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

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IMCC and MuCol annual meeting 2024, CERN
2024-03-13
Contents

- XSuite presentation
- Simulation setup
- Example of start-to-end simulations
- 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)
  
  o Covering with a single toolkit of injectors, LHC, HL-LHC and design studies (e.g. PBC, FCC hh & ee)
  
  o Exploitation of modern computing platforms (e.g. GPUs) for a wide range of applications
  
  o Strong simplification of development and maintenance process (removes several duplications)

<table>
<thead>
<tr>
<th>Available</th>
<th>In development</th>
<th>Not available</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAD-X track</th>
<th>Sixtrack</th>
<th>Sixtracklib</th>
<th>PyHEADTAIL</th>
<th>COMBI</th>
<th>Xsuite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full lattice description</td>
<td>Dynamic effects (time, noise)</td>
<td>Beam-beam 4d (weak-strong)</td>
<td>e-cloud incoherent</td>
<td>Advanced collision features</td>
<td>Impefectronics</td>
</tr>
</tbody>
</table>

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RCS chain transverse coherent stability

G. Iadarola et al., Xsuite: An integrated beam physics simulation framework

CEI section meeting 03/11/2022
XSuite presentation

**Hardware**

- **External libraries** (lower-level, interface with hardware)

**External libraries**

- CFFI
- PyOpenCL
- CuPy

**Hardware**

- Intel
- AMD
- NVIDIA

**Physics modules**

- **Xpart**
  - generation of particles distributions

- **Xfields**
  - computation of EM fields from particle ensembles

- **Xtrack**
  - single particle tracking engine

- **Xdeps**
  - Dependency manager, deferred expressions

- **Xcoll**
  - Collimation methods

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

G. Iadarola et al., *ibid*
XSuite presentation

Physics modules
- Xpart: generation of particle distributions
- Xtrack: single particle tracking engine
- Xfields: computation of EM fields from particle ensembles
- Xdeps: dependency manager, deferred expressions
- Xcoll: collimation methods

Xobjects
- Interface to different computing platforms (CPUs and GPUs of different vendors)

CFFI, PyOpenCL, CuPy

Intel, AMD, NVIDIA

PyHEADTAIL.particles, PyHEADTAIL.impedances, PyHEADTAIL.feedback
XSuite presentation

xpart.enable_pyheadtail_interface()

- 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
Contents

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- Simulation setup
- Example of start-to-end simulations
- Evaluation of TESLA cavities impact on transverse stability, with 3 RCS
- Evaluation of TESLA cavities impact on transverse stability, with 4 RCS
RCS parameters and beam dynamics scripts

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

Scripts and notebooks related to the 10 TeV collider

Python package with modules for machine parameters

Scripts and notebooks for the different RCS
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
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.
• 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

LineSegmentMap
Longitudinal map (including acceleration) + Transverse map

```python
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., dp=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,
                                             qa=None, bta=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,
                                             dpx=chroma_x, dpy=chroma_y,
                                             detx_x=0.0, detx_y=0.0, dety_x=0.0, dety_y=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,
                                             equiv_emit_x=0.0, equiv_emit_y=0.0, equiv_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}')
```
Simulation setup

```python
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, alphax=alpha_x, alphay=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,
    qa=None, bet=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,
    dpx=chroma_x, dpy=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 = 0.8, damping_rate_y = 0.8, 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(wakefield)
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}')
```

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RCS chain transverse coherent stability
Simulation setup

ParticleMonitor
Longitudinal and Transverse apertures

```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)
Simulation setup

Create the XSuite line used for tracking

```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=-10e-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

- 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

RCS 1
- 63 – 313 GeV

RCS 2
- 313 - 750 GeV

RCS 3
- 750 - 1500 GeV

RCS 4
- 1.5 - 5.0 TeV
Simulation setup

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

```python
# 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
distribution_type = ThermalDistribution,

matcher = RFBucketMatcher(rbucket=rbucket,
                           distribution_type=ThermalDistribution,
                           target_longitudinal_emittance=target_longitudinal_emittance)

z_particles, delta_particles = matcher.generate(macroparticle_number=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-rbucket.zeta,
    x=x_in_sigmas, px=px_in_sigmas,
    y=y_in_sigmas, py=py_in_sigmas,
    norm_emit_x, norm_emit_y,
    weight=initial_bunch_intensity/n_macroparticles)
```
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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 $(17+55+66) \times 32 = 4416$ measurement points

RCS chain, longitudinal beam properties
$Q'_{x} = 0$, initial offset 0.0 $\mu$m

![Graph showing $\sigma_x$, $\epsilon_l$, and Loss rate over Monitor number](image)
Example of start-to-end simulations

RCS chain transverse coherent stability

Bunch is matched longitudinally at injection into RCS 1

Some particles are lost in the first turns after injection

RCS chain, longitudinal beam properties

$Q'_x = 0$, initial offset $0.0 \, \mu m$
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)

RCS chain, horizontal beam properties
$Q_\chi' = 0$, initial offset $0.0 \mu m$

- RCS 1
- RCS 2
- RCS 3

- Norm, emittance $\varepsilon_x [\mu m \text{ rad}]$
- $\varepsilon_x, \text{end}/\varepsilon_x, \text{start} = 1.000$

- $\bar{x} [\text{mm}]$

- Loss rate [%]

Monitor number

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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 (~$\frac{1}{4}$ 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 $\mu$m to 1 mm
# Beam and machine parameters for the RCS

