Transverse Impedance Studies for Existing and Future Light Sources: ALBA and SLS2 upgrade

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Within the CLIC DR collaboration with LOWϵRING community

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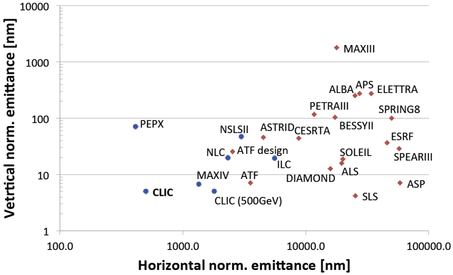
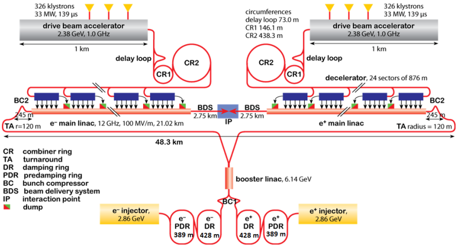
Overview

Damping Rings and Light Sources

- **Collaboration** between synchrotron light sources, storage rings, damping rings as well as e^+/e^- ring colliders
- **Common work** on the design of low emittance machines
- The state of the art in design of accelerator systems has approached the targets of damping rings



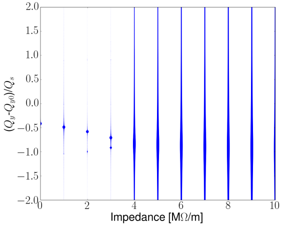


CLIC Damping Rings

- Two main rings to generate the low emittance beams
  - High current of 4.1×10^9 particles/bunch
  - Short bunch length of 1.8 mm
  - Normalized emittances $\sim 500 \times 5$ nm (x,y)
  - Vacuum chamber radius $\sim$9 mm
- Collective effects can be severe and degrade the beam quality, potential show-stopper
- Emphasis on impedance studies in the transverse plane: single bunch thresholds $>$ design current

Single Bunch Thresholds

- **Transverse impedance model**: estimate the available **budget** (maximum possible impedance for stable operation under nominal parameters)
- **Building the impedance model**: Evaluate the impedance of all the machine elements. **Broad-band resonator** (f=5 GHz, Q=1, R_s is scanned) and several **resistive wall** contributors (NEG-coated stainless steel vacuum chamber)



- Transverse Mode Coupling Instability (TMCI) for 0 chromaticity
- Threshold in y plane at 4 MΩ/m
- Threshold in y plane at 1 MΩ/m for positive chromaticity

Simulation Tools

Computation of wakes and impedances

- **Semi-analytical approach**: ImpedanceWake2D[1], 2D code for resistive wall, round/flat geometries, multilayer structures with specified EM properties
- **Numerical approach**: CST Particle Studio, can simulate 3D complicated structures. Limited at high frequencies

Beam dynamics code

- HEADTAIL code[2]: simulates the interaction between a single bunch and impedances using macroparticles

Benchmark the simulation tools

[1] N. Mounet, CERN-THESIS-2012-055 - 226 p
[2] G. Rumolo and F. Zimmermann, CERN-SL-Note- 2002-036 AP

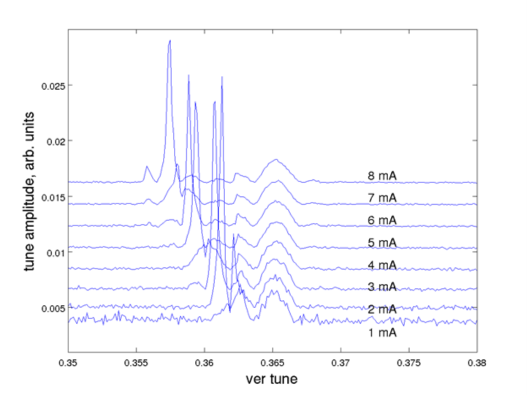
Measurements in the ALBA synchrotron light source

ALBA: 3rd generation 3 GeV synchrotron near Barcelona, in operation since 2012 with currently 7 beamlines

- Single bunch, 0 chromaticity, tune shift with intensity to define the instability thresholds in the vertical plane
- **Goals**: validate the existing impedance model and benchmark the simulation tools

