Impedance budget and effect of chamber coating on CLIC DR beam stability

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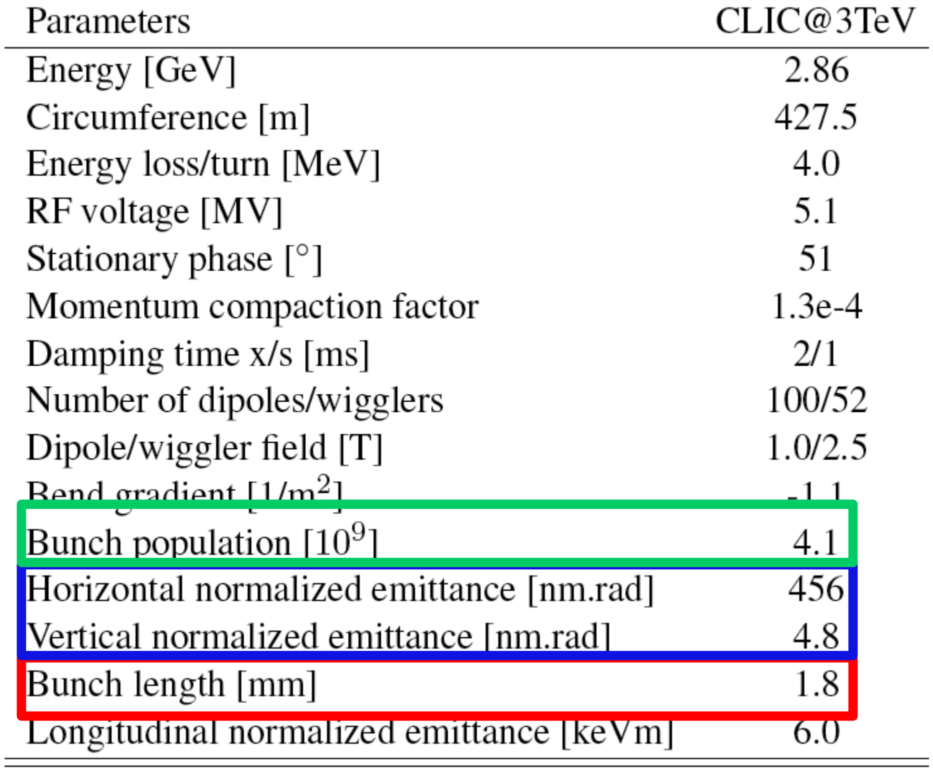
Outline

- Introduction
- Highlights of the first results
- Experimental part
- Future planning

Introduction (I)
Damping Rings

CLIC DR parameters



Parameters	CLIC@3TeV
Energy [GeV]	2.86
Circumference [m]	427.5
Energy loss/turn [MeV]	4.0
RF voltage [MV]	5.1
Stationary phase [°]	51
Momentum compaction factor	1.3e-4
Damping time x/s [ms]	2/1
Number of dipoles/wigglers	100/52
Dipole/wiggler field [T]	1.0/2.5
Bend gradient [1/m^2]	-1.1
Bunch population [10^9]	4.1
Horizontal normalized emittance [nm.rad]	456
Vertical normalized emittance [nm.rad]	4.8
Bunch length [mm]	1.8
Longitudinal normalized emittance [keVm]	6.0

- Small emittance, short bunch length and high current
- Rise to collective effects which can degrade the beam quality

Introduction (II)
Collective effects

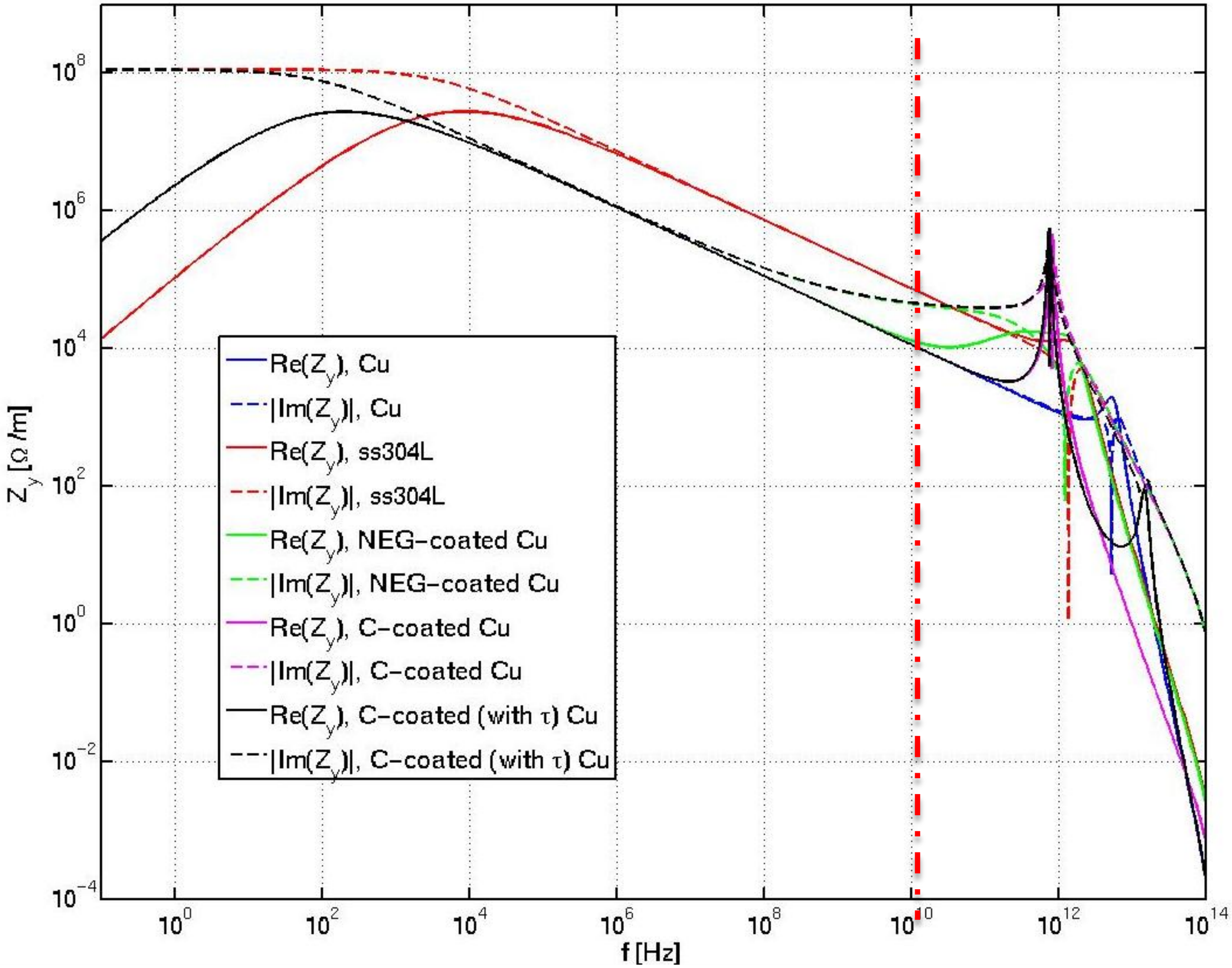
- Focus on instabilities driven by impedance
- Define the conditions to ensure safe operation under nominal conditions
- Define an impedance budget

