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

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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
- Their study and control will be crucial

Introduction (II)
Collective effects

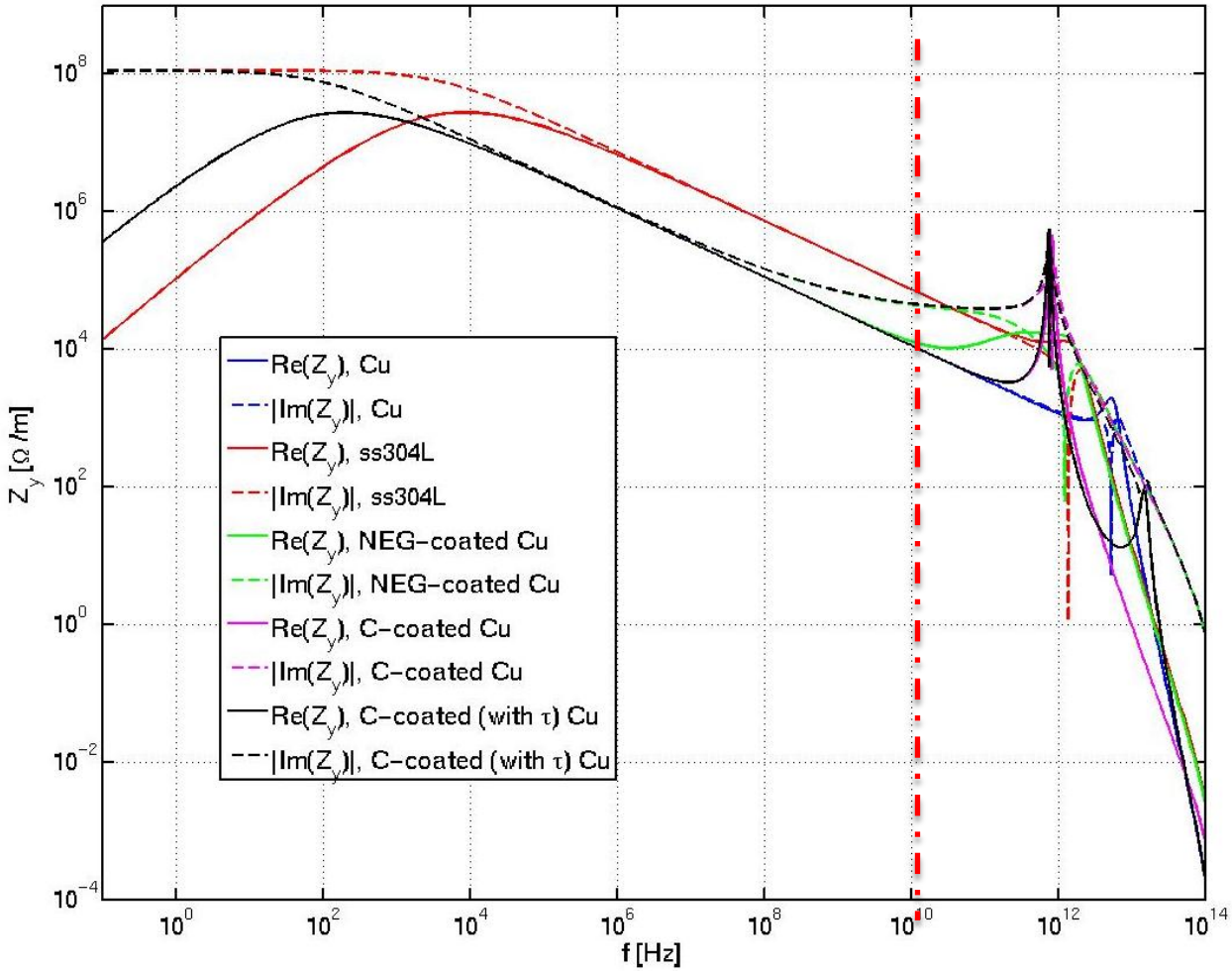
- Focus on instabilities driven by impedance
- Define the conditions to ensure safe operation under nominal conditions
- Define an impedance budget

