Update on transverse collective effect studies for the RCS

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- Introduction
- Effect of a transverse offset of the bunch in RF cavities
- Estimation of two-beam instability growth-rate with RF cavities

Introduction

- At the Collaboration meeting in October 2022
  - Presentation on RCS1 collective effect studies
  - First investigation on the impact of (many) RF cavities on transverse stability
- Since the last collaboration meeting
  - Refined impedance model with all cavities and high-order modes
  - First estimates of bunch offset effect and two-beam instability growth-rate in cavities

Contents

Goal of the study

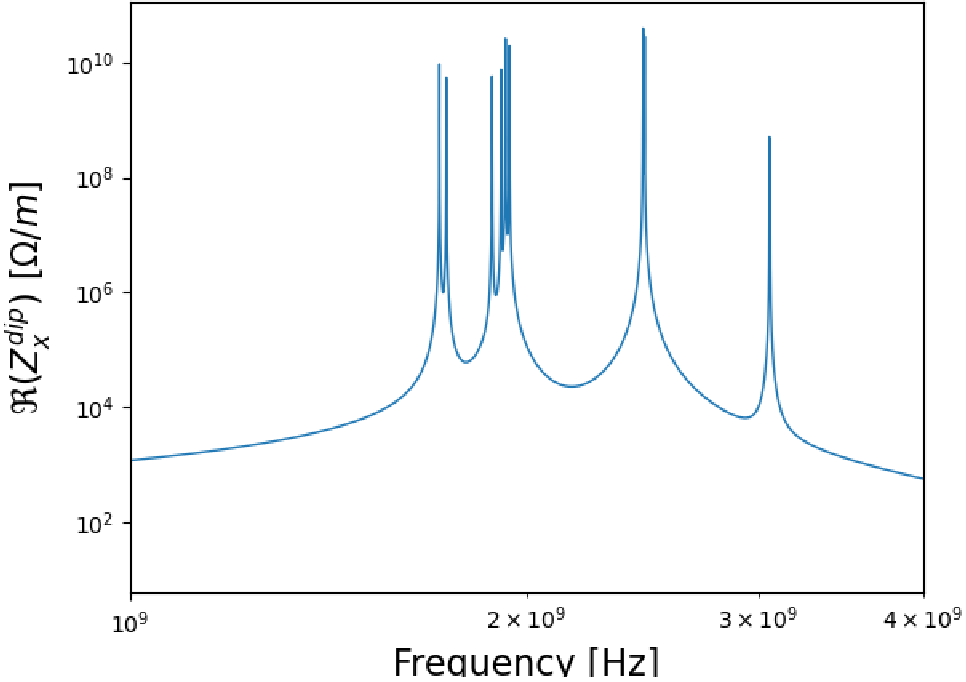
- Transverse offset could degrade the transverse emittance
  - Injections errors can come from field errors in kicker magnets, transfer line steering…
  - Transverse offset at the impedance location (RF cavities) can also be amplified
- Check the tolerance we have and investigate mitigation measures

Main hypotheses for the study

- Single 63 GeV muon beam, 14.7 GeV energy gain per turn
- **O(700) RF** cavities distributed over **32 stations**
- Assume the chromaticity is corrected to zero **$Q'_x = Q'_y = 0$**
- No detuning from octupoles
- **Muon decay**, and subsequent intensity loss, **not included**
- **Single-beam impedance** considered
- Initial bunch intensity of $2.6 \cdot 10^{12}$ muons

