Impedance and transverse stability studies for the 10 TeV collider

D. Amorim, E. Métral

Thanks to L. Bottura, X. Buffat, C. Carli, E. Kvikne,
T. Pieloni, D. Schulte, K. Skoufaris, P. Borges de Sousa,
R. van Weelderen, M. Vanwelde

IMCC and MuCol annual meeting 2025

Swiss Accelerator Research and Technology

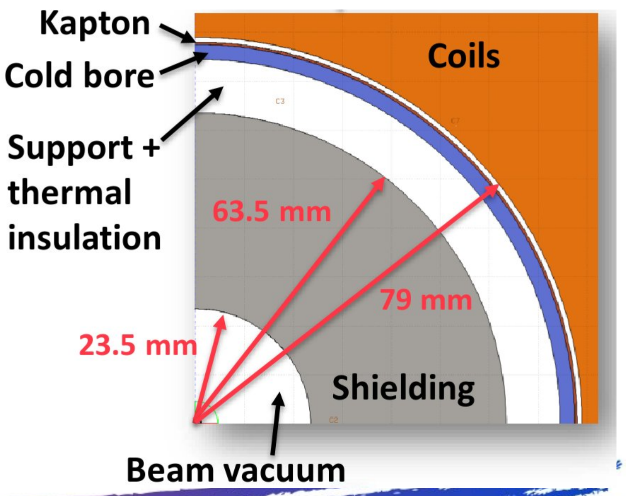
This work was performed under the auspices and with support from the Swiss Accelerator Research and Technology (CHART) program (www.chart.ch).

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

Collider 10 TeV parameters

- Short bunch length σ_z**=1.5 mm** and large $\Delta p/p_0 = 10^{-3}$:
  - Very large RF voltage would be needed, even with small slippage factor (GV range with $\eta \sim 10^{-6}$) → unpractical
  - Operation without RF is foreseen. It implies correcting α_p to zero
- Resistive wall would be the main contributor to transverse beam coupling impedance
  - Tungsten liner is required to shield the superconducting coils from muon decay products
  - In the proposed radial build of the magnet: **inner radius of 23.5 mm**

A. Lechner et al., Design meeting 09/2023



	Thickness	Outer radius
Beam aperture	23.49	23.49
Coating (copper)	0.01	23.5
Radiation absorber (tungsten alloy)	40	63.5
Shielding support and thermal insulation	11	74.5
Cold bore	3	77.5
Insulation (Kapton)	0.5	78
Clearance to coils	1	79

IMCC/MuCol tentative parameters

First impedance model for the 10 TeV collider

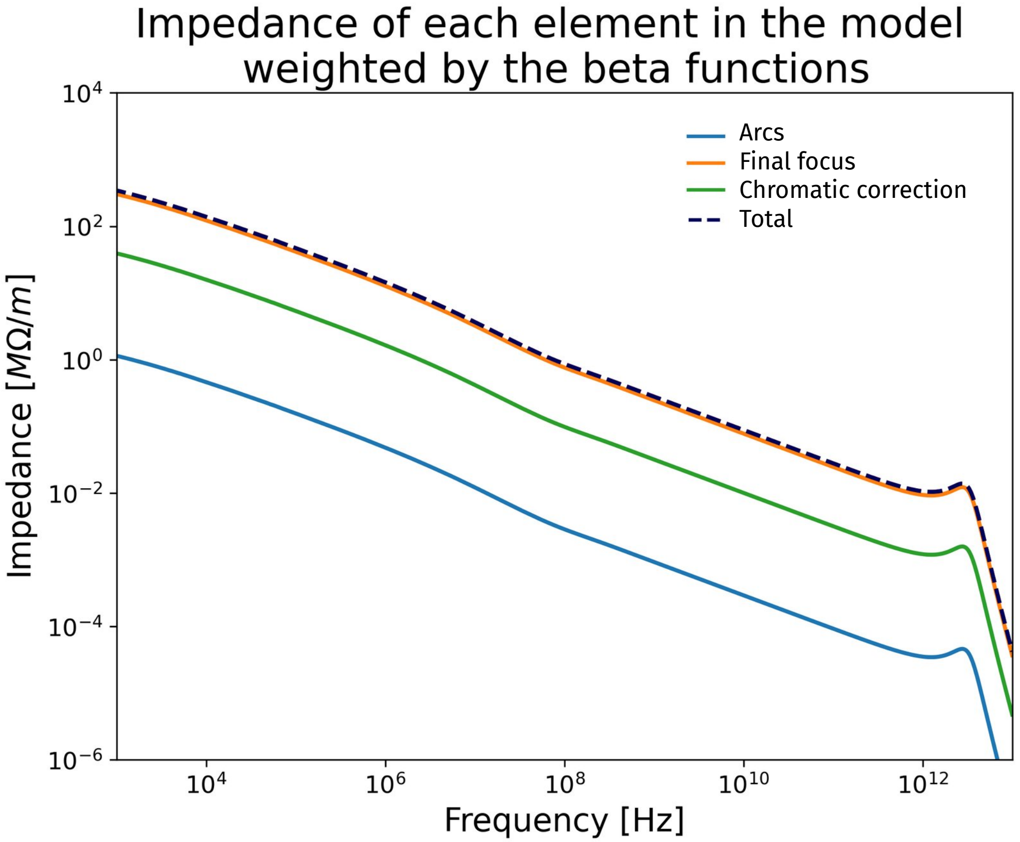
- Twiss beta functions (and therefore beam size) vary strongly along the ring
  - The magnet bore and the beam chamber radii should follow these variation
  - Each elements in the impedance model is weighted by $\beta_{x,y,\ \mathrm{element}}$ / $<\beta_{x,y}>$