Tune shift with increasing single bunch intensity and closed undulators

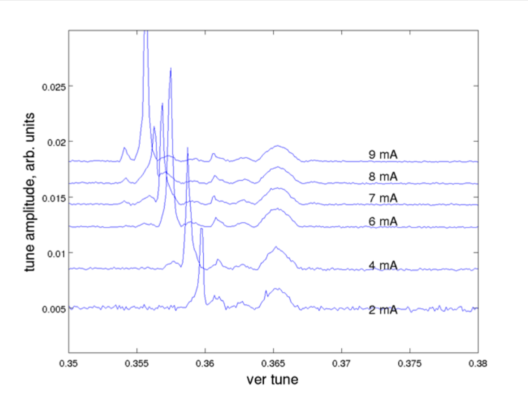
- 1-9 mA single bunch intensity, 2.1 MV, 0 chromaticity, nominal tune $Q_{y0} = 8.362$
- Mode m=-1 very closely to m=0 peak just before the instability onset
- **TMCI** threshold at **8.8 mA**



Courtesy U.Iriso

Tune shift with increasing single bunch intensity and open undulators (aperture from 5.6 to 30 mm)

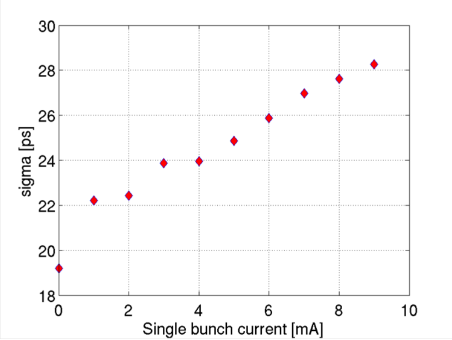
- 2-10 mA intensity, 2.1 MV, 0 chromaticity
- **TMCI** threshold at **9.8 mA**
- **Observe higher threshold with open undulators as expected**



Courtesy U.Iriso

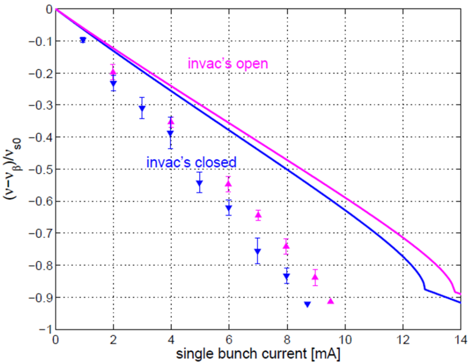
Bunch Length Parametrization

- The bunch length was also monitored during the shifts. Bunch lengthening due to potential well distortion
- A good bunch length parametrization with current contributed essentially to the following results



Current impedance model: MOSES result for 0 chromaticity

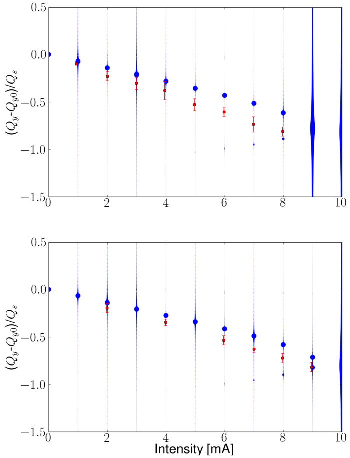
- Current impedance model: 4 BBR, 7 multi-layer RRW (including StSt standard vacuum chamber, IVUs, NEG-coated Al chamber, wiggler etc)
- Measured mode detuning is stronger and TMCI-threshold is lower than the model
- A 55% **higher model impedance** would be necessary to reproduce the measured values



Courtesy T.F.Günzel

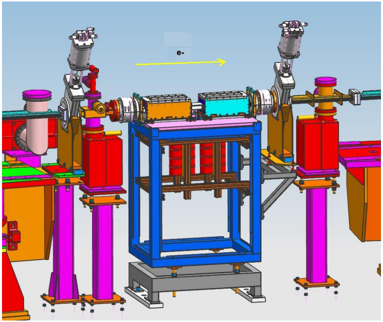
Impedance Model: Adding a 5^{th} BBR in HEADTAIL