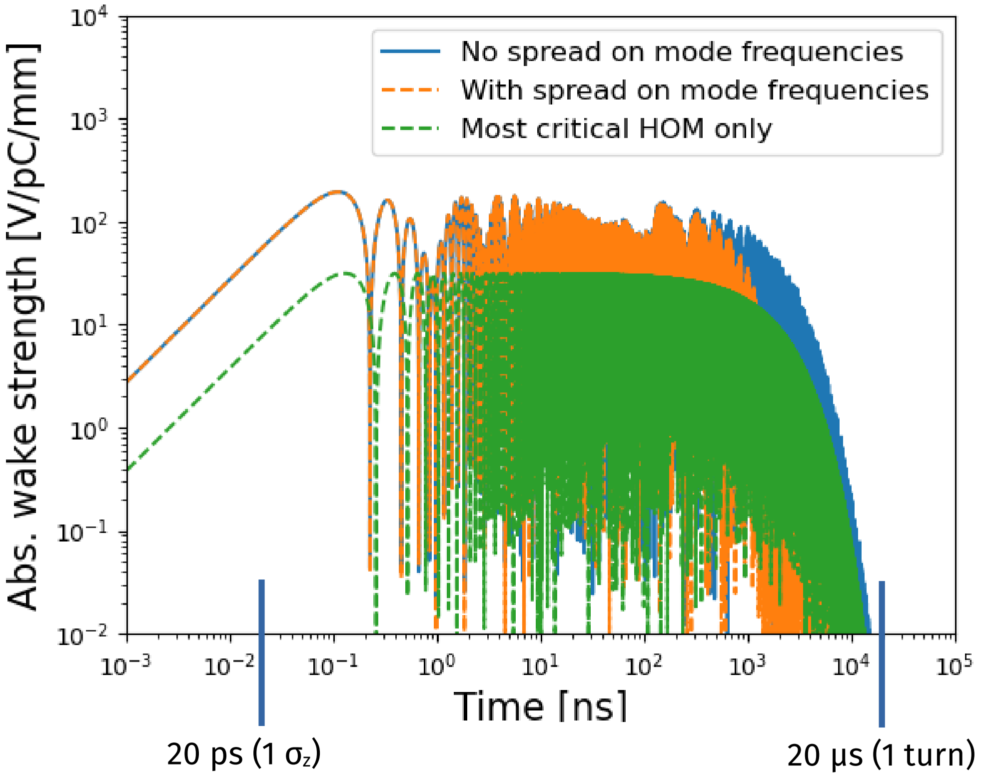
Impedance model with TESLA cavity HOMs

- Impedance model: 670 Low Loss (LL) TESLA type RF cavities (see J. Sekutowicz et al.)
  - HOMs described in the paper, no frequency detuning of the modes between cavities



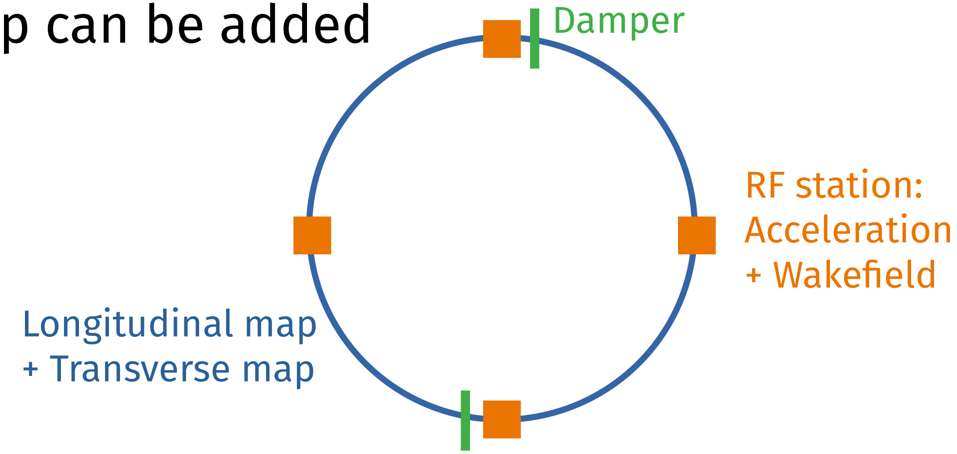
Wakefield with TESLA cavity HOMs

- Assume that the HOM frequencies f_{res} are distributed according to a Gaussian probability function with $\sigma = 10^{-4} \cdot f_{res,\,0}$
- Adding a spread on HOM frequency doesn't affect the short range wake (1σ bunch length in RCS 1 ≈ 20 ps)



Simulation setup

- Simulations performed with tracking code PyHEADTAIL
  - The ring is divided in **32 RF stations**
  - Acceleration + Wakefield at each station
  - Longitudinal + Transverse tracking between stations
  - Between 1 and 32 Damper tracking step can be added



Beam and machine parameters for the RCS 1

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Beam parameters	Unit	Value
Synchrotron tune Q_s		1.8
Synchrotron period	turns	0.55
Bunch length 1σ	**mm**	**5.7**
Bunch intensity	**Particles per bunch**	**2.6e12**
ε_x / ε_y	**µm rad**	**25**
# of macropaticles		**50000**