Section	Length per section [m]	Number of sections [-]	Total length per section [m]	$\beta_{x,y}$ [m]
Arcs	2930	2	5860	90/70
Chromatic correction and matching section	583	4	2332	7767/2613
Interaction region	365	2	730	**192000/165500**
Total			8920	17800/14400

- Create and compare two simple impedance model for the collider
  - All vacuum chambers with radius r = 16 mm
  - Final focus chamber with r = 35 mm, all other chambers r = 16mm

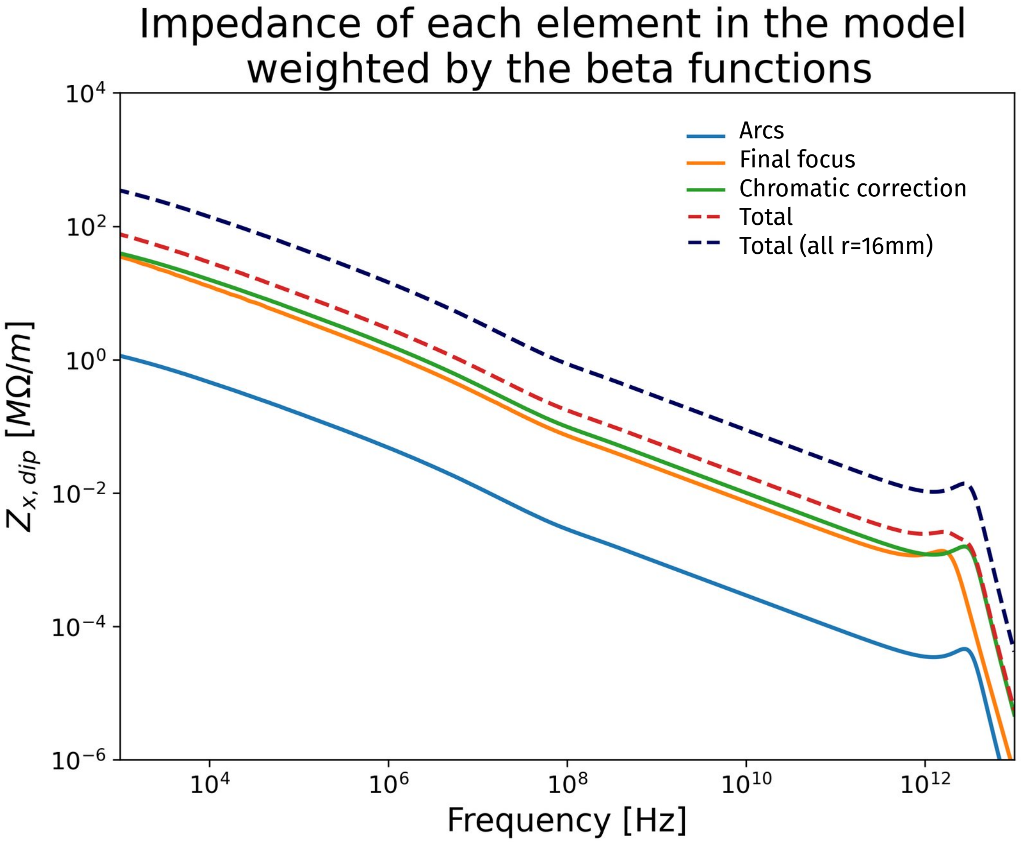
Impedance model 1
All chambers with r=16 mm