## Machine parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>RCS 1</th>
<th>RCS 2</th>
<th>RCS 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>m</td>
<td>5990</td>
<td>5990</td>
<td>10700</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$10^{12}$</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Beam momentum</td>
<td>GeV/c</td>
<td>63</td>
<td>313.8</td>
<td>750</td>
</tr>
<tr>
<td>Energy increase per turn</td>
<td>GeV</td>
<td>14.7</td>
<td>7.9</td>
<td>11.3</td>
</tr>
<tr>
<td>Rev. frequency</td>
<td>kHz</td>
<td>50</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Harmonic number</td>
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<td>25957</td>
<td>46295</td>
</tr>
<tr>
<td>RF voltage</td>
<td>GV</td>
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<td>11.22</td>
<td>16.1</td>
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<td>$\alpha_p$</td>
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<tr>
<td>Avg. beta $x/y$</td>
<td>m</td>
<td>50 / 50</td>
<td>50 / 50</td>
<td>50 / 50</td>
</tr>
<tr>
<td>Chromaticity $Q'_x/Q'_y$</td>
<td></td>
<td>scan</td>
<td>scan</td>
<td>scan</td>
</tr>
<tr>
<td>Detuning from octupoles $x/y$</td>
<td>m$^{-1}$</td>
<td>0 / 0</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
</tbody>
</table>

# Beam parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch length $1\sigma$</td>
<td>mm</td>
<td>5.7</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>Particles per bunch</td>
<td>$2.7e12$</td>
</tr>
<tr>
<td>$\varepsilon_x / \varepsilon_y$</td>
<td>$\mu$m rad</td>
<td>25</td>
</tr>
<tr>
<td># of macroparticles</td>
<td></td>
<td>400k</td>
</tr>
<tr>
<td># of turns wakefield</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td># of slices wakefield</td>
<td></td>
<td>2000</td>
</tr>
</tbody>
</table>

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)

RCS chain, horizontal beam properties $Q'_x = 0$, initial offset 1000.0 µm

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 $\varepsilon(\text{end of RCS 3})/\varepsilon(\text{start of RCS 1})$
Example of start-to-end simulations

See attached video of the longitudinal and transverse bunch profile evolution
Results of scans versus (positive) chromaticity

No emittance growth (ratio=1)

Large emittance growth (ratio > 10)
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

Emittance growth ratio
$Q' = 20$, impedance scaling 1.0

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RCS chain transverse coherent stability
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 $\mu$m
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 $Q' > \sim 0$

- 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

<table>
<thead>
<tr>
<th>Positive Q’</th>
<th>Negative Q’</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal R/Q of the HOMs</strong></td>
<td>Q’&gt;15 + any damper offset up to 100 μm</td>
</tr>
<tr>
<td><strong>Half R/Q of the HOMs</strong></td>
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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 (~$\frac{1}{4}$ 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

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<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
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<tr>
<td>Harmonic number</td>
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<td>25957</td>
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<td>46295</td>
<td>151433</td>
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<tr>
<td>RF voltage</td>
<td>GV</td>
<td>20.9</td>
<td>11.22</td>
<td>16.1</td>
<td>90.0</td>
</tr>
<tr>
<td>α_p</td>
<td></td>
<td>0.0024</td>
<td>0.0024</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Avg. beta x/y</td>
<td>m</td>
<td>50 / 50</td>
<td>50 / 50</td>
<td>50 / 50</td>
<td>50 / 50</td>
</tr>
<tr>
<td>Chromaticity Q'_x/Q'_y</td>
<td></td>
<td>scan</td>
<td>scan</td>
<td>scan</td>
<td>scan</td>
</tr>
<tr>
<td>Detuning from octupoles x/y</td>
<td>m^{-1}</td>
<td>0 / 0</td>
<td>0 / 0</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
</tbody>
</table>

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)

RCS chain, horizontal beam properties
$Q_x = 20$, initial offset 0.0 $\mu$m
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 \(\rightarrow\) like dividing the R/Q of every mode by 2

- We recover some transverse coherent stability but a strong damper is needed
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

<table>
<thead>
<tr>
<th></th>
<th>Positive Q’</th>
<th>Negative Q’</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal R/Q of the HOMs</strong></td>
<td>Q’&gt;15 + 10-turn damper offset up to 1 ( \mu m )</td>
<td>Always unstable</td>
</tr>
<tr>
<td><strong>Half R/Q of the HOMs</strong></td>
<td>Q’&gt;0 + any damper Offset up to 100 ( \mu m )</td>
<td>Q’&lt; -15 + 4-turn damper Offset up to 100 ( \mu m )</td>
</tr>
</tbody>
</table>

- 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 \( \frac{3}{4} \) of the ring (currently running), start and \( \frac{1}{2} \) of the ring.
- Include the muon decay effect: the intensity reduction will help with transverse coherent stability
  - Bunch intensity in RCS 1 at injection: \( 2.7 \times 10^{12} \)
  - Bunch intensity in RCS 4 at injection: \( 2.0 \times 10^{12} \)
  - **25 % reduction in intensity between RCS 1 and RCS 4**
- Check in detail the effect of chromaticity combined with offset (effect of sextupoles feed-down)
- Include the detailed lattice in simulations (see L. Soubirou presentation on the RCS geometry and lattice)
Convergence test for HOMs Q factor

- Change the resonator Q from $Q=10^5$ to $Q=10^6$
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 $\mu$m
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 $Q' > \sim 0$
- An initial transverse offset can be tolerated, up to 10-100 $\mu$m
Convergence test with # of MP and # of wakefield slices

- Check the impact of the number of macroparticles and number of slices for the wakefield
- Scan # of wakefield slices: 2000, 4000, 8000
- Scan # of macroparticles: 200k, 400k, 800k and 1200k
- Results shown for Q’=10, impedance scaling factor of 0.5
Influence of # of wake slices

- No visible influence of the number of slices of the wakefield → we are good to use 2000 slices for the simulations
Influence of # of macroparticles

• Not much influence either → 200k macroparticles seems OK