Parameters from F. Batsch RCS tables

Machine parameters	Unit	Value
Circumference	m	5990
Beam momentum	GeV/c	63
Energy increase per turn	GeV	14.7
Rev. frequency	kHz	50
RF frequency	MHz	1300
Harmonic number		25957
RF voltage	GV	20.9
α_p		0.0024
Avg. beta x/y	m	50 / 50
Chromaticity Q'_x/Q'_y		0/ 0
Detuning from octupoles x/y	m^{-1}	0 / 0

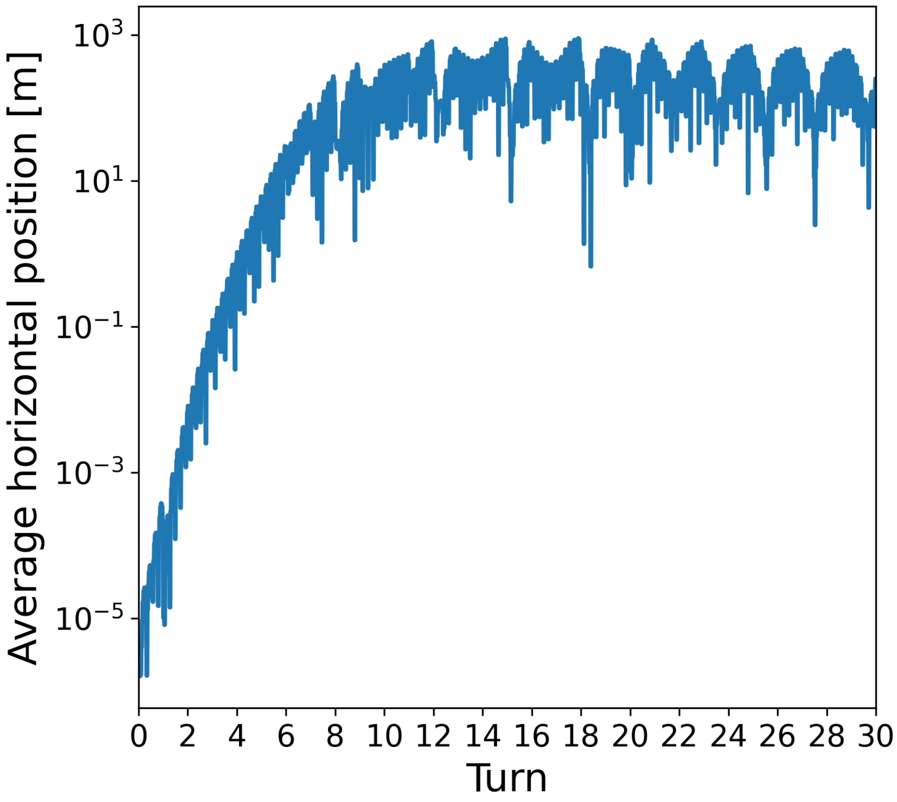
Parameter scan for the transverse offset study

- Perform scan on different parameters:
  - Initial transverse bunch offset from 0.1 μm to 5 mm
  - Transverse feedback damping time from 2-turn to 20-turn and no damper
  - Number of damper elements along the ring, from 1 to 32

