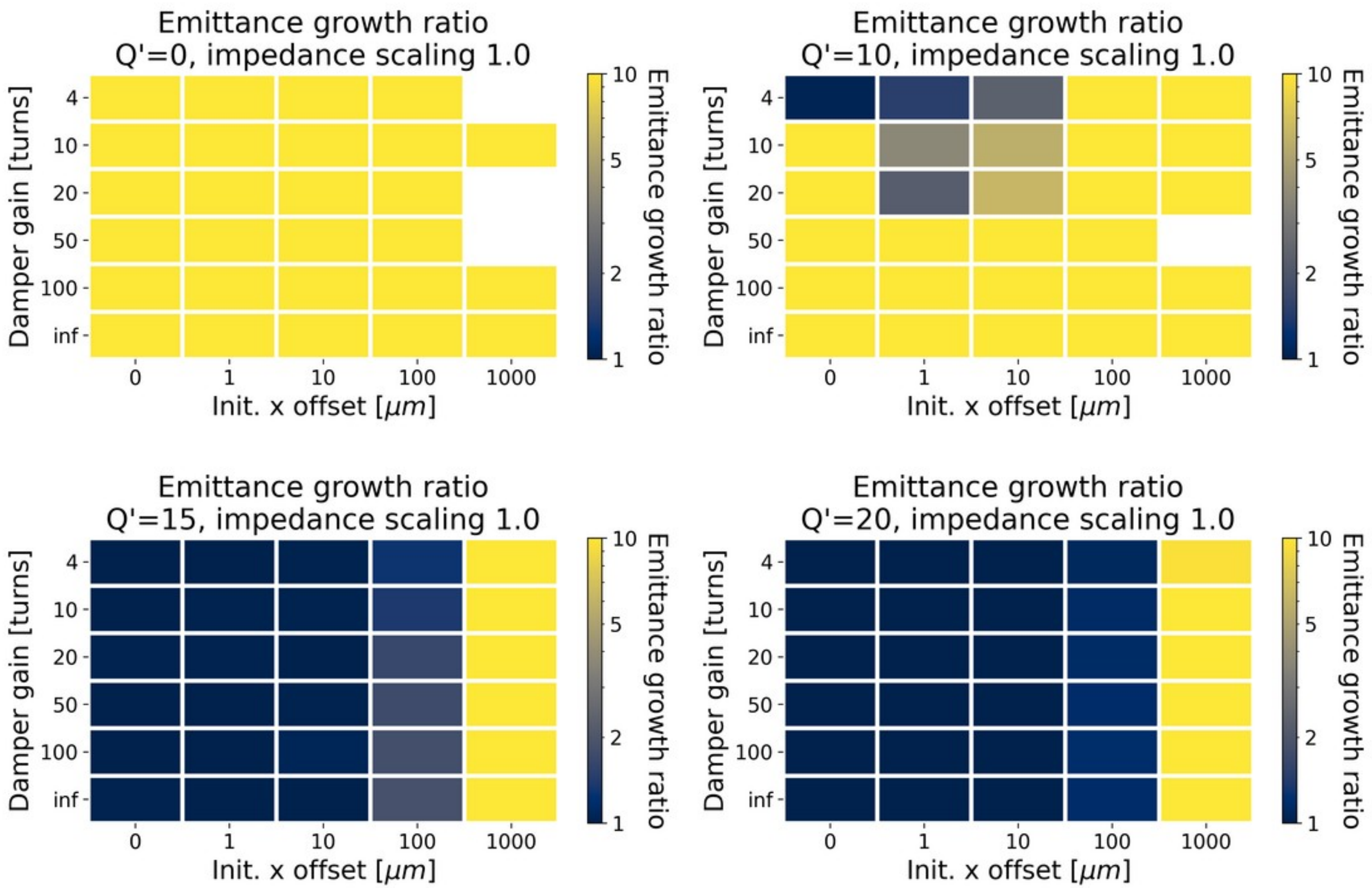
Results of scans versus (positive) chromaticity