To suppress some of the collective effects, coating will be used

- Positron Damping Ring (PDR): electron-cloud effects → amorphous carbon (aC)
- Electron Damping Ring (EDR): fast ion instabilities → need for ultra-low vacuum pressure → Non-Evaporable Getter (NEG)

- Only some of the scenarios are simulated so far…

Resistive Wall Vertical Impedance: Various options for the wigglers pipe



⇒a-C necessary for e$^-$ cloud mitigation

⇒NEG for good vacuum

⇒Coating is "transparent" up to ~*10* GHz

⇒ But at higher frequencies some narrow peaks appear

⇒ Important to define the contribution of the resistive wall

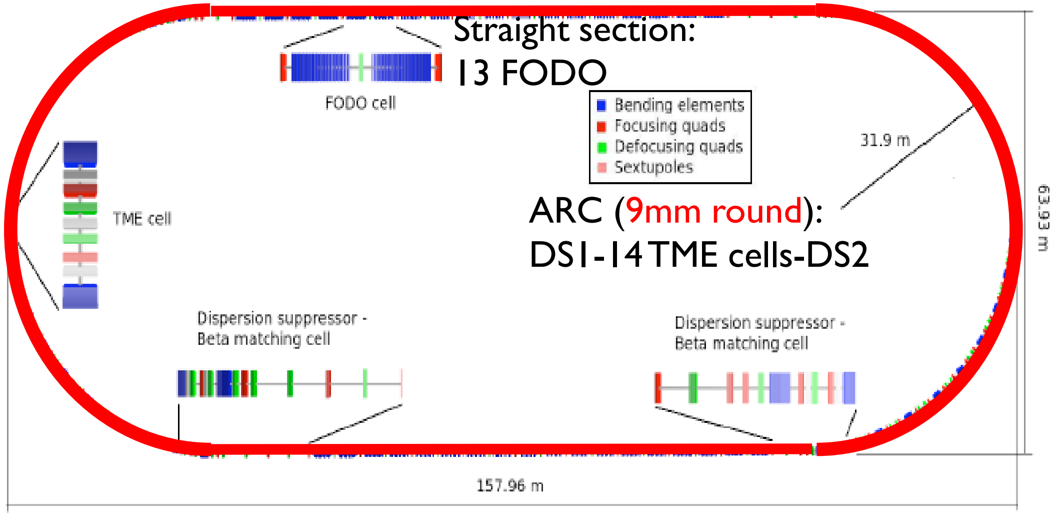
Coated copper will only contribute by a very small percentage in the impedance while coated stainless steel will have a larger contribution

N. Mounet

First results (I)
Single bunch simulations without space charge to define the instability thresholds

- HEADTAIL code
  - Simulates single/multi bunch collective phenomena associated with impedances (or electron cloud)
  - Computes the evolution of the bunch by bunch centroid as a function of time over an adjustable number of turns

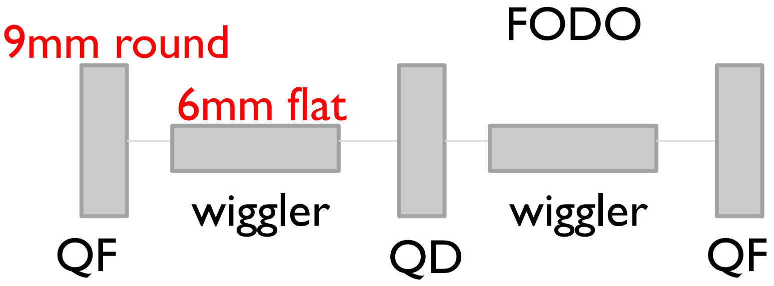
First results (II)
Estimating the machine impedance budget with a 4-kick approximation



Straight section:
13 FODO

ARC (9mm round):
DS1-14 TME cells-DS2

- A uniform **coating of NEG, 2μm** thickness, was assumed around the ring made from **stainless steel**
- The contributions from the resistive wall of the beam chamber were singled out for both the arc dipoles and the wigglers



1 kick → broadband resonator (S_{kick}=1m)

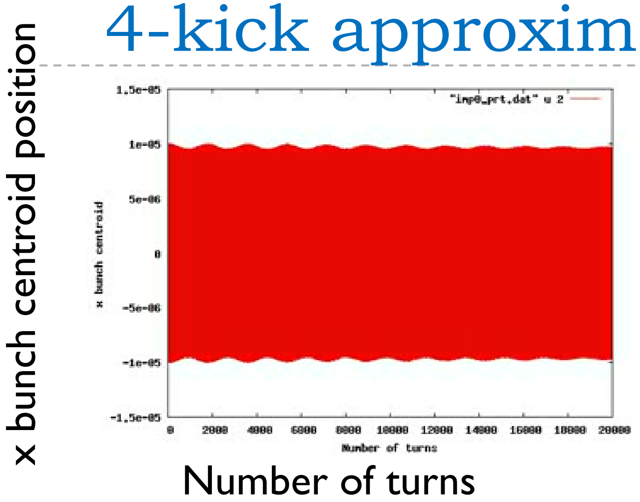
2 kick → arc (L=270.2m, 9mm, round,<bx>=2.976m, <by>=8.829m, S_{kick}=150m)

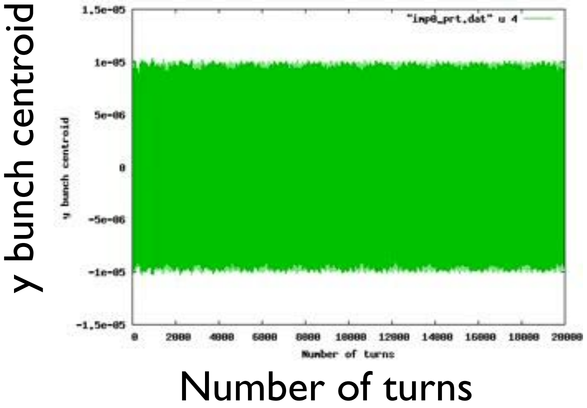
3 kick → wigglers (L=104m, 6mm, flat, <bx>=4.200m, <by>=9.839m, S_{kick}=41.3m)