<u>To suppress some of the collective effects, coating will be used</u>

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

➢ Since the DR are under design, only some possible scenarios have been 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

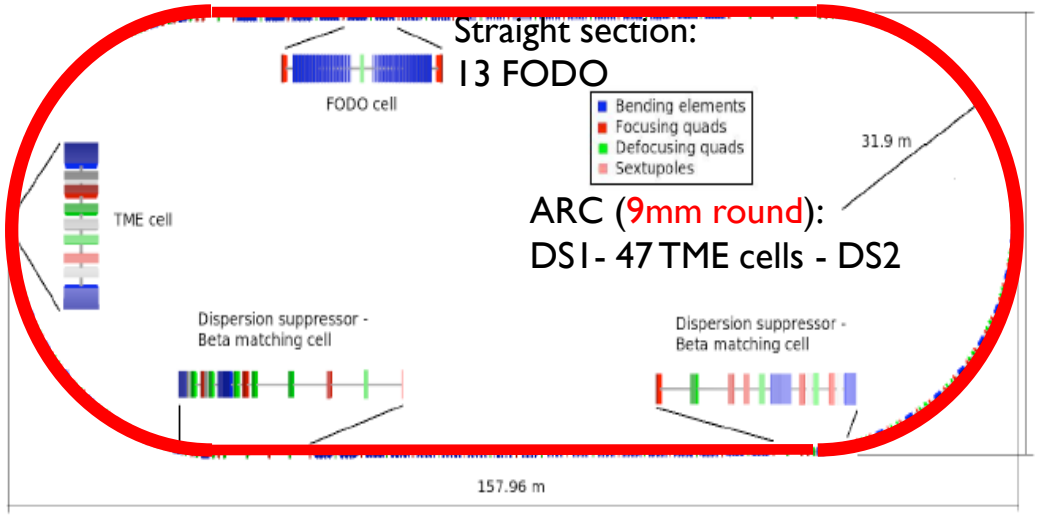
N. Mounet

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

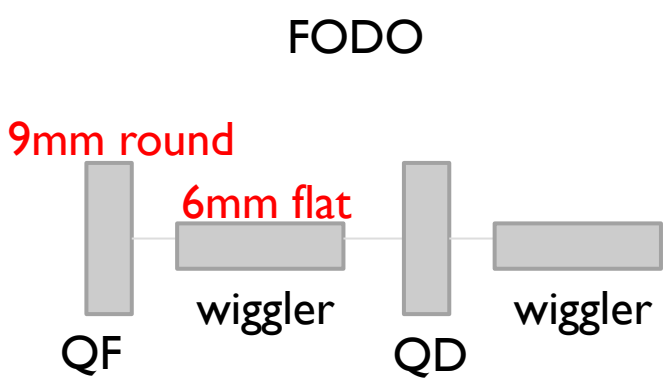
- HEADTAIL code
  - Simulates single/multi bunch collective phenomena associated with impedances (or electron cloud)
  - Computes the evolution of the bunch by bunch centroid as a function of time over an adjustable number of turns

- Goal
  - Estimate the available impedance budget for the various elements to be installed after known impedance sources such us the broad-band resonator, the resistive wall and the kickers are considered

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



- 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



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

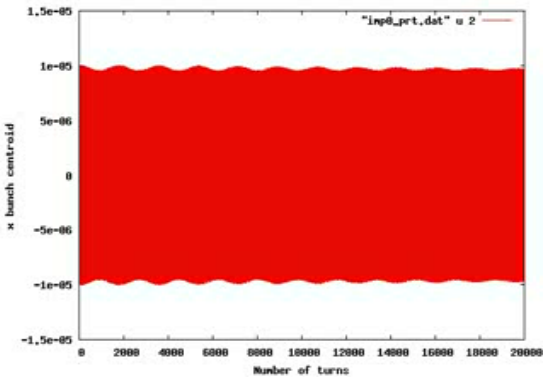
2nd kick → arc (L=270.2m, 9mm, round,<bx>=2.976m, <by>=8.829m, S_{kick}=150m)