Simulation for chromaticity Q’=20

Impedance model scaling factor

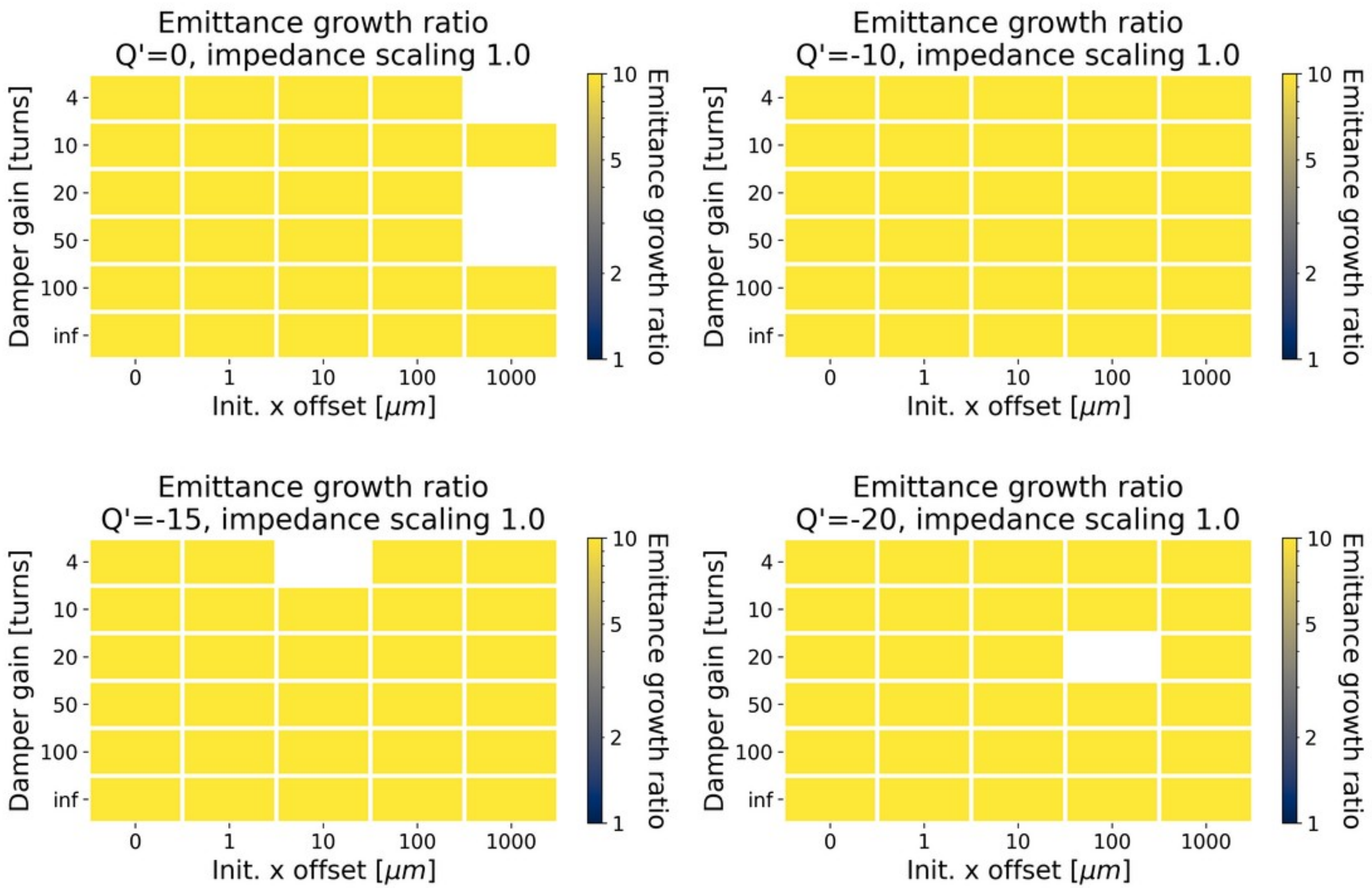


Results of scans versus (positive) chromaticity



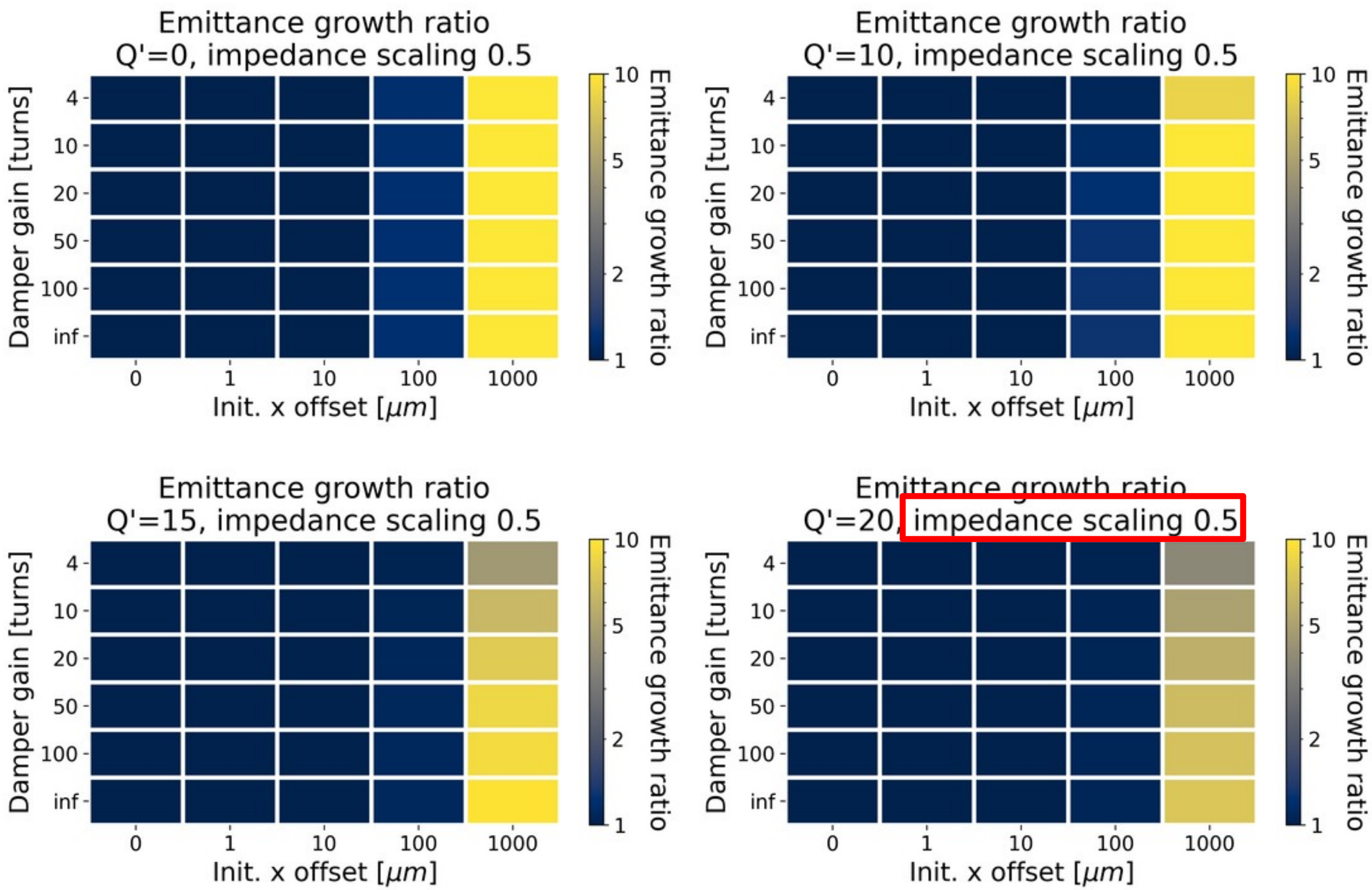
- Positive chromaticity is required to stabilize the beam, at least Q'=+15
- The transverse damper is not required for high chromaticities
- An initial transverse offset can be tolerated, up to 10-100 μm