4 kick → rest of the FODO (L=53.3m, 9mm, round,<bx>=5.665m, <by>=8.582m, S_{kick}=39.2m)

First results (III)

Estimating the machine impedance budget with a 4-kick approximation – single bunch simulations

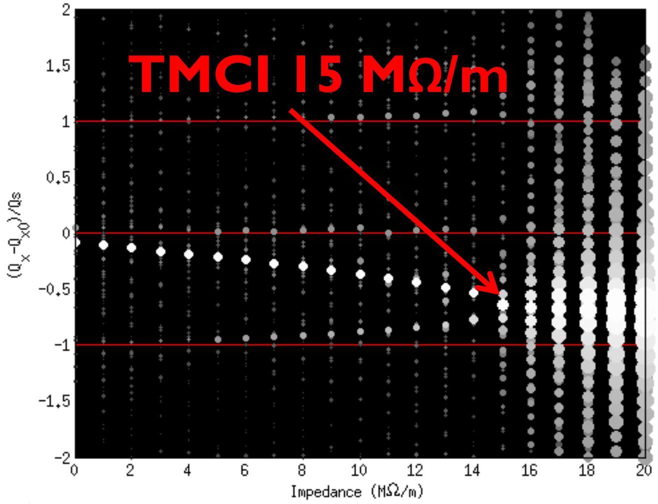


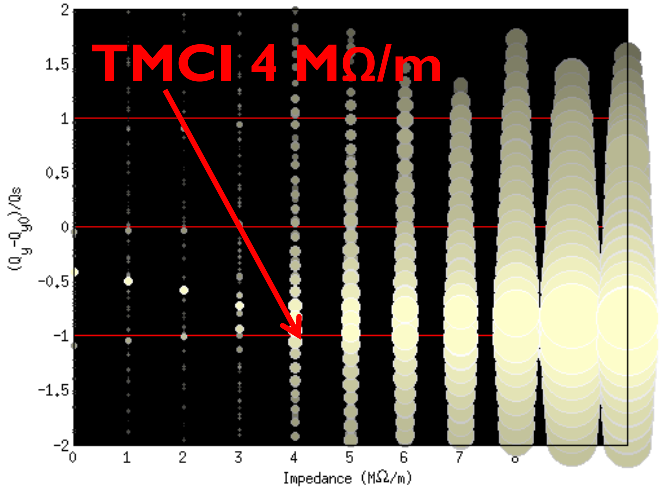


HEADTAIL output:
Position of the centroid over the number of turns

FFT/
Sussix

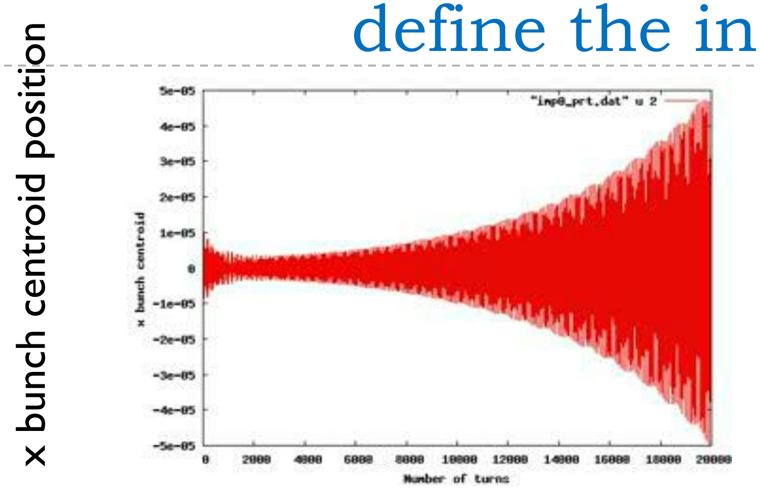
Mode spectrum of the horizontal and vertical coherent motion as a function of impedance

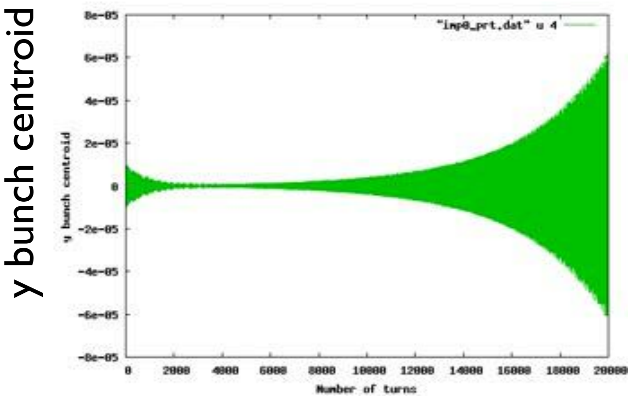




For zero chromaticity, the (remaining) impedance budget is estimated at 4 MΩ/m (7 MΩ/m for the BB only)

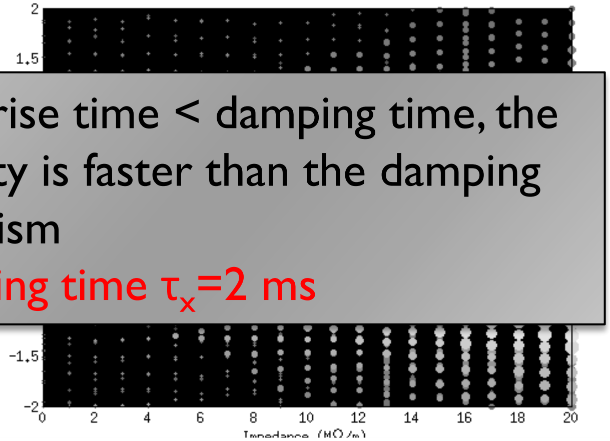
First results (III)
Single bunch simulations without space charge to define the instability thresholds



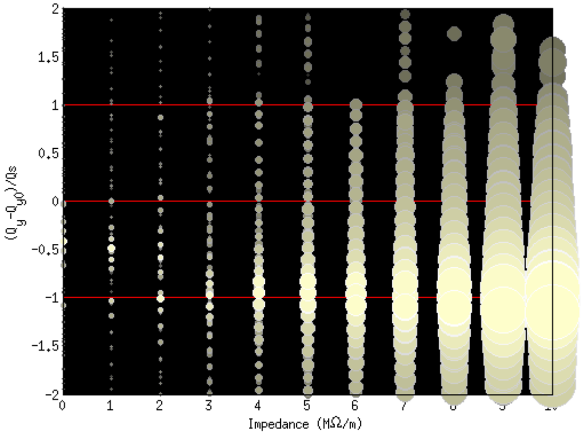


ξx	0.055
ξ_y	0.057

- Another type of instability occurs, called the head-tail instability
- Compare the rise time of instability with the damping time to define the threshold