- Indication for missing impedance contribution/s. 60% missing impedance to explain the measured slope
- Around 85% of the found mode detuning is explained with a 5^{th} BBR (f_r = 1 GHz, Q = 1 and R_s=1.6 MΩ/m)
- Physical explanation - first attempts are focused on the injection kickers



Measurements in ALBA- Part 2

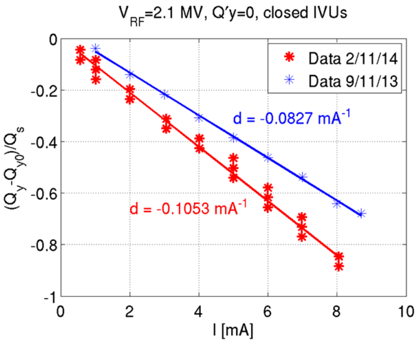
- New pinger magnet was installed during the summer. Same geometry as the injection kickers



Measurements in ALBA- Part 2

- Possibility to compare tune shifts with last year and see directly the effect of the magnet
- Tune shift with intensity to define the instability thresholds in the vertical plane
- Single bunch, 0 chromaticity
- Measurements performed for closed undulators

Comparison of the Tune Shifts- Effect of Pinger Magnet

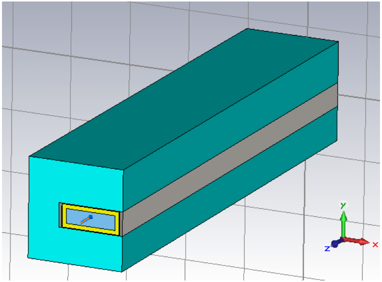


$$Im(Z_{\text{eff}}) = -\frac{8\pi^2\gamma\omega_\beta\sigma_z\Delta Q}{\Delta N r_0 c^2 \Gamma\left(\frac{1}{2}\right)} \text{ [Chao]}$$

- 4.6% difference in the TMCI thresholds (TMCI at 8.4 mA), 4.4% difference in the slopes
- 9/11/13: $Im(Z_{\text{eff}})$=(419±14) kΩ/m
- 2/11/14: $Im(Z_{\text{eff}})$=(434±5) kΩ/m
- Model prediction: $Im(Z_{\text{eff}}^{tot})$=156 kΩ/m. Explains around 40% of the measured impedance
- **$Im(Z_{\text{eff}}^{pinger})$=15 kΩ/m**
- Simulate the effect of the magnet

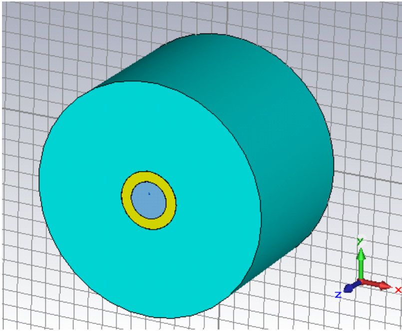
ALBA Kickers

- 4 kickers of 0.78 m each
- C-shape kicker
  - Vacuum, r=11.5 mm
  - Ti coating of 0.4 μm
  - Ceramic 6.5 mm thick (yellow)
  - Air 1 mm
  - Ferrite 55 mm thick (blue)
- To study their contribution using HEADTAIL, the wake functions are needed as input
- Wake functions with CST: 147 billions of meshcells...
- Alternative: use ImpedanceWake2D (IW2D)