Results of scans versus (negative) chromaticity



- Beam is always unstable, whatever the chromaticity or damper setting

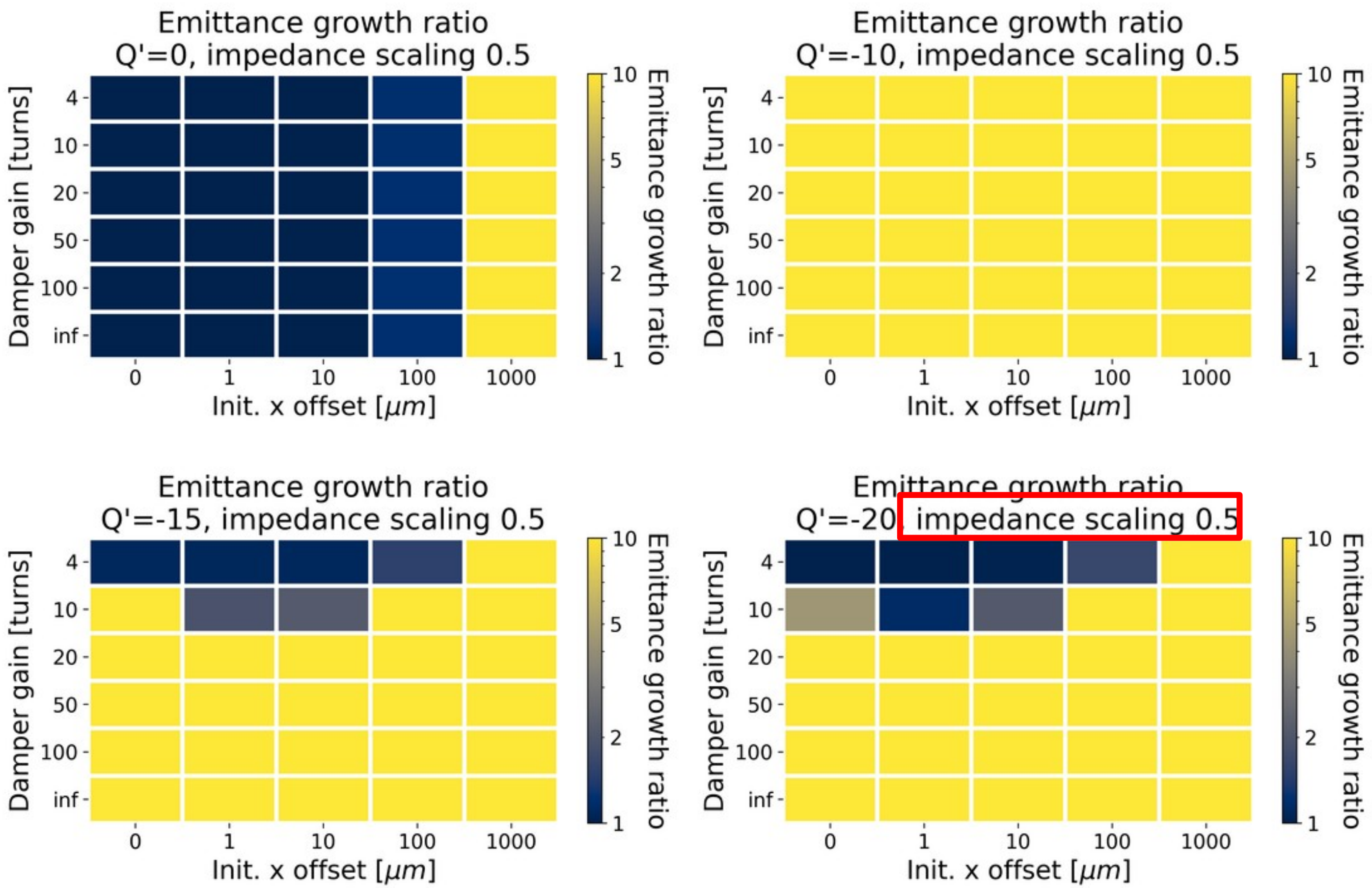
Reducing the R/Q of the modes



- 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

Reducing the R/Q of the modes, negative Q’



- Only a strong damper, combined with the R/Q reduction, can stabilize the beam with negative chromaticity

Summary for three RCS

	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'>10 + any damper Offset up to 100 μm	Q'< -15 + 4-turn damper Offset up to 100 μm

Contents

- XSuite presentation
- Simulation setup
- Example of start-to-end simulations and future work
- Evaluation of TESLA cavities impact on transverse stability, with 3 RCS
- Evaluation of TESLA cavities impact on transverse stability, with 4 RCS

RCS parameters, including RCS 4

- Impedance model
  - 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

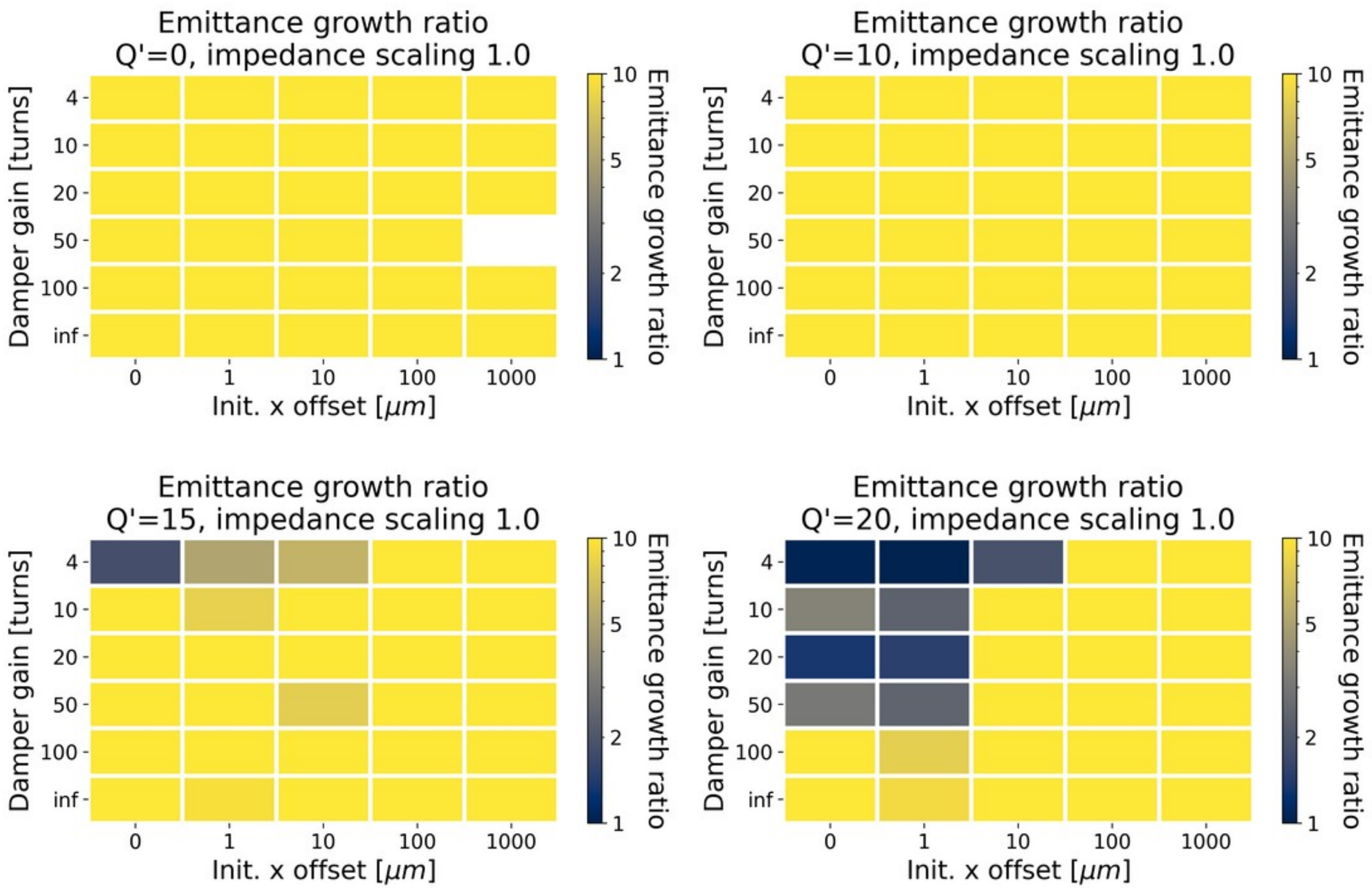
Beam and machine parameters for the RCS

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
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