- If the rise time < damping time, the instability is faster than the damping mechanism
- Damping time τ_x=2 ms



- No mode coupling observed
- Higher TMCI thresholds
- Mode 0 is damped
- Higher order modes get excited (m = -1)

For positive chromaticity, the impedance budget is estimated now at 1 MΩ/m (4 MΩ/m for the BB only)

Material EM properties characterization

⇒Unknown material properties of NEG and a-C at high frequencies (CLIC@ 500 GHz)

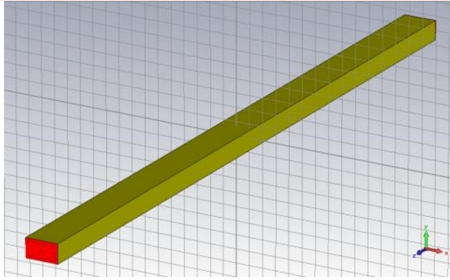
⇒Combine experimental results with CST simulations to characterize the electrical conductivity of *NEG*

⇒Powerful tool for this kind of measurements

Experimental method

50 cm Cu wg
9-12 GHz

CST MWS simulation

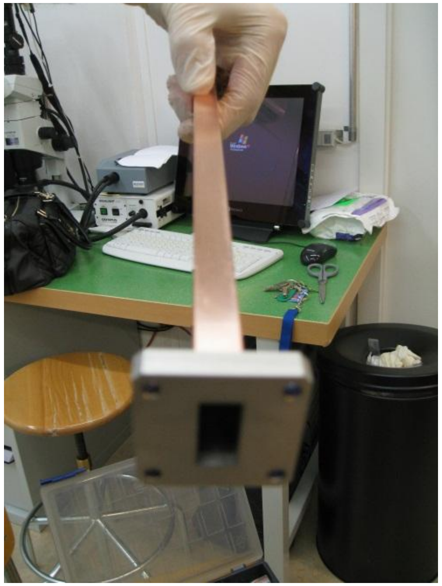


$S21(\sigma)$ Intersection $(f, S21)$

Material properties σ, ε, μ → Calculation of the wake fields → Study of instabilities with HEADTAIL

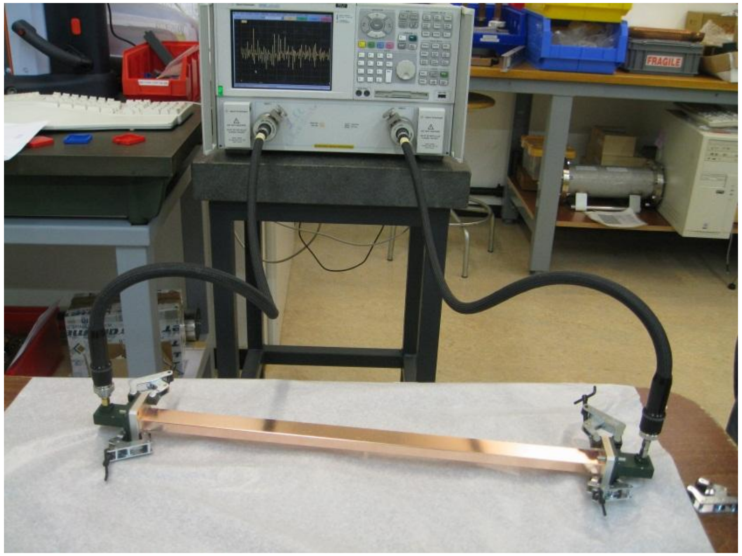
Experimental Method (I)

- Waveguide Method
  - First tested at low frequencies, from **9-12 GHz**
  - Use of a standard X-band waveguide, 50 cm length
  - Network analyzer
  - Measurement of the transmission coefficient S_{21}



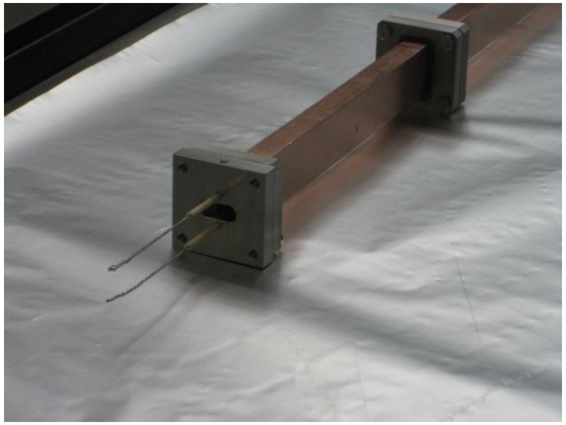
X band Cu waveguide of 50 cm length

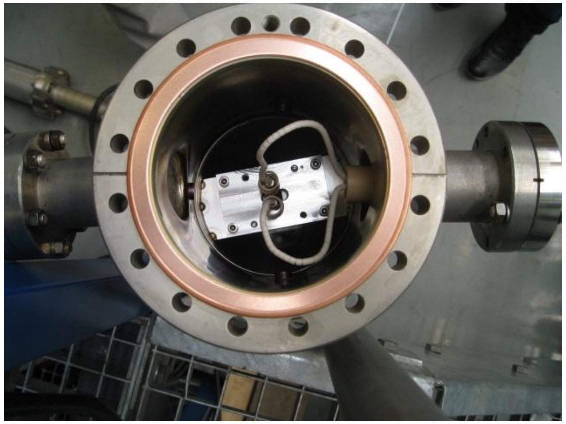
Experimental setup



Experimental Method (II)

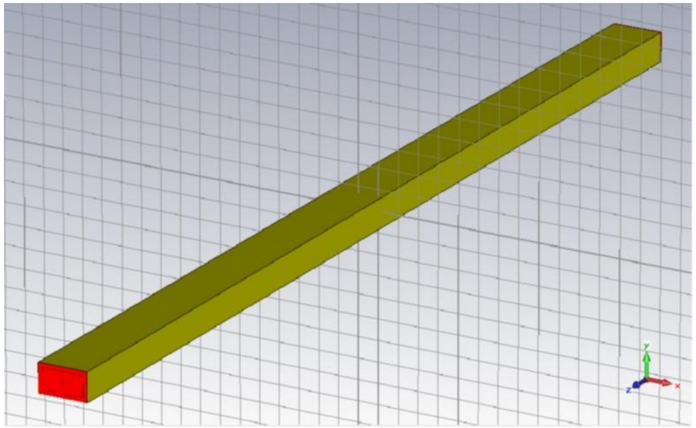
- NEG coated Cu waveguide
  - Same Cu waveguide used before is now coated with NEG
- <u>Coating procedure</u>
  - Elemental wires intertwisted together produce a thin Ti-Zr-V film by magnetron sputtering
  - Coating was targeted to be as thick as possible (9 μm from first x-rays results)