- The final focus region plays a key role for the impedance
- If all the vacuum chambers have the same radius, the total impedance will be dominated by the final focus region
  - Even though it is only < ~10 % of the total collider length



Impedance model 2
Final focus chamber at r=35 mm

- Increase the chamber radius to 35 mm only for the final focus region
  - Corresponds to 75 mm bore radius with 40 mm of shielding
- The final focus region contribution is clearly reduced, and the total impedance is divided by ~2 over the whole frequency range



Collider 10 TeV parameters

- Impedance model
  - Scan the radius of a 10-km long chamber
  - Scan materials: copper coated tungsten, pure copper at 80 K
- Main assumptions for the collider are:
  - **Single beam** simulations
  - 1 RF station, one transverse damper unit, located at start of the ring
  - **No RF voltage** (α_p = 0 and V_{RF} = 0 MV)
  - **Muon decay effect is included** → intensity decreases over time
- Scan several parameters
  - Chromaticity Q'_x from Q'_x=-20 to Q'_x=+20, while keeping Q'_y=0
  - Transverse damping time: 20-turn and no damper
  - Initial transverse offset of the bunch, no offset or 500 μm

  Track for 10000 turns
  - Muon half-life at 5 TeV is ~2000 turns, luminosity lifetime is ~1600 turns: we **look at emittance values after 1600 turns**

Beam and machine parameters for the Collider

International MUON Collider Collaboration

- Tracking simulations are performed with the XSuite + PyHEADTAIL code
  - See my IMCC 2024 meeting presentation for more details

Beam parameters	Unit	Value
Bunch length 1σ	**mm**	**1.5**
Bunch $\Delta p/p_0$ 1σ	**-**	**1e-3**
Bunch intensity at inejction	**Particles per bunch**	**1.8e12**
Longitudinal emittance $\varepsilon_l = \sigma_z\sigma_E$	**MeV m**	**7.5**
Transverse emittance ε_x / ε_y	**µm rad**	**25**
# of macropaticles	-	200k
# of turns wakefield	-	5
# of slices wakefield	-	2000

Machine parameters	Unit	Collider 10 TeV
Circumference	m	10000
Bunch intensity	10^{12}	1.8
Beam momentum	GeV/c	5000.0
Energy increase per turn	GeV	0
Rev. frequency	kHz	30
RF frequency	MHz	Not relevant since RF voltage is set to zero
Harmonic number	-	
RF voltage	**GV**	**0**
α_p	**-**	**0.0**
Chromaticity Q'_x/Q'_y		Scan Q'_x/Q'_y=0
Detuning from octupoles x/y	m^{-1}	0 / 0

Example of simulation

- This **example** is **with decay** and shows the **transverse** plane properties