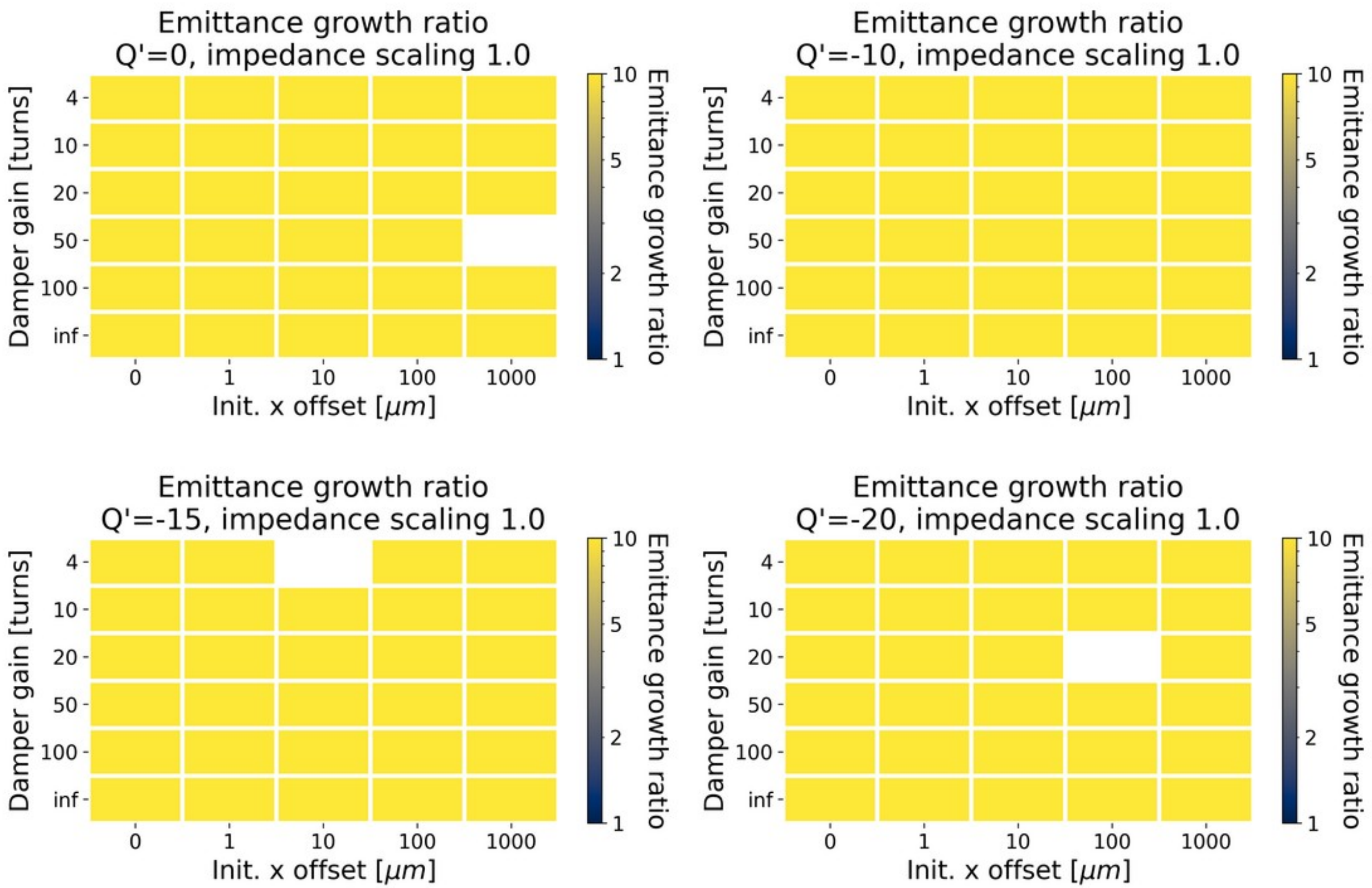
Parameters from F. Batsch RCS tables

Results of scans versus (positive) chromaticity



- Adding RCS 4, with **3000 cavities,** strongly degrades the situation
- 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**

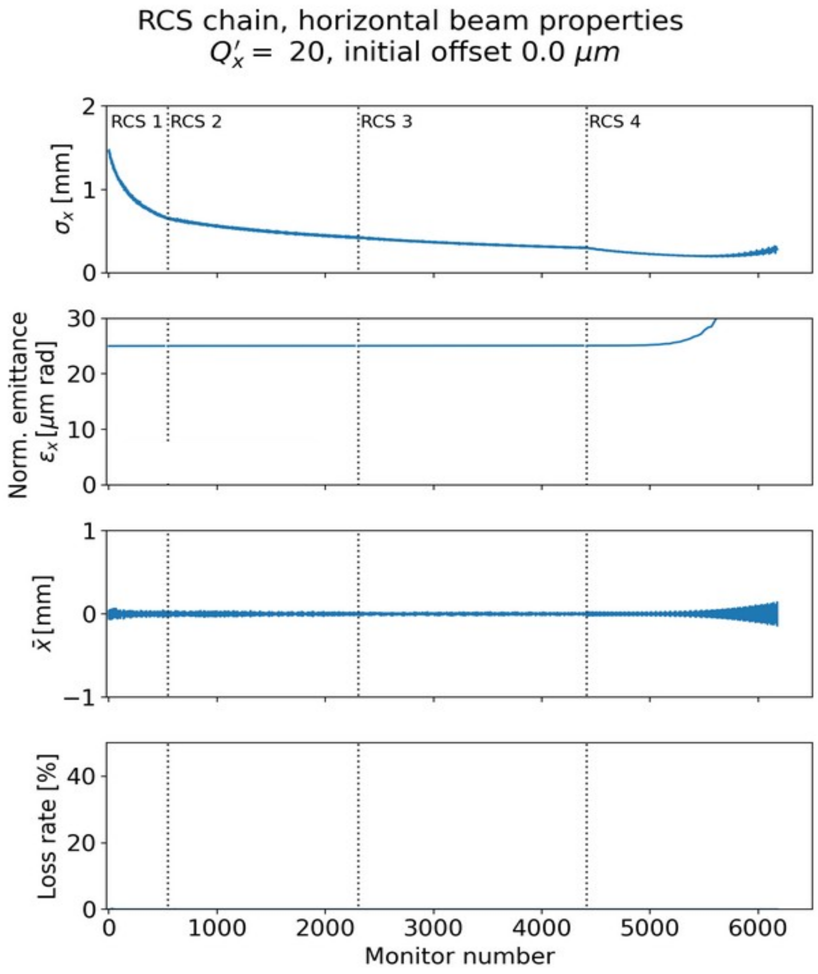
Results of scans versus (negative) chromaticity