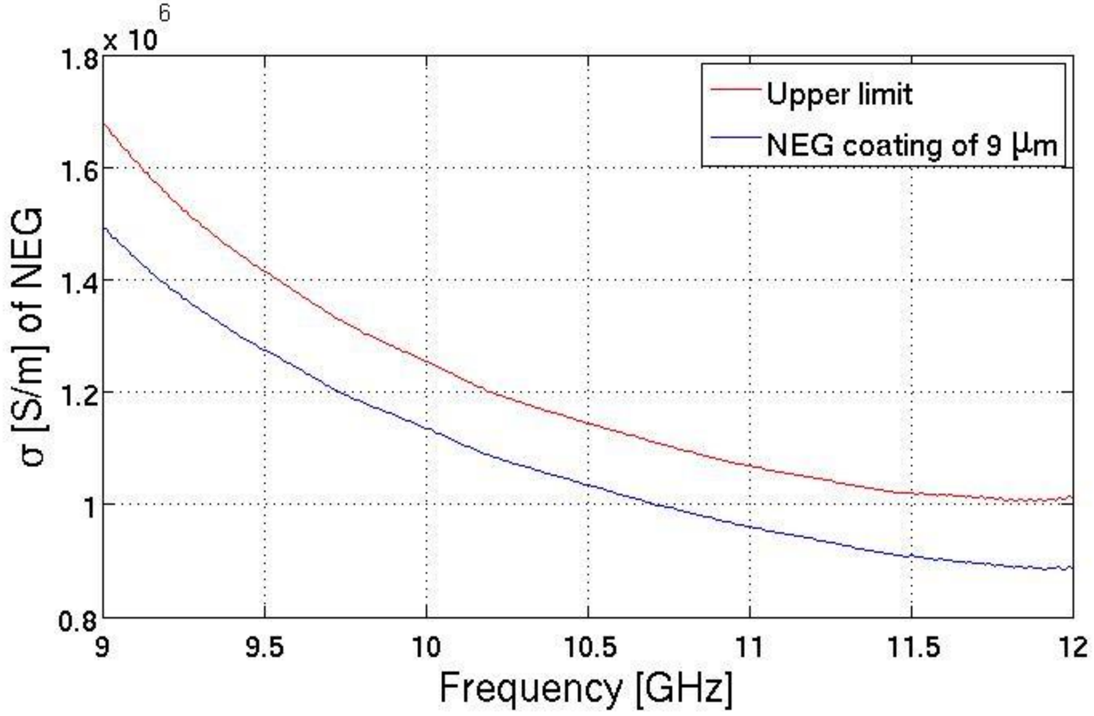
3D EM Simulations (I)
CST Microwave Studio

- Software package for electromagnetic field simulations
- The tool Transient Solver also delivers as results the S-parameters
- CST is used to simulate the Cu waveguide (same dimensions as the ones used in the experiment → simulating the experimental setup)



X band Cu waveguide simulated with CST MWS

3D EM Simulations and measurements (II) Conductivity of NEG



- Upper limit for the conductivity of NEG in this frequency range
- Preliminary results

•Is there an important effect depending on the conductivity of NEG?

•HEADTAIL simulations for σ_{NEG} =1.6 10^6 S/m

Results on the impedance budget (4 kicks) Effect of NEG conductivity & coating

Pipe material/ coating	**Chromaticity**	**Threshold in x plane (MΩ/m)**	**Threshold in y plane (MΩ/m)**	**Impedance budget (MΩ/m)**
ss/ NEG 2μm (σ_{NEG} = 10^6 S/m)	0	15	4	4
	ξx = 0.055/ξy = 0.057	2	1	1
ss/ NEG 2μm (σ_{NEG} =1.6 10^6 S/m)	0	16	5	5
	ξx = 0.055/ξy = 0.057	2	1	1
ss/ Cu 10 μm / NEG 2 μm (σ_{NEG} =1.6 10^6 S/m)	0	16	5	5
	ξx = 0.055/ξy = 0.057	2.5	2	2

The characterization of NEG properties is important

Different coating doesn’t have a very big effect

Experimental part (II)
Beam dynamics measurements at SLS

- CLIC damping rings target ultra-low emittance in all 3 dimensions for relatively high bunch density
- SLS:Vertical emittance reduced to a minimum value of **0.9±0.4pm** (CLIC damping rings target vertical emittance) which is a **new world record**
- **SLS ideal for beam dynamics measurements**
- **Validate the models used by comparing to a real machine**

⇒ First MD sessions : the goal was to measure the beam transfer function (BTF) in both transverse and longitudinal plane, test the diagnostics and the scripts to collect the data to ensure future successful MD sessions

⇒ Future MD sessions: single bunch measurements, tuneshift with intensity

Future work - planning

⇒Multi-kick code to simulate several impedance contributions (kickers, cavities,etc)

⇒Effect of coating in impedance (wigglers, rest of the ring) → possible scenarios of materials → NEG/aC coating

⇒Space charge influence on the coherent modes→ indications from the theoretical study of A.Burov

⇒Damping mechanism to predict instabilities

⇒Effect of the resistive wall with coating by studying the effect of its long range part (multi-bunch effects) with the goal of defining specifications for the transverse feedback system

⇒Study the thresholds to preserve also the stability in the longitudinal plane

⇒Waveguide measurements for NEG/aC coating on copper and stainless steel

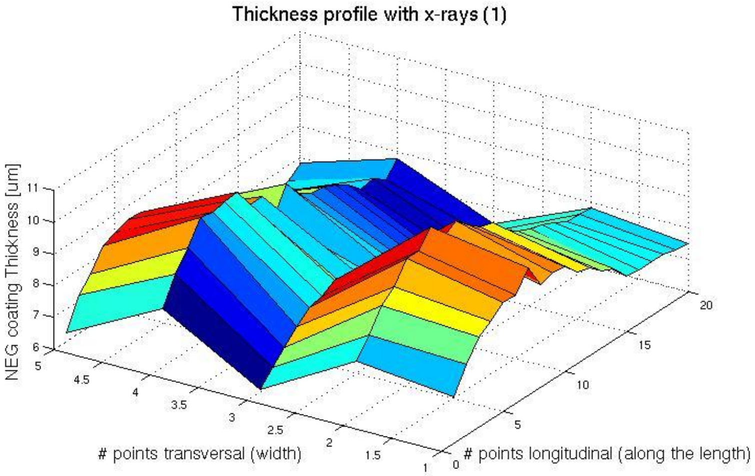
⇒Beam dynamics measurements at SLS (single bunch tuneshift over intensity, impedance with IBS measurements)

Challenges…

- Ultra high brilliance of the beams
- Small emittances and small chambers → collective effects
- Those regimes are becoming more and more important for existing lepton machines as well as for future ones (CLIC/ILC)
- Low Emittance Lepton Rings – unexplored regimes
  - Effect of coating
  - How space charge will affect the TMCI thresholds- is not negligible as it is for other lepton machines. Theoretical studies exist but never been applied to simulations.