Single bunch can become quickly unstable

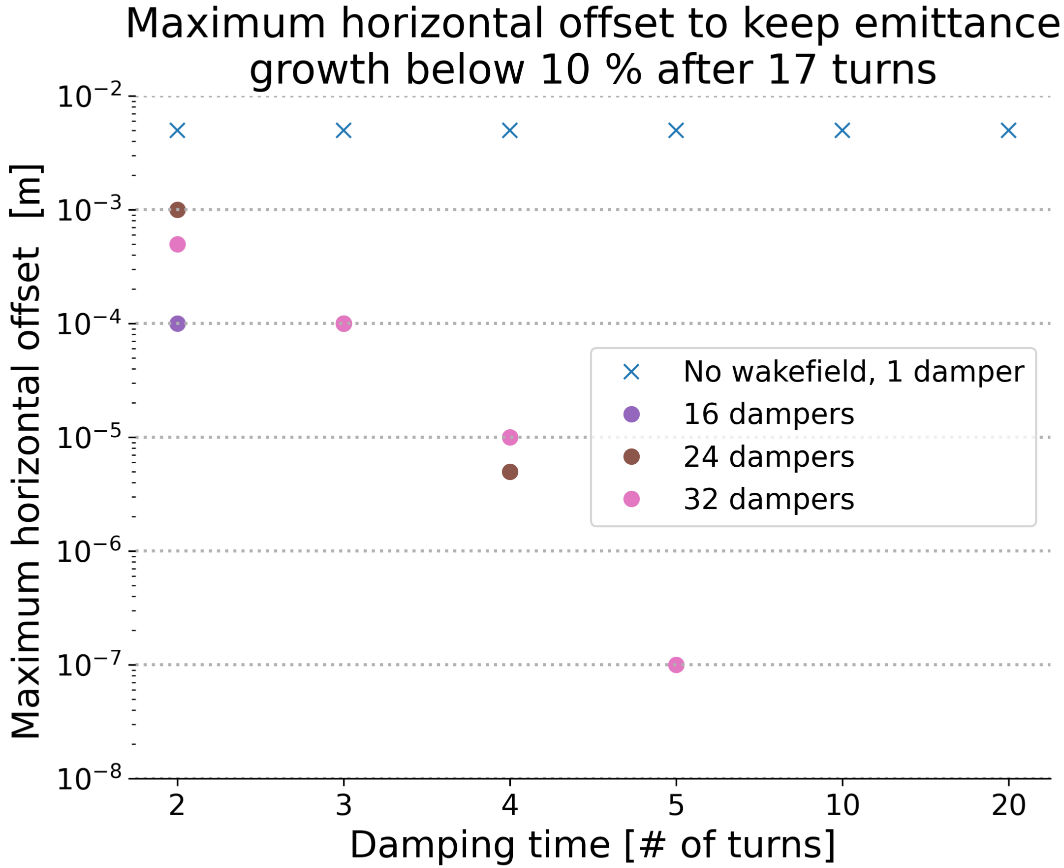
Transverse phase space video of unstable bunch

1 µm initial offset, 4 dampers along the ring, 2-turn damping time



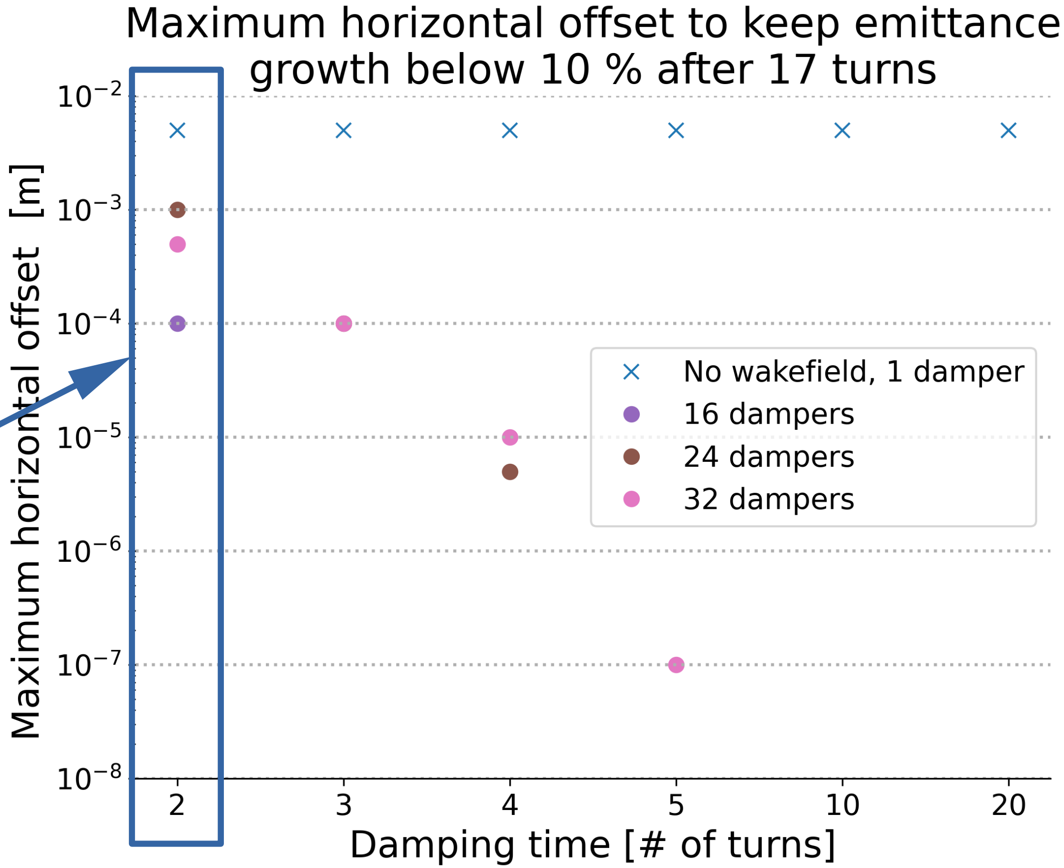
Maximum tolerable offset versus number of dampers + damping time