- Beam is always unstable

Example of start-to-end simulation with RCS 4

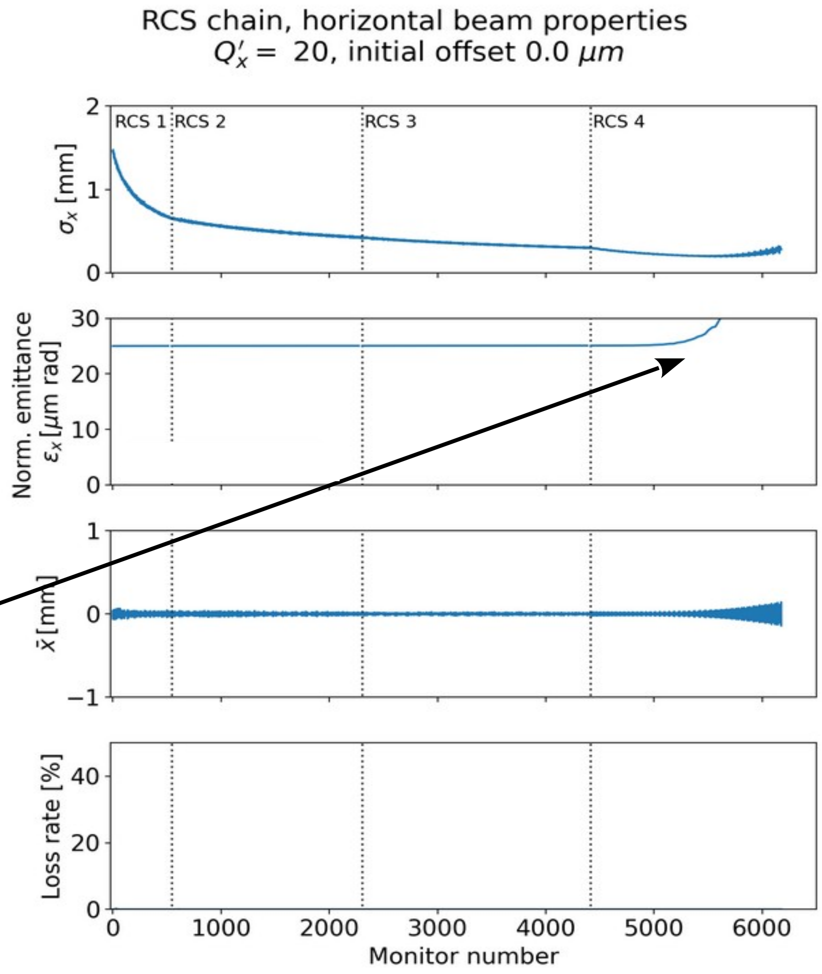
- Chromaticity **Q' = 20**
- **No initial transverse offset**
- A **50-turn transverse damper** is included in each ring (at station #9)



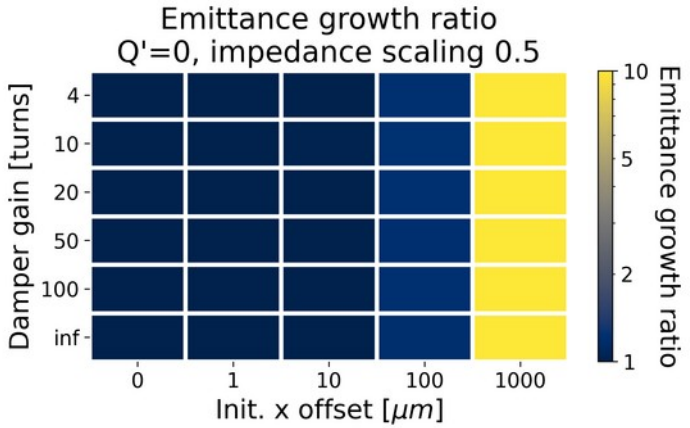
Example of start-to-end simulation with RCS 4

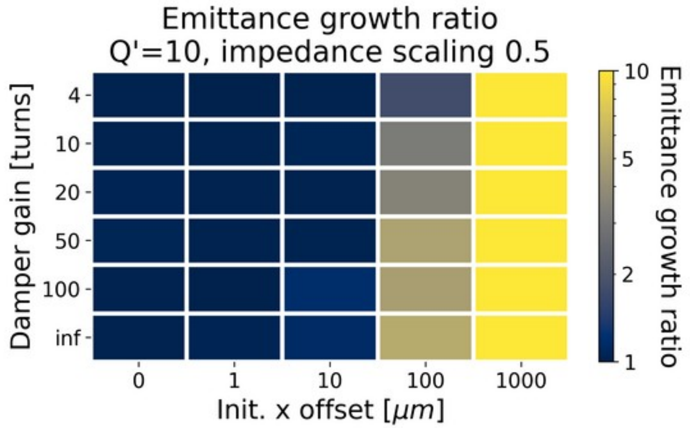
- Chromaticity **Q' = 20**
- **No initial transverse offset**
- A **50-turn transverse damper** is included in each ring (at station #9)