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

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

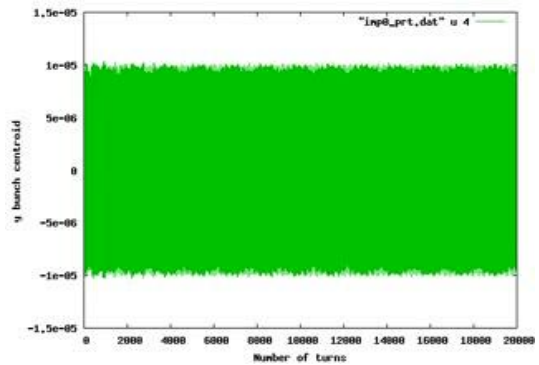
First results (III)
Estimating the machine impedance budget with a 4-kick approximation – single bunch simulations

x bunch centroid position



Number of turns

y bunch centroid

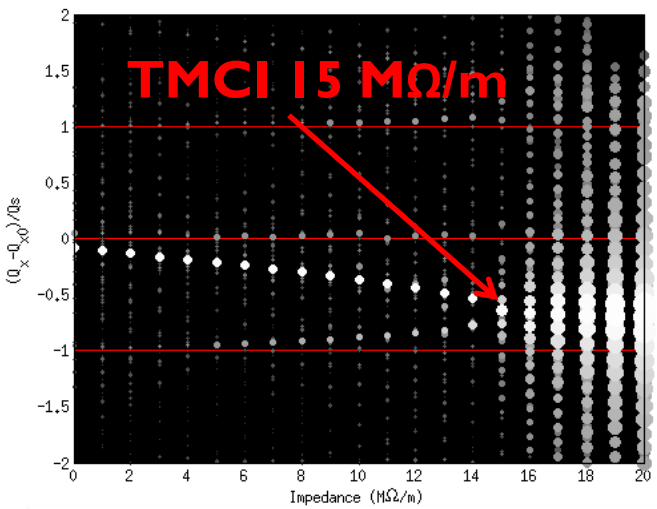


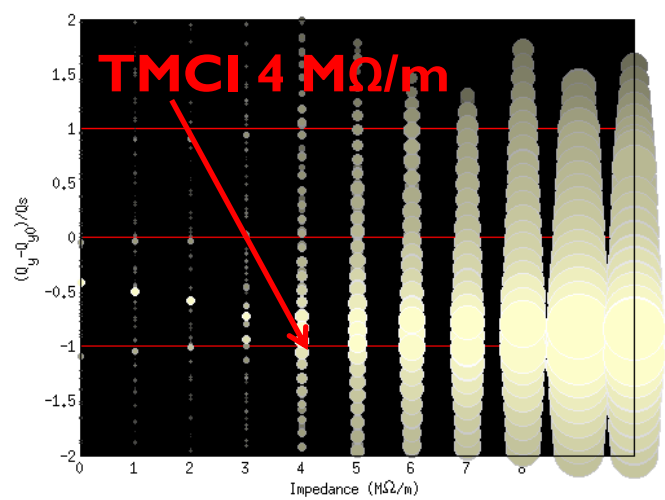
Number of turns

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

FFT/
Sussix

<u>Mode spectrum of the horizontal and vertical coherent motion as a function of impedance</u>