Challenges…

- Measure properties at high frequencies…
  - Up to 500 GHz/ 500 GHz Network analyzer (EPFL)
  - Very short waveguides, Y-band (0.5 x 0.25 mm)
- Challenges
  - Manufacture of the small waveguide
  - Coating technique
  - Profile measurements
- Simulation
  - Non-uniform coating


Thickness profile with x-rays (1)

Acknowledgements

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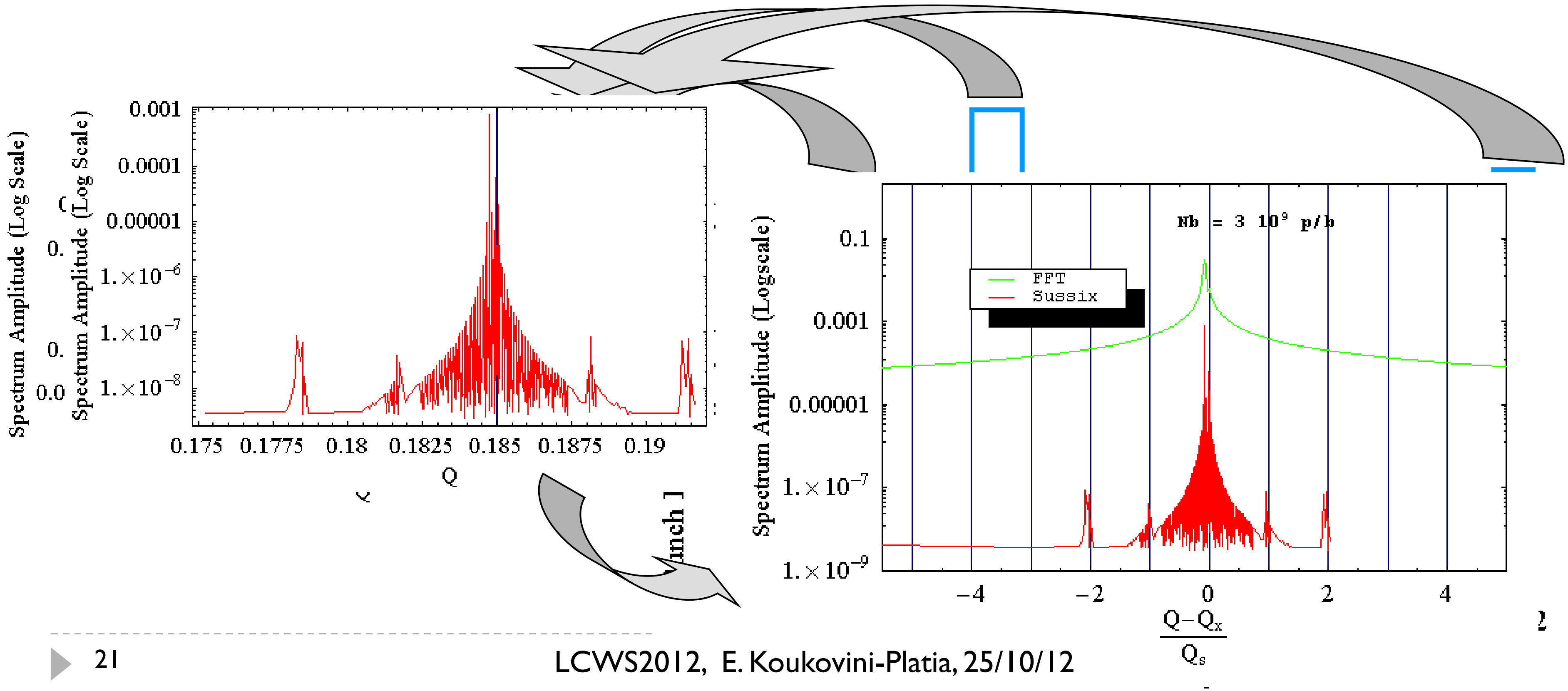
M. Taborelli

Thank you for your attention!

Backup slides

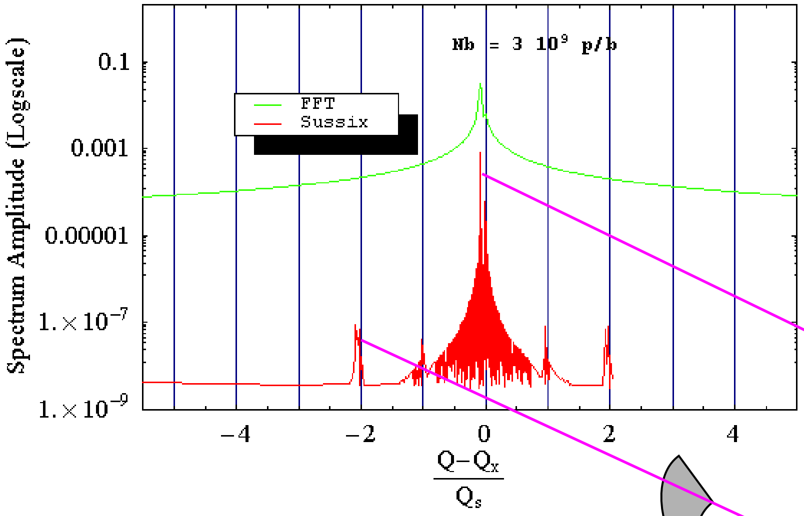
Methods : *What to do with HEADTAIL outputs ?*

1. Extract the position of the centroid of the bunch (vertical or horizontal) turn after turn → simulated BPM signal
2. Apply a classical FFT to this simulated BPM signal (*x*)
3. Apply SUSSIX* to this same simulated BPM signal (actually $x - j\,\beta_x x'$)
4. Translate the tune spectrum by $Q_{x0}=0$ and normalize it to Q_s