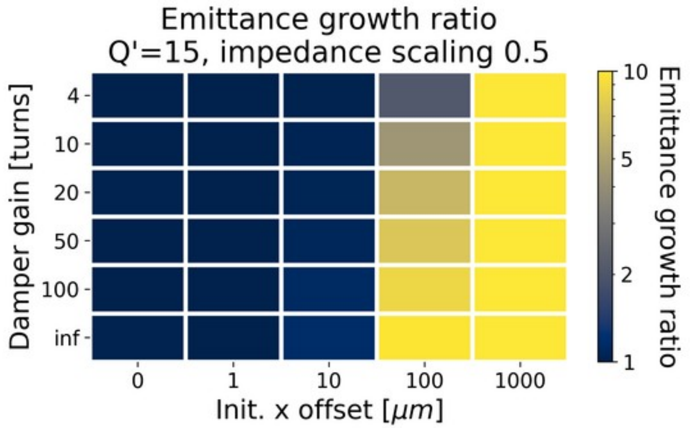
The instability clearly starts in RCS4

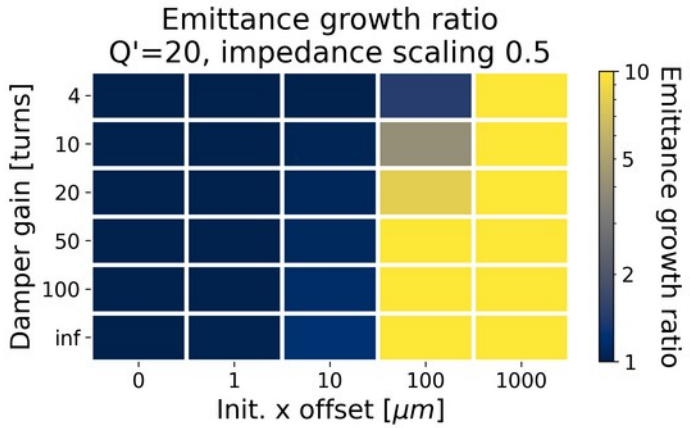


Reducing the R/Q of the modes



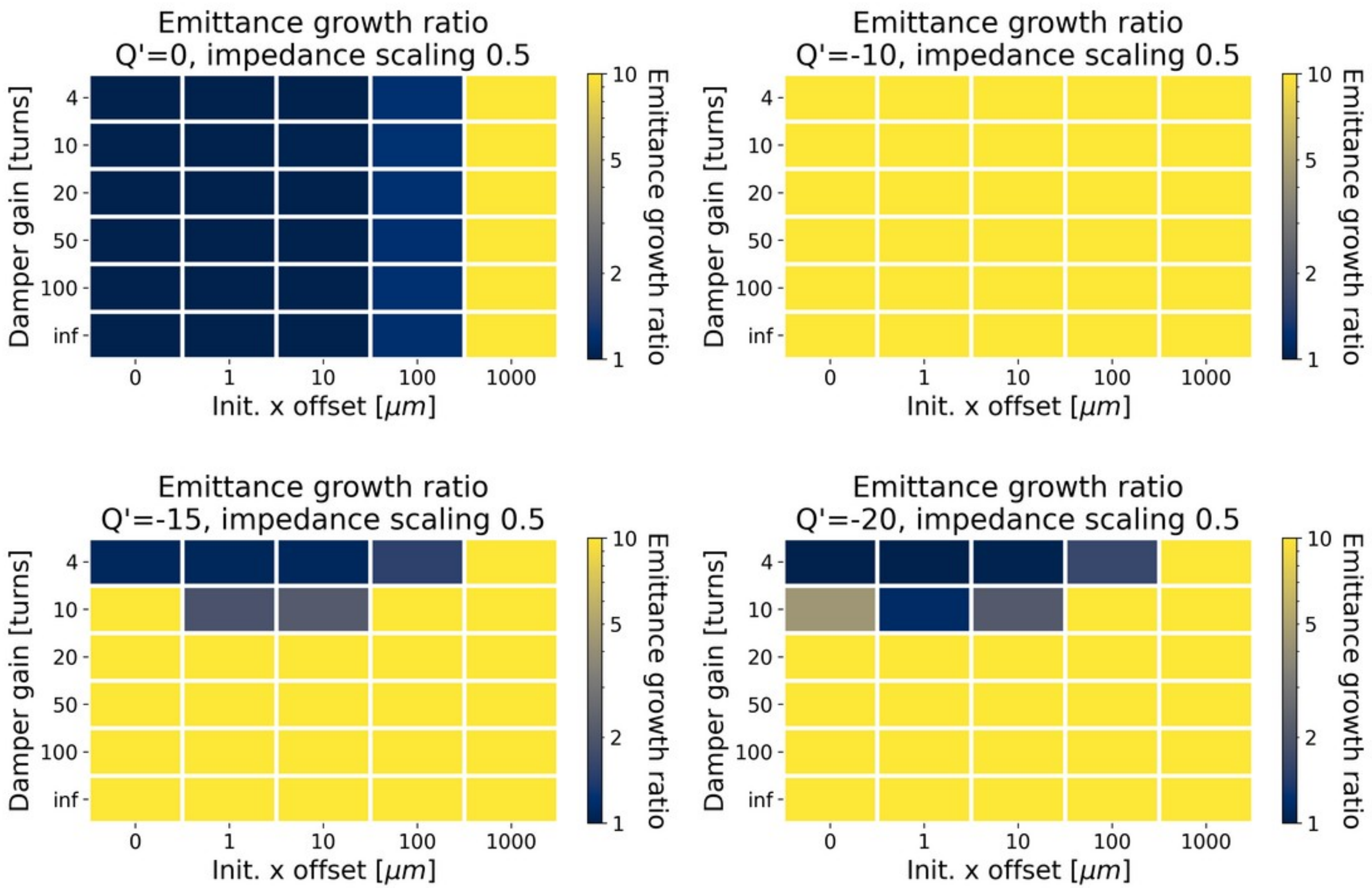






- Here the full impedance model is scaled by a factor 0.5 → like dividing the R/Q of every mode by 2
- We recover transverse coherent stability with larger offset

Reducing the R/Q of the modes, negative Q'

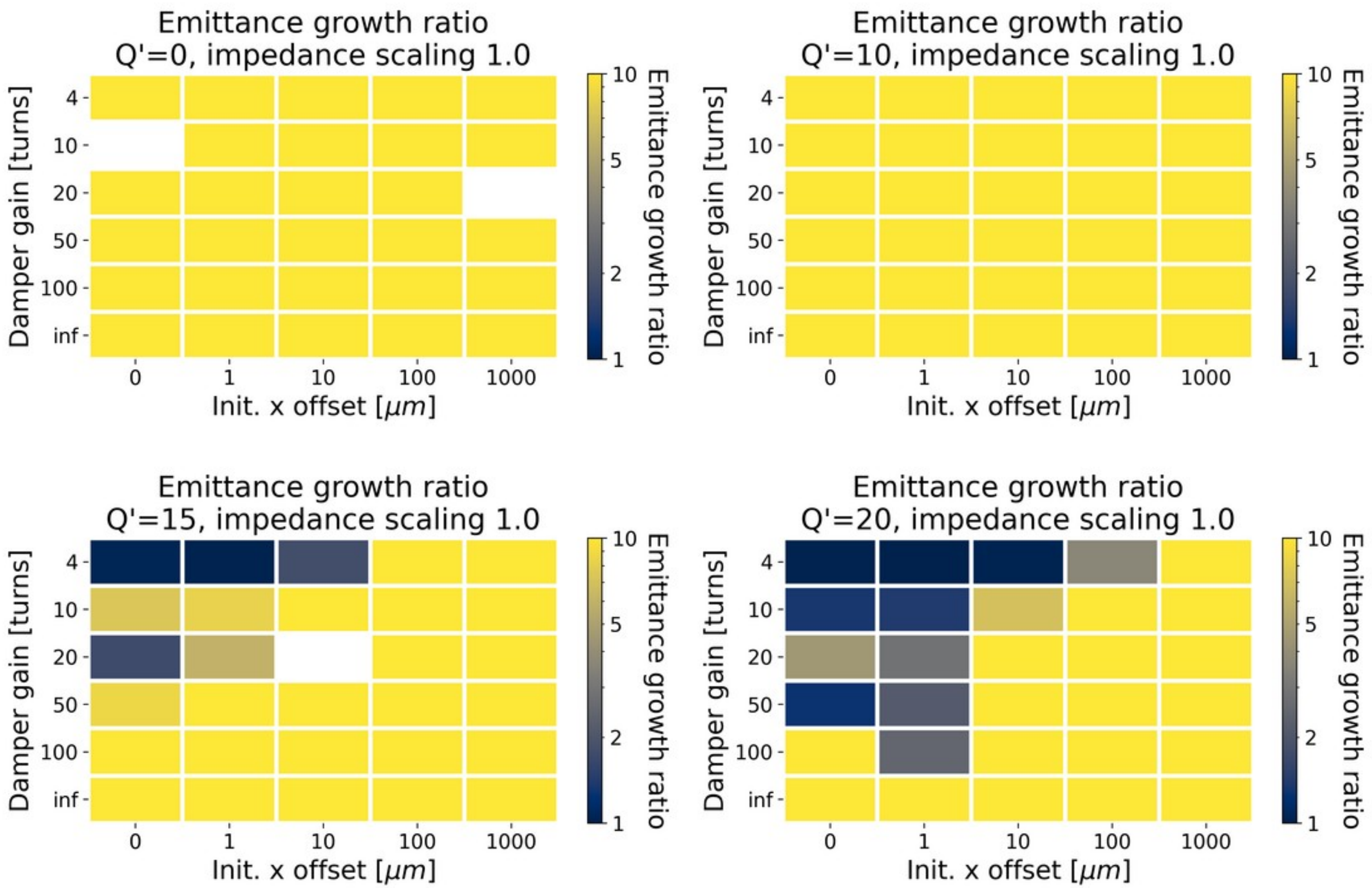


- Here the full impedance model is scaled by a factor 0.5 → like dividing the R/Q of every mode by 2
- We recover transverse coherent stability with larger offset