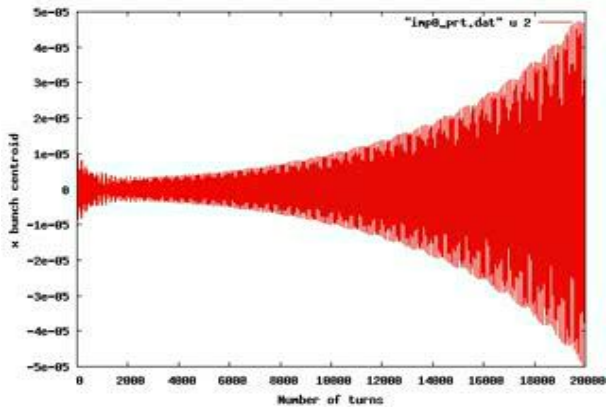




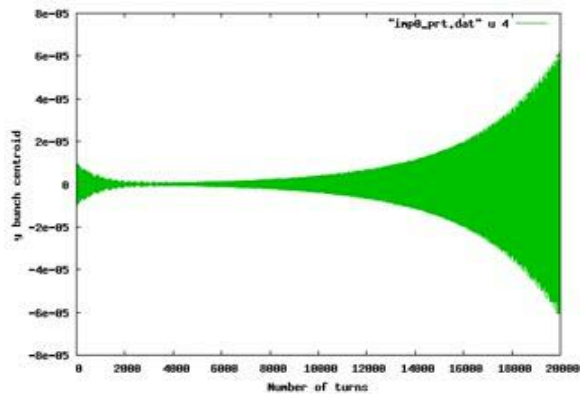
For zero chromaticity, the (remaining) impedance budget is estimated at 4 MΩ/m (7 MΩ/m for the BB only)

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

x bunch centroid position

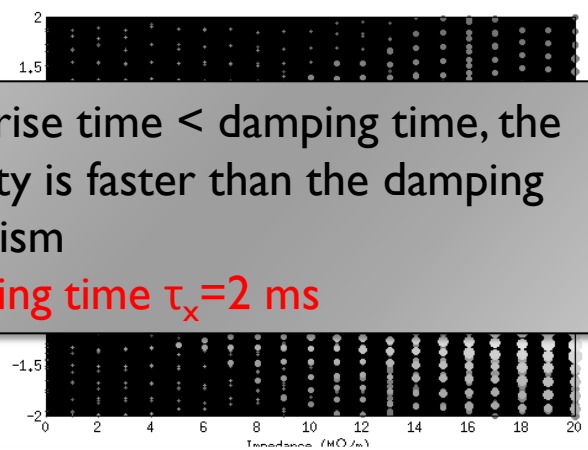


y bunch centroid

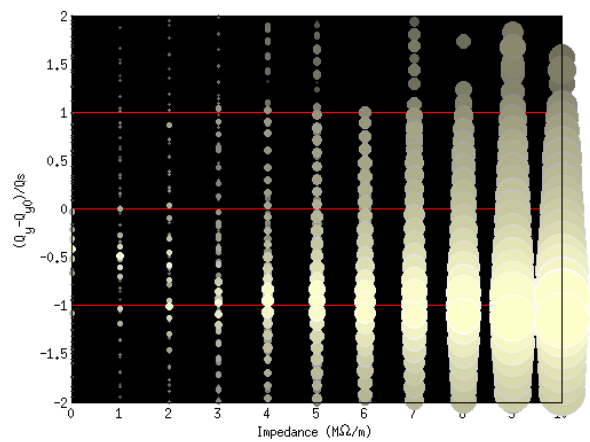


ξ_x	0.055
ξ_y	0.057

- 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

⇒Measurement of material EM properties in the high frequency range of NEG and a-C at high frequencies (CLIC@ 500 GHz)

⇒Establishing and testing a method to measure the properties of NEG

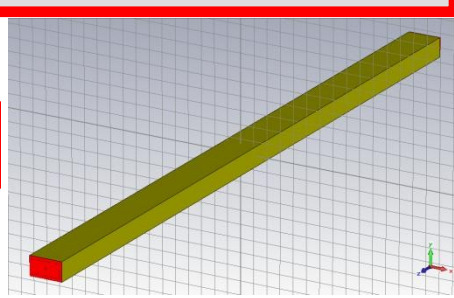
⇒Combine experimental results with CST simulations to characterize the electrical conductivity of *NEG*