- Multiple transverse damper units along the ring are required to stabilize the beam
- Strong dampers are needed to tolerate a larger offset



Take home: small offset can be tolerated and many dampers are required

- At least **16 dampers required, half the RF stations**
- **With 16 dampers the initial bunch offset** should be **smaller than 100 µm** to preserve transverse emittance



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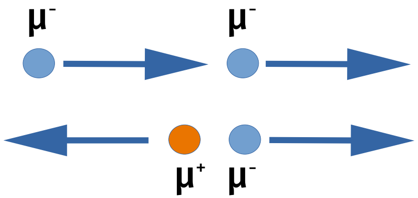
Principle of growth-rate estimate

- Analytic estimate following J. Wang derivations for LEP cavities
  - Estimate instability growth-rate for co-moving versus counter-moving particles



  - In LEP case: 4 bunches per beam, no crossing in RF cavities
  - 640 cavity cells treated as independent cavities
- Estimation applied to the RCS case
  - Single bunch per beam
  - 670 TESLA cavities (multi-cells). The HOM table is given for one full cavity → treat each cavity as one element in the model.

First quick estimate for the RCS 1

- First estimate assumes that all HOMs have the same frequency
  - Co-moving "growth-rate" / counter moving "growth-rate":
    $\alpha\ /\ \bar{\alpha} = 34.6\ s^{-1}\ /\ 37.7\ s^{-1} \approx 1$
  - Similar growth rate for the co-moving and counter-moving beams
  - With this first pessimistic estimate, the instability growth-rate would be a factor 2 larger
- The spread in the cavity HOMs frequencies would reduce both the co-moving and counter-moving growth rates
  - This case is derived in Wang paper and being evaluated for the RCS

Conclusions and next steps

- From tracking studies, the **bunch offset at the impedance location need to be optimized**, and **many transverse dampers** are **required**
  - The large number of cavities and strong HOMs lead to **fast transverse blow-up in the first turns**
  - Many strong transverse damper units are needed to keep the beam stable
  - **Beam-beam effects** are being investigated, and **could mitigate the instability** (RCS 1 beam-beam parameter is similar to the 10 TeV collider)
- **Growth-rates** from **two beam impedance** were first estimated analytically
  - Similar growth-rate for counter-moving and co-moving beams → in first estimate the growth-rate is a **factor 2 larger because of the second beam**
  - **Effect of cavity HOM frequency spread** is being investigated and could mitigate this effect

Thank you for your attention

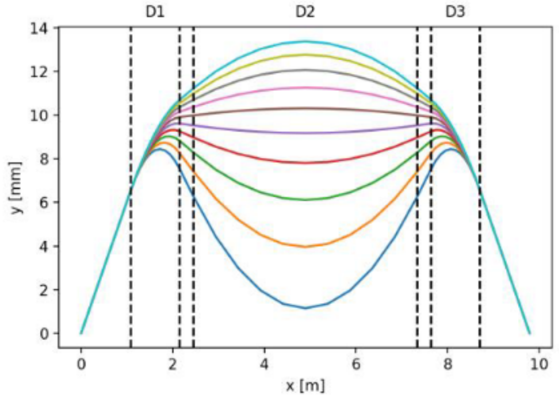
International MUON Collider Collaboration

Trajectory during ramp

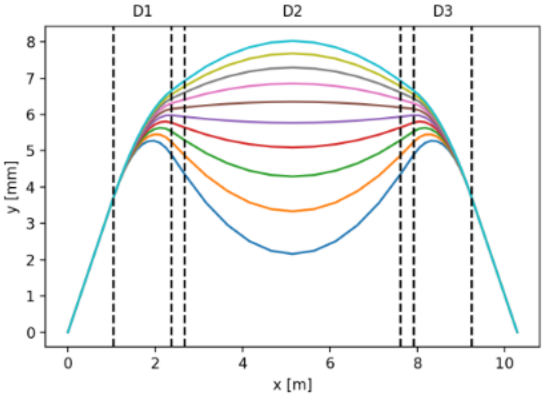
A. Chancé, RCS parameters and optimization

- From injection to extraction the trajectory goes from the inner side to the outer side.
- The trajectory difference goes up to more than 13 mm.

RCS2



RCS3



RCS4