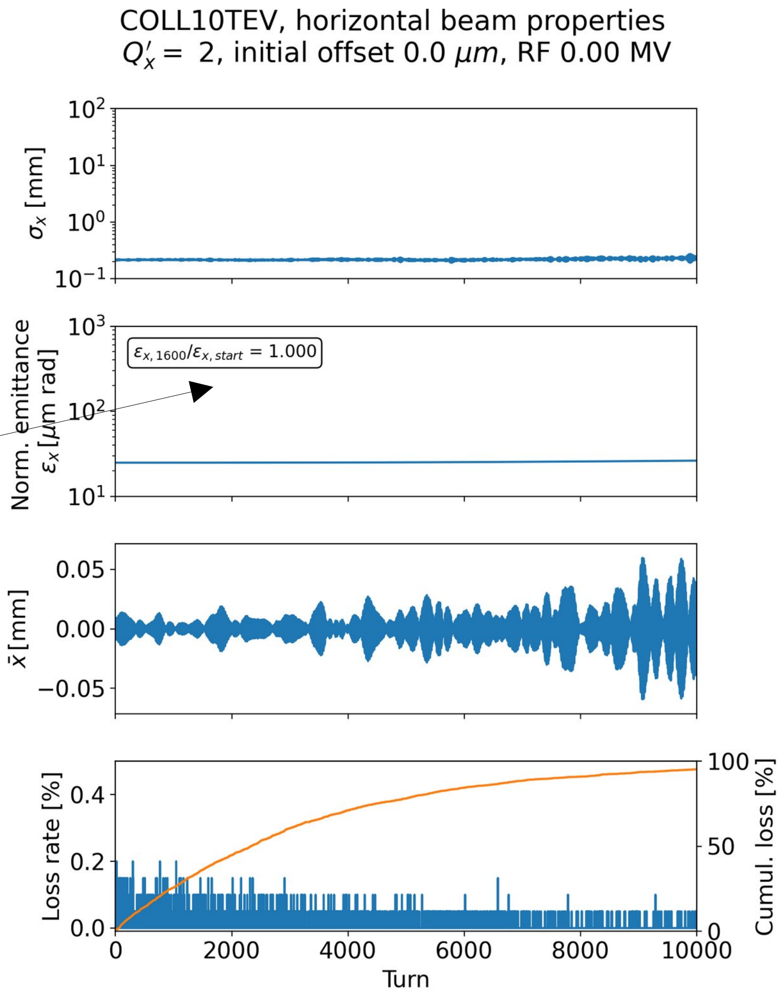
1σ horizontal bunch size

Normalized horizontal emittance

To check if a transverse instability occurs, we will compute the emittance ratio $\varepsilon_{turn\ n} / \varepsilon_{start}$

Horizontal centroid average position

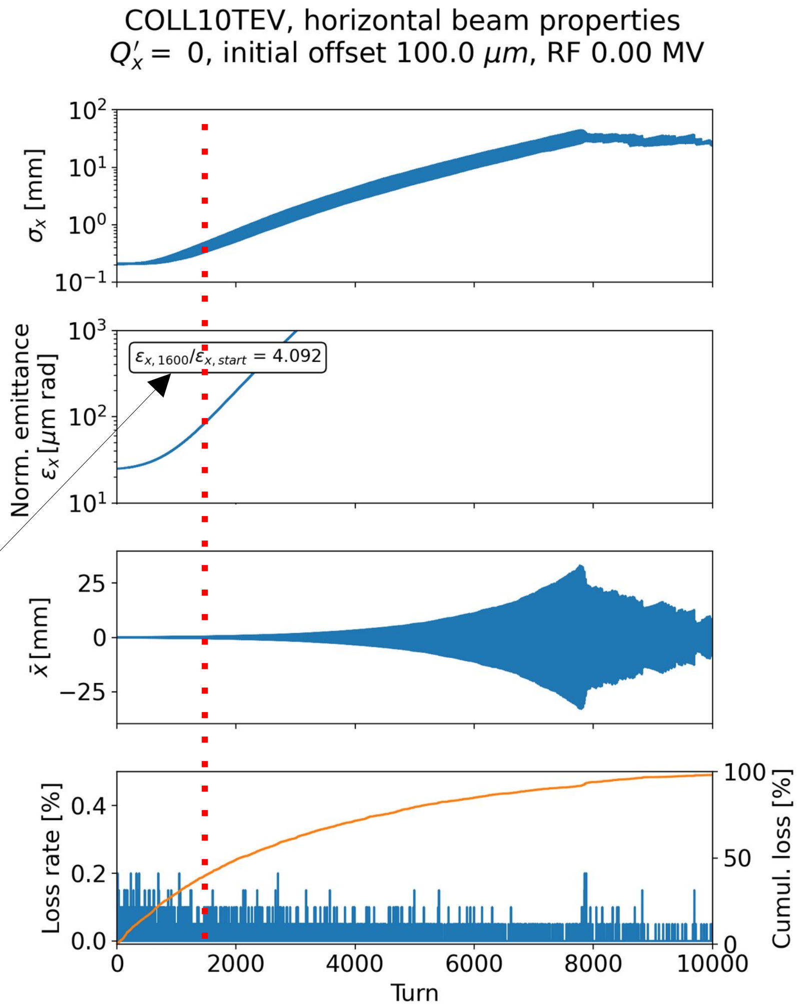
Particle losses



Example of simulation

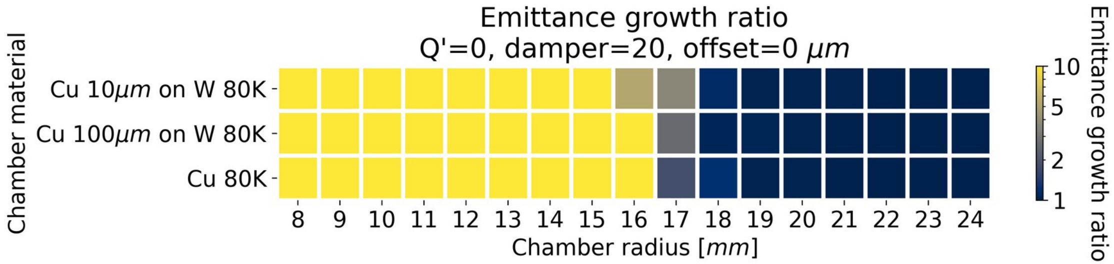
- Chromaticity **Q' = 0**
- **100 µm transverse offset**
- **No transverse damper** is included