⇒Powerful tool for this kind of measurements

Experimental method

50 cm Cu wg
9-12 GHz

CST MWS simulation

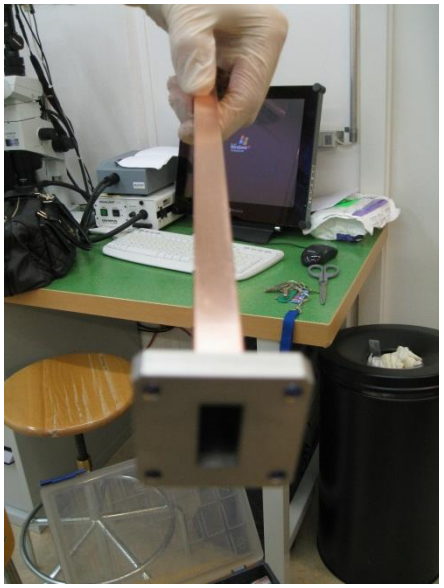


$S21(\sigma)$ → Intersection ← $(f, S21)$

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

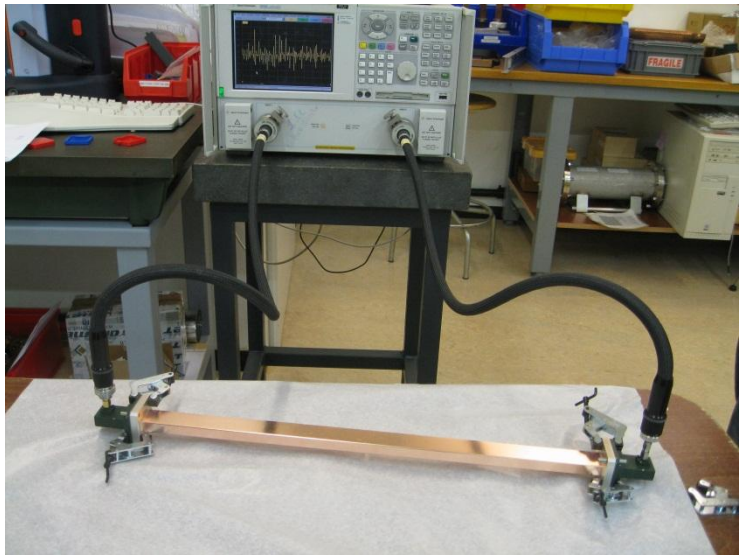
Experimental Method (I)

- 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}



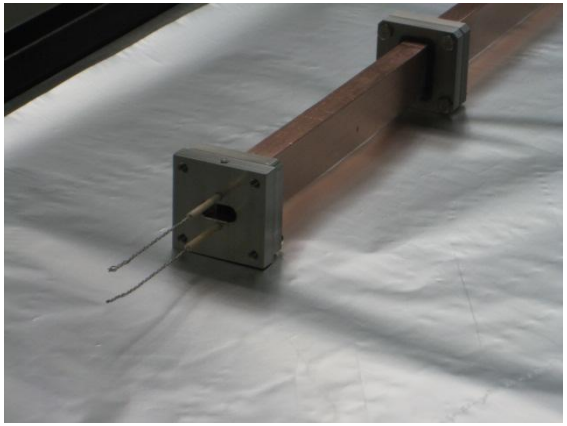
X band Cu waveguide of 50 cm length

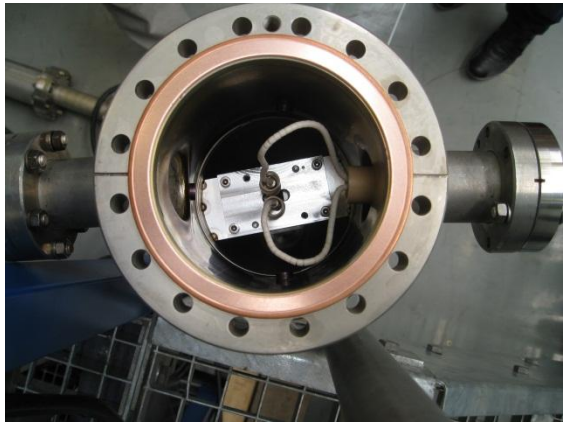
Experimental setup



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)