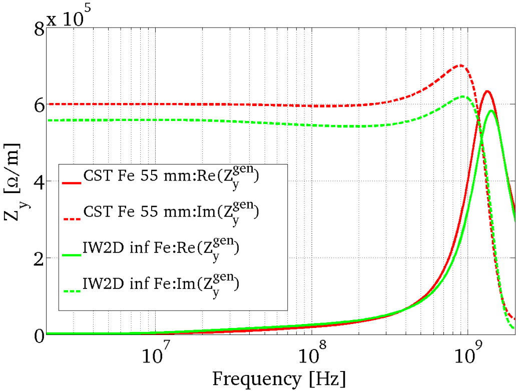


CST and IW2D comparison for round multilayer structure

- CST
  - Vacuum with r=11.5 mm
  - Ceramic 6.5 mm thick (yellow)
  - Ferrite 55 mm thick (blue)
  - Offset source and test in y plane to calculate the generalized impedance
  - Background PEC
- IW2D 2 layers, round, r=11.5 mm
  - Ceramic: $\sigma = 10^{-12}$ S/m, $\varepsilon' = 9.3$, d=6.5 mm
  - Ferrite: $\sigma = 10^{-4}$ S/m, $\varepsilon' = 12$, $\mu = 460$, $f_{rev} = 20$ MHz, d=infinity



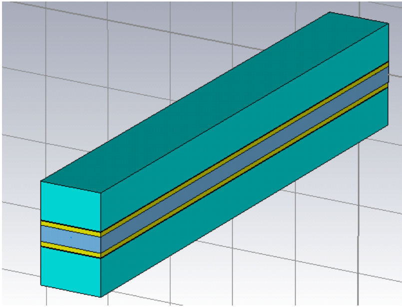
CST and IW2D comparison for round multilayer structure



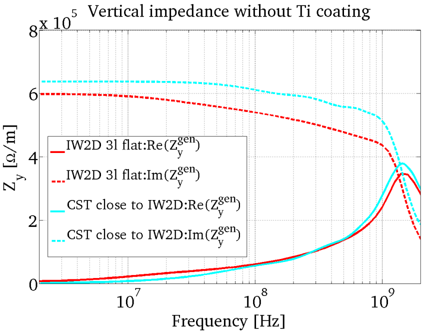
- Good agreement between CST and IW2D within 5%

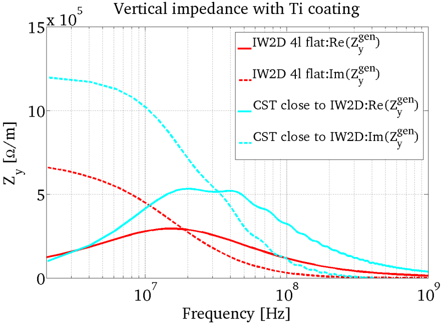
CST and IW2D comparison for multilayer flat structure (1)

- CST
  - Vacuum, r=11.5 mm
  - with and without the Ti of 0.4 μm
  - Ceramic 6.5 mm thick (yellow)
  - Air 1 mm
  - Ferrite 55 mm thick (blue)
  - Background normal
- IW2D 3 or 4 layers (depending if there was coating of Ti or not), flat, r=11.5 mm



CST and IW2D comparison for multilayer flat structure (2)

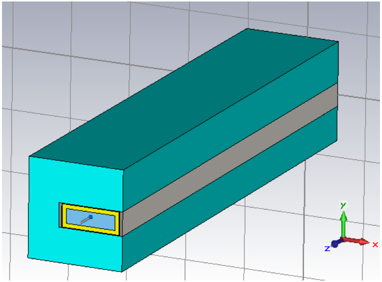




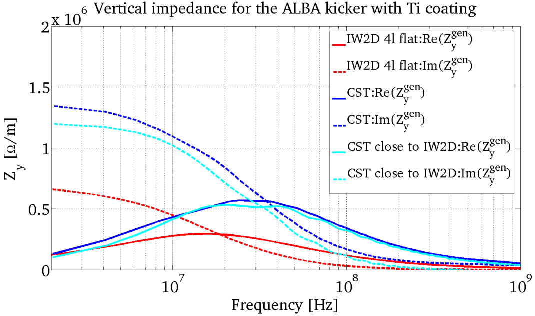
- Much better agreement between CST and IW2D without the Ti coating. Factor of 2 difference in the case of Ti coating

CST and IW2D comparison for the real kicker (1)