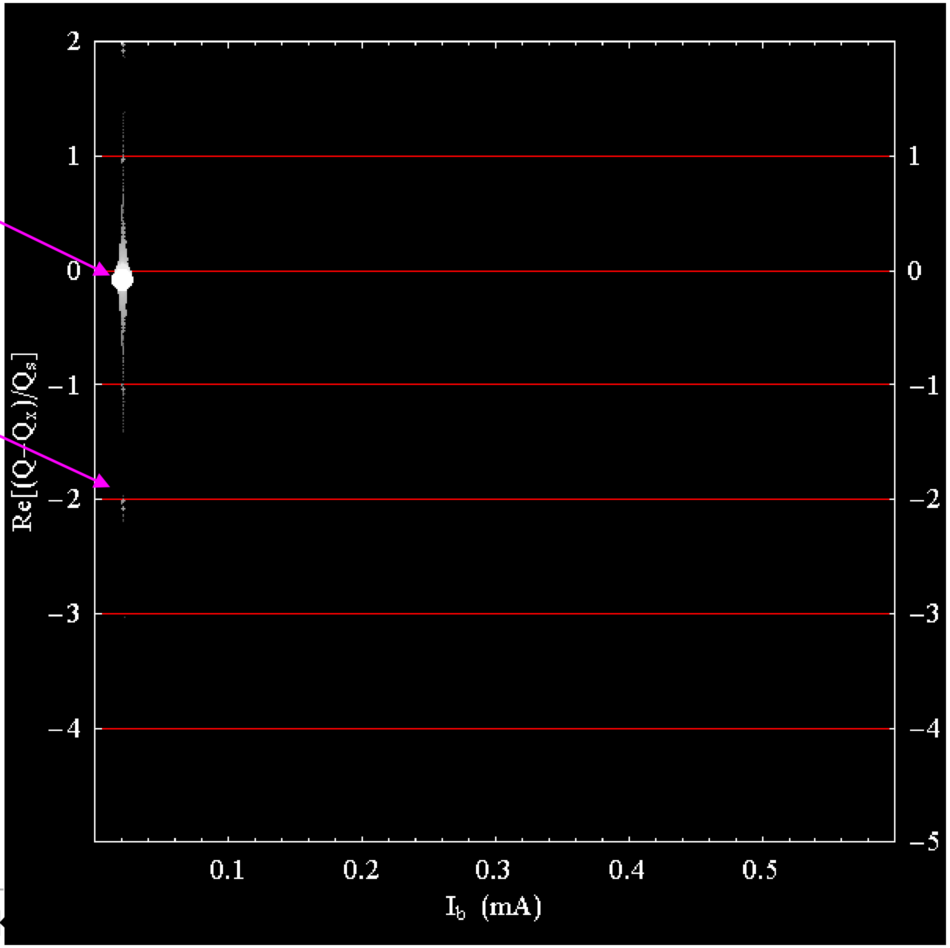


Another visualization of the tune spectrum

for Nb = 3 10^9 p/b (I_b = 0.02 mA)

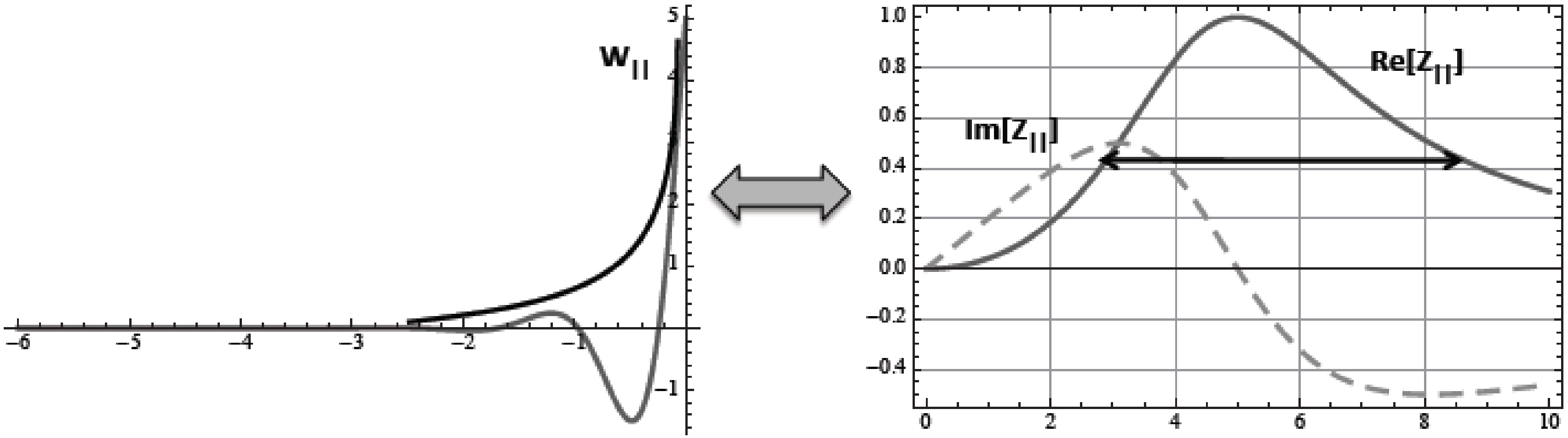


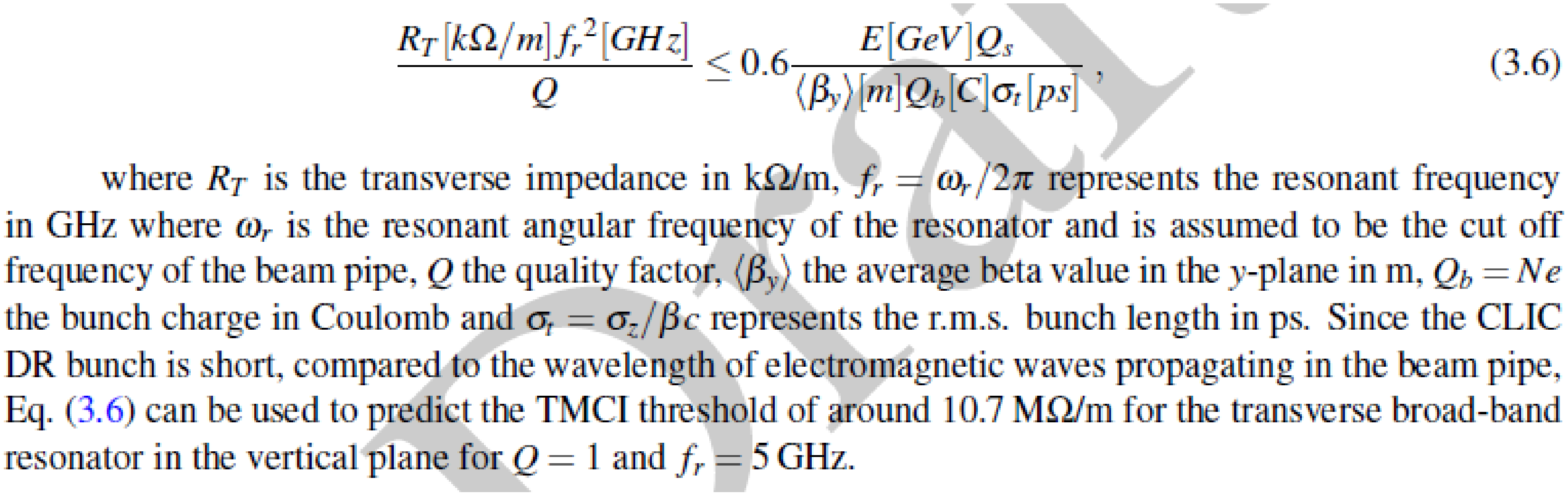
Displaying the Sussix spectrum on one line per bunch intensity