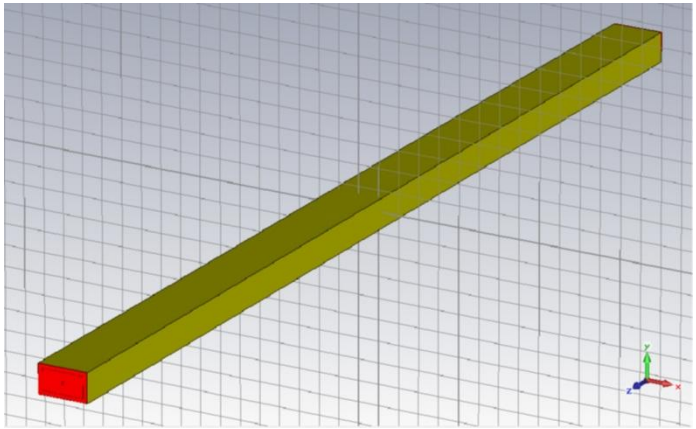




3D EM Simulations (I)
CST Microwave Studio

- 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

1. Use a spare Cu waveguide and check the reproducibility of the measurements
2. Use an existing stainless steel waveguide as a reference- will define the accuracy of the method

X band ss waveguide of 50 cm length

- Is this frequency dependency physical? (repeat measurements with a spare Cu wg to check reproducibility)
- Is there an important effect depending on the conductivity of NEG?
- Rerun 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 in the high frequency regime

Different coating has an effect, mainly important for positive chromaticity

Experimental part (II)
Beam dynamics measurements at SLS

- CLIC damping rings target at ultra-low emittance in all 3 dimensions for relatively high bunch density
- SLS achieved a **new world record** in low vertical emittance, **0.9±0.4pm**
- Ideal for beam dynamics measurements
- Goal → Validate the models used by comparing to a real machine

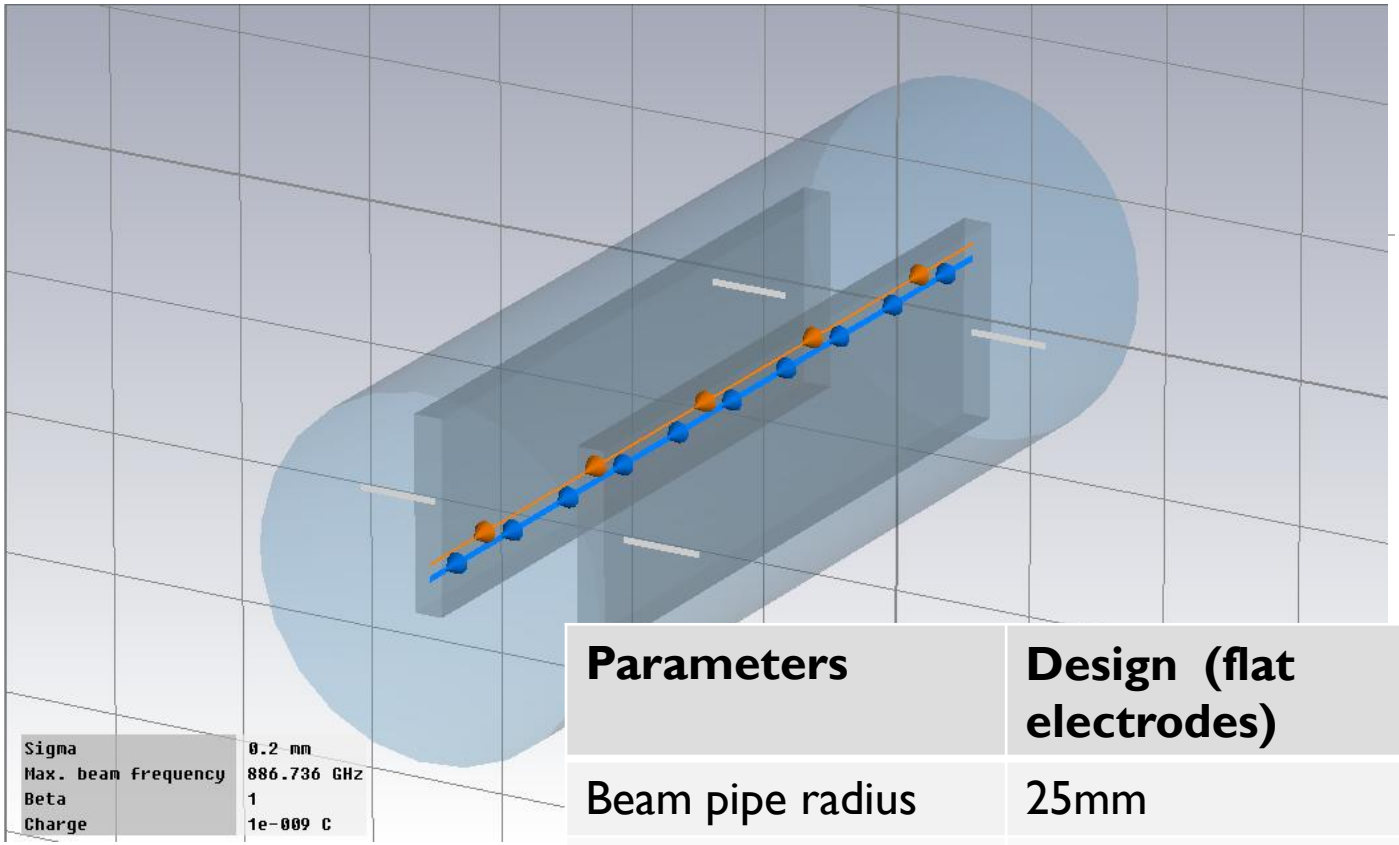
▪ First MD sessions : the goal was to measure the beam transfer function (BTF) in both transverse and longitudinal plane, test the diagnostics and the scripts to collect the data to ensure future successful MD sessions