- CST C-shape kicker
  - Vacuum, r=11.5 mm
  - Ti of 0.4 μm
  - Ceramic 6.5 mm thick (yellow)
  - Ferrite 55 mm thick (blue)
  - 2 electrodes as PEC
  - Background normal
- IW2D 4 layers, flat, r=11.5 mm
  - Ti: $\sigma = 2.38 \times 10^6$ S/m, d= 0.4 μm
  - Ceramic: $\sigma = 10^{-12}$ S/m, $\varepsilon' = 9.3$, d=6.5 mm
  - Air: $\sigma = 5 \times 10^{-17}$ S/m, d= 1 mm
  - Ferrite: $\sigma = 10^{-4}$ S/m, $\varepsilon' = 12$, $\mu = 460$, $f_{rev} = 20$ MHz, d=infinity

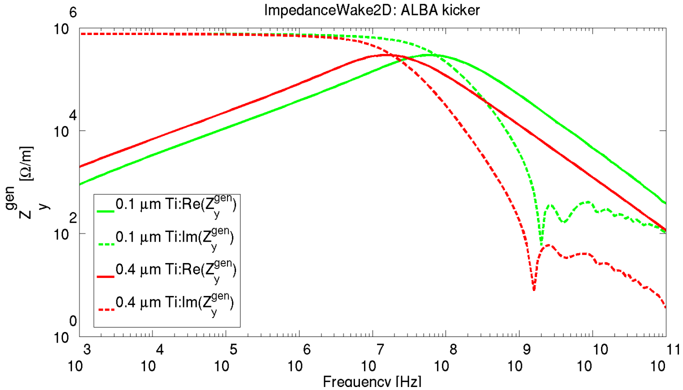


CST and IW2D comparison for the real kicker (2)



- C-shape and flat structure in CST give similar impedance results within 5%
- Can use the simplified geometry to calculate the wakes
- ImpedanceWake2D to calculate the wake function

Effective impedance of the pinger magnet



- 0.4 μm Ti: Im(Z_{eff})=1.97-3.2 kΩ/m
- 0.1 μm Ti: Im(Z_{eff})=9.3-14 kΩ/m
- A 4 times thinner coating would explain the measured effect

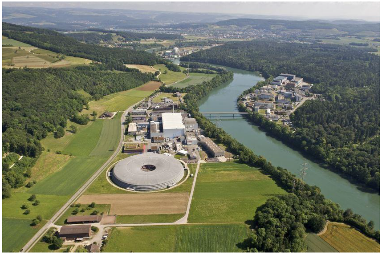
Simulation of the pinger's effective impedance (2)

- 4 kickers and 1 pinger magnet were coated during the same process
- Thickness of Ti is estimated (from measurements of resistance) between 3.6-4.02 μm
- For such coating, ~3 kΩ/m expected from simulation

Future work

- The impedance model of the pinger should be enriched to include the transitions too
- More simulations on the model itself
- Improve the existing impedance model to match measurements

Studies for the Swiss Light Source (SLS) Upgrade



3rd generation 2.4 GeV light source with 13 years of successful operation and 18 beam lines

- Stay competitive, replace SLS with significantly lower emittance design. Lattices considered have a very low and even negative momentum compaction factor
- Narrow NEG-coated copper pipes, radius of 10 mm
- Collective effects will be crucial for the SLS-2 upgrade
- One of the main limitations is the **resistive wall instability**

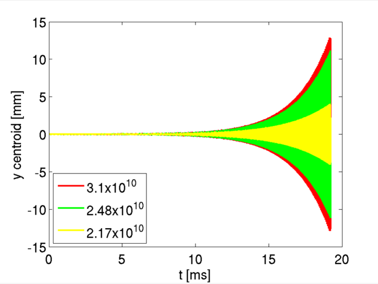
Lowest emittance prototype: beam and machine parameters

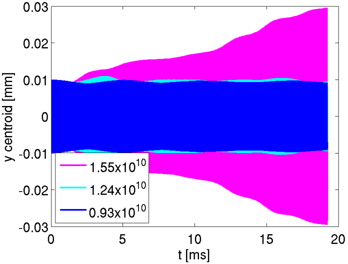
E (GeV)	2.4
C (m)	288
α_p	$-5.4\text{x}10^{-5}$
ε_x^g (pm)	73
ε_y^g (pm)	5
ν_x / ν_y	39.4 / 13.17
ν_s	0.00037
σ_z (mm)*	7.4
γ	4700
V_{RF} (MV)	0.7
h	96
$\delta p/p_0$	0.0011