The dots are brighter and bigger if the amplitude is larger

Broadband Resonator

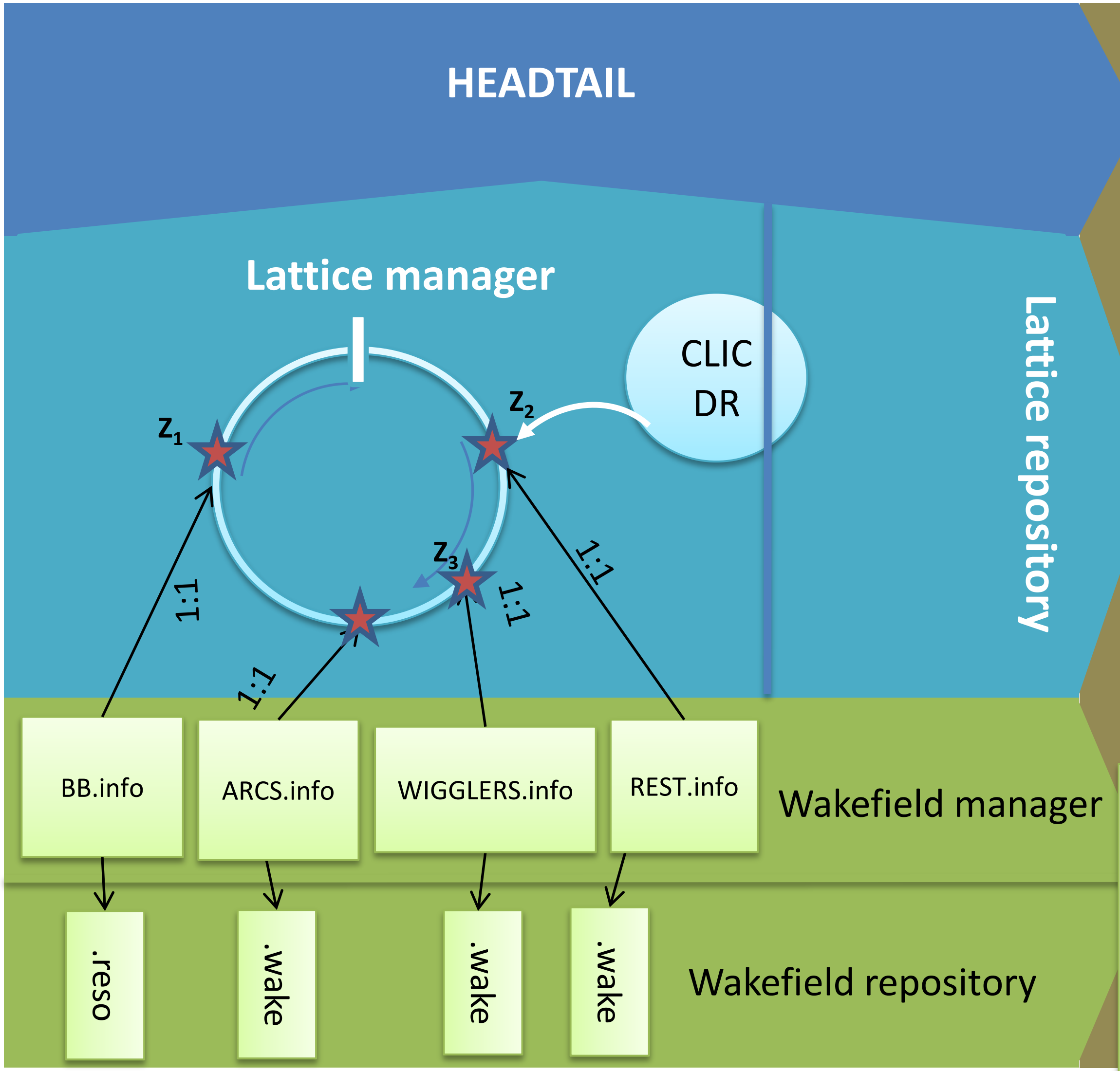




$$\frac{R_T\,[k\Omega/m]\,f_r^{\,2}\,[GHz]}{Q} \leq 0.6\frac{E\,[GeV]\,Q_s}{\langle\beta_y\rangle[m]\,Q_b[C]\,\sigma_t\,[ps]}\,, \qquad (3.6)$$

where R_T is the transverse impedance in kΩ/m, $f_r = \omega_r/2\pi$ represents the resonant frequency in GHz where ω_r is the resonant angular frequency of the resonator and is assumed to be the cut off frequency of the beam pipe, Q the quality factor, $\langle\beta_y\rangle$ the average beta value in the y-plane in m, $Q_b = Ne$ the bunch charge in Coulomb and $\sigma_t = \sigma_z/\beta c$ represents the r.m.s. bunch length in ps. Since the CLIC DR bunch is short, compared to the wavelength of electromagnetic waves propagating in the beam pipe, Eq. (3.6) can be used to predict the TMCI threshold of around 10.7 MΩ/m for the transverse broad-band resonator in the vertical plane for $Q = 1$ and $f_r = 5$ GHz.

Example of the 4 kicks applied



ARCS.info to manage a wake table

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INTERACTION: IMPEDANCE
TYPE: 1
TABLE_TYPE: 4
SCALE: 0
BETX: 2.976
BETY: 8.829
MULTIPLY: 0
MULTIPLY_COEFF: 1

Name of .wake