Including RCS 4, two dampers in RCS 4

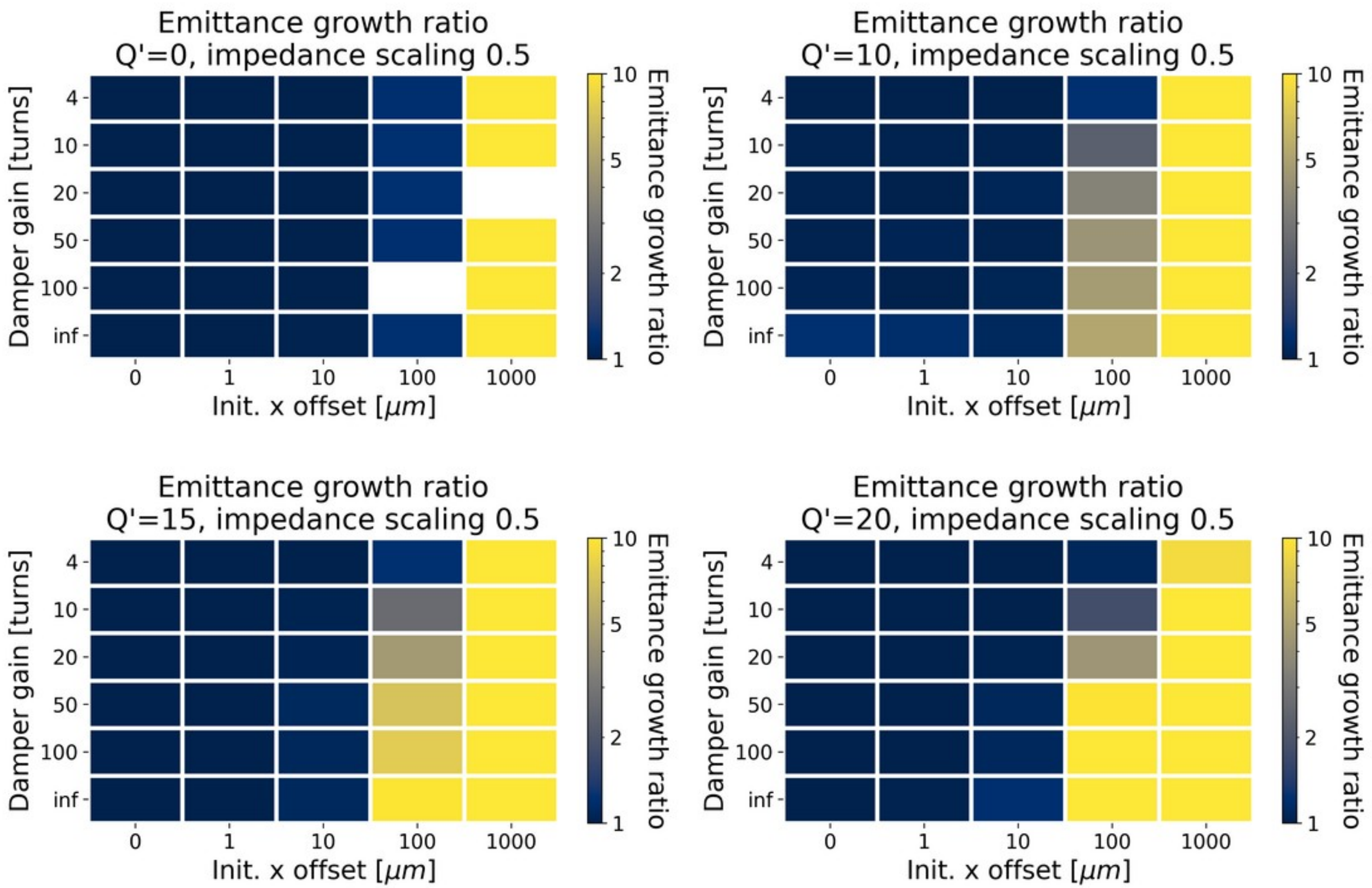
- Modify the RCS 4 configuration (other RCS kept identical)
  - **Two transverse damper units**, located at RF station 9 and 25 (~¼ and ~¾ of the ring)
- All other parameters and scan kept identical

Two dampers in RCS 4, positive chromaticity



- Situation remains similar to the case with one damper only

Two dampers in RCS 4, reducing the R/Q



- Still with positive chromaticity
- Situation remains similar to the case with one damper only → the reduction of R/Q of the mode remains clearly the most effective way to mitigate the instability

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

- Adding a second transverse damper to RCS 4 doesn't improve significantly the picture

Overview and next steps

- With **three RCS**, start-to-end simulations show that **TESLA type cavities can be used**, but **require some instability mitigation**
  - With chromaticity **Q'=20**, a weak or even no transverse damper is required
  - **Transverse offset up to 0.1 mm** are admissible
- Introducing the **RCS 4** (1.5 TeV → 5 TeV) **strongly degrades** transverse coherent beam **stability**
  - Need chromaticity **Q'=20 with strong damper** (4-turn to 10-turn)
  - Little or **no transverse offset is admissible**

Overview and next steps

- In **RCS 4**, investigate the **addition of transverse damper** located at ¾ of the ring (currently running), start and ½ of the ring.