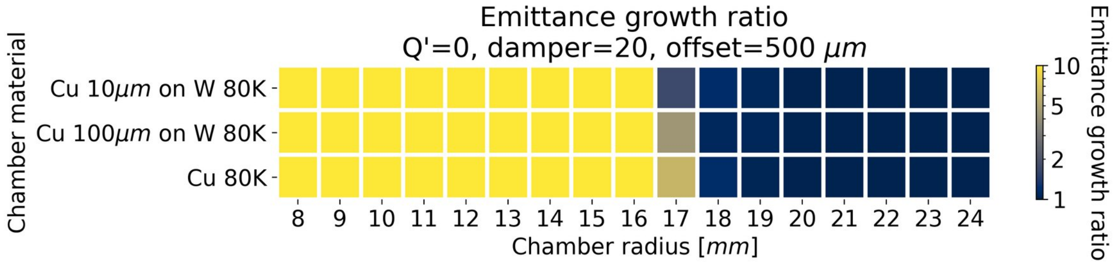
Emittance ratio after 1600 turns
= 1 luminosity lifetime



Results of simulations scan for different radii

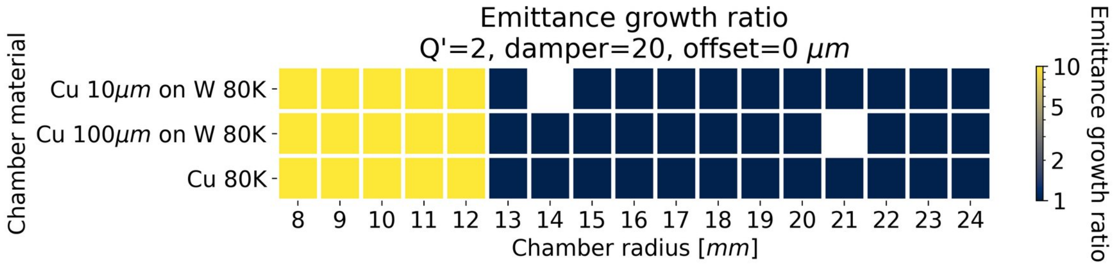
- With Q'=0 and a transverse damper, 16 mm chamber radius for the whole ring leads to emittance blow-up

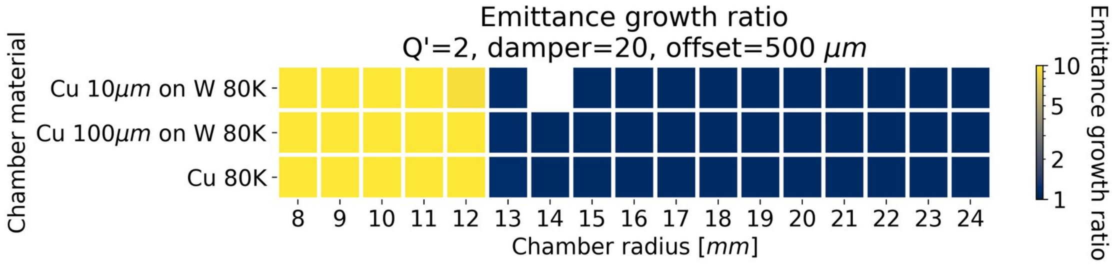




Results of simulations scan for different radii

- A radius r=16mm can be used for the whole collider ring if chromaticity and a transverse damper are introduced
- An initial bunch offset of 500 μm can also be tolerated without strong emittance blow-up





Conclusion

- First simplistic impedance model of the collider show that the **final focus region** vacuum chambers will be a **large contributor to the total impedance**
  - Model could be further refined using the detailed lattice, the magnet bore radii and the shielding thicknesses for the different elements in the region
- Scan of the chamber radius, assuming the same radius for the whole ring (conservative assumption) show that **16 mm radius could be achieved**
  - This requires **chromaticity** (at least Q'=±2) and a **20-turn transverse damper**

	r = 16 mm	Minimum radius for stability
Q'=0, 20-turn damper	**Unstable**	**r = 18 mm**
Q'=2, 20-turn damper	**Stable**	**r = 13 mm**

Thank you !

International
UON Collider
Collaboration

MuCol

Co-funded by
the European Union

CHART
Swiss Accelerator
Research and
Technology

Funded by the European Union (EU).Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.