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

Future tasks

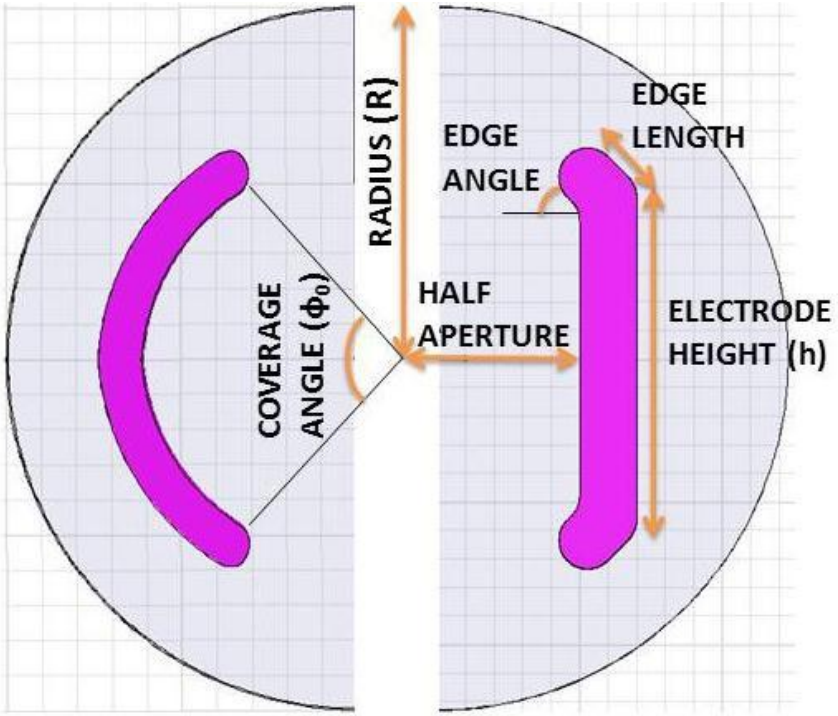
- Multi-kick code to simulate several impedance contributions (kickers, cavities,etc)
- Effect of coating in impedance (wigglers, rest of the ring) → possible scenarios of materials → NEG/aC coating
- Space charge influence on the coherent modes→ indications from the theoretical study of A.Burov
- Programming the radiation damping mechanism in HEADTAIL 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)

Stripline kickers