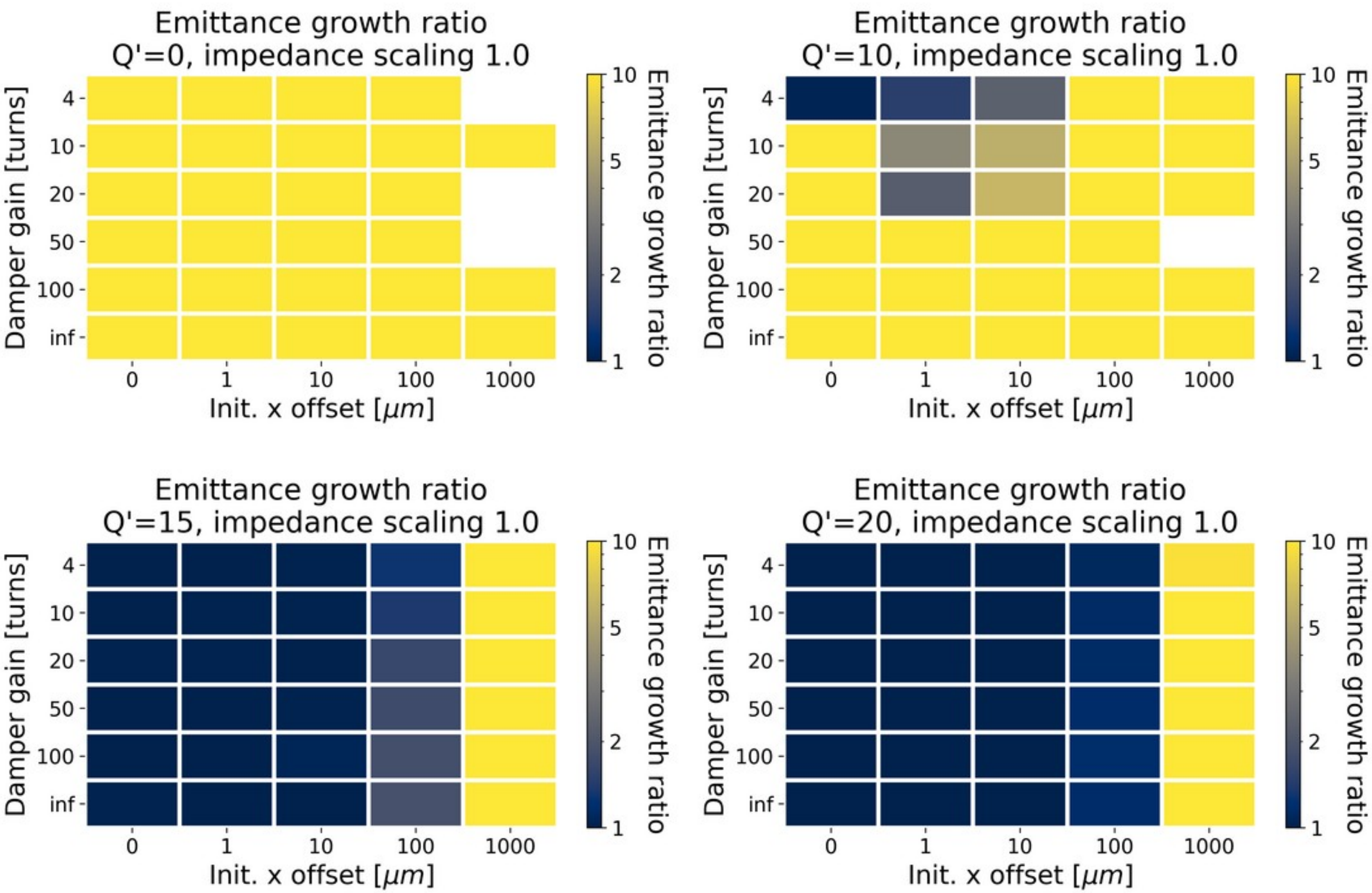
- Include the muon decay effect: the intensity reduction will help with transverse coherent stability
  - Bunch intensity in RCS 1 at injection: 2.7e12
  - Bunch intensity in RCS 4 at injection: 2.0e12
  - **25 % reduction in intensity between RCS 1 and RCS 4**

Thank you!

Convergence test for HOMs Q factor

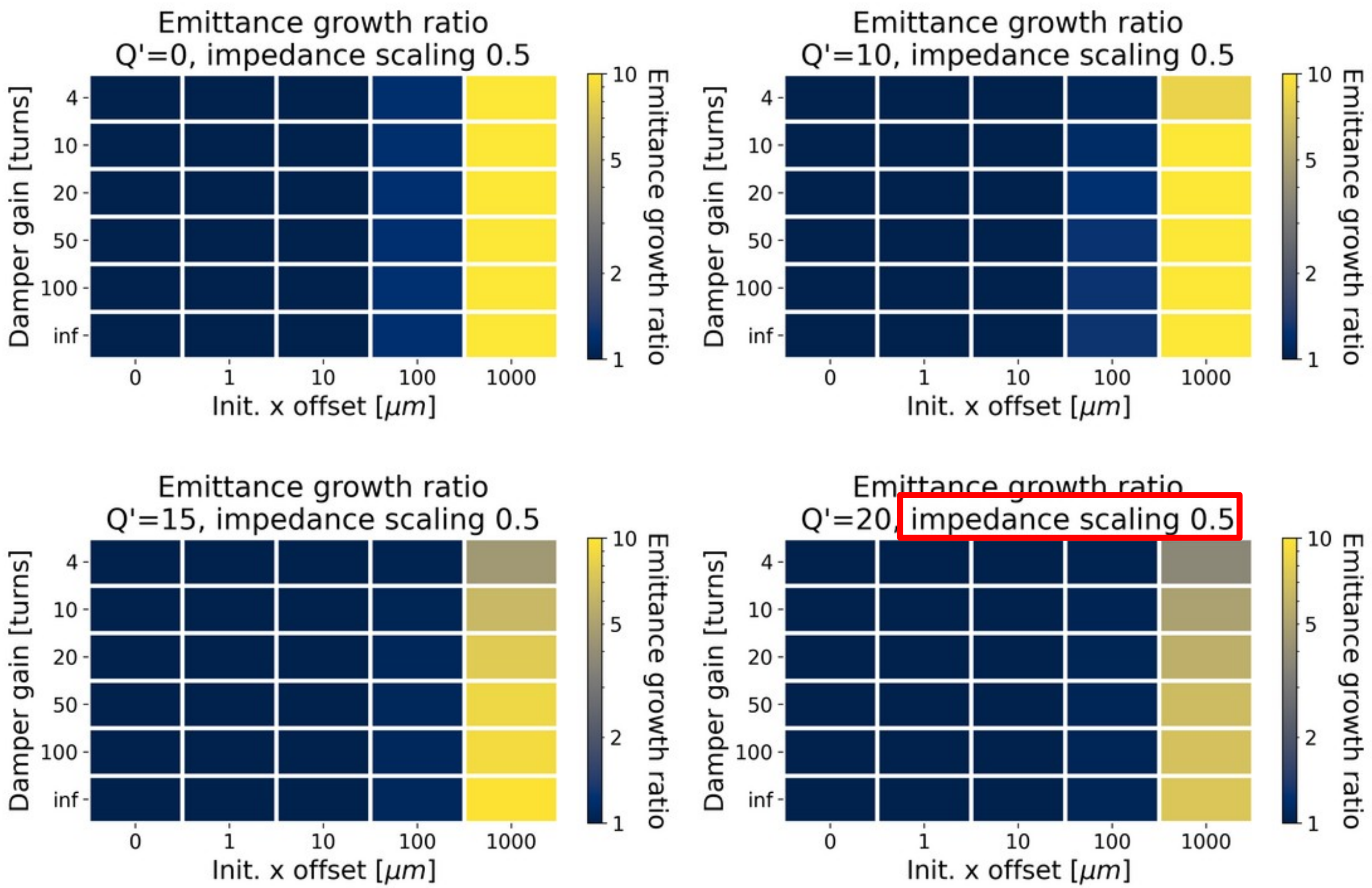
- Q = 105, 106, 107

HOMs Q=10^6 with positive 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

HOMs Q=10^6 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