N_p	$3.1\text{x}10^{10}$
$<b_x>$ (m)	6.65
$<b_y>$ (m)	6.13
τ_x (ms)	5.58
τ_y (ms)	7.56

* Bunch length is without IBS/ 3HC. A 3HC will be considered to lengthen the bunch by a factor of 3

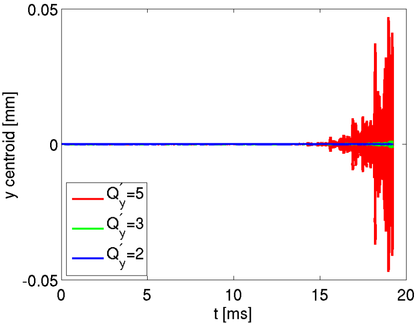
Resistive wall with zero chromaticity





- Beam is unstable for the nominal intensity due to TMCI. At least a 2.5 lower bunch population is required for the stability
- Operation with zero chromaticity is not an option

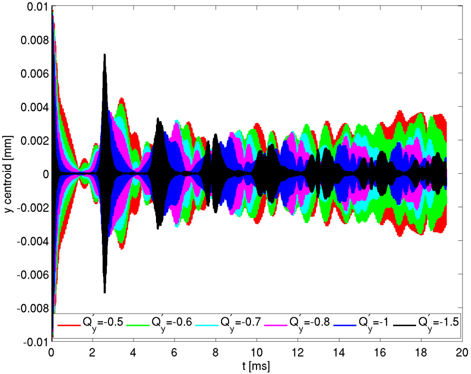
Resistive wall with positive chromaticity



Q'_y	**Rise time (ms)**
1	1.9
2	1.6
3	1.2
5	1

- Compare rise time with **7.5 ms damping time.** Instability is faster
- Negative momentum compaction factor: Head-tail instability occurs at positive chromaticity
- Inverse situation from what is usually observed in light sources that operate well above transition

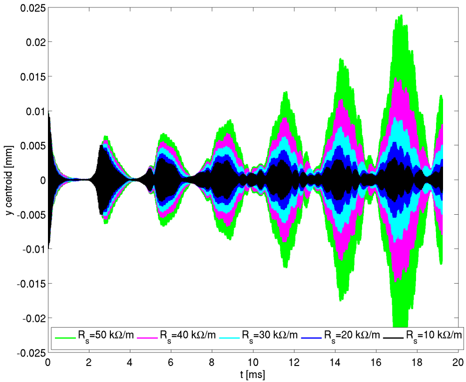
Resistive wall with negative chromaticity



Q'_y	**Rise time (ms)**
-0.5	13.6
-0.6	18.5

- Compare rise time with 7.5 ms damping time. Instability is slower
- **Beam is stable with nominal bunch intensity**
- What is the available budget for negative chromaticity?

Resistive wall and a broad-band resonator with negative chromaticity -1: f_r=8 GHz, Q=1



R_s (kΩ/m)	Rise time (ms)
40	7.49
50	6.4
100	3.1

- Remaining budget for stable operation when Q'_y=-1 is less than 40 kΩ/m
- Very small budget considering that the impedance model is yet quite basic

Which chromaticity allows a budget of 500 kΩ/m

Q'_y	R_s **(kΩ/m)**	**Rise time (ms)**
-5	500	5.96
-6	500	7.67
-7	500	8

- Operation with higher negative chromaticity than -6 will allow a budget of 0.5 MΩ/m
- Studies on dynamic aperture and Touschek lifetime are needed

Most aggressive lattice studied. Lattices with positive momentum compaction factor and large negative momentum compaction factor are also considered. Comparative study will follow

Summary

- **Transverse impedance budget for the CLIC DR**: 1 MΩ/m for slightly positive chromaticity and will be further reduced when other contributors are added in the model
- **ALBA synchrotron**: Single bunch measurements. Expected effect observed of open undulators and pinger magnet. Comparison between model and measurements: 60% missing impedance from current model
- **SLS-2 upgrade**: Operation with high negative chromaticity is an option for the most aggressive lattice scenario

Thank you for your attention!

Back up slides

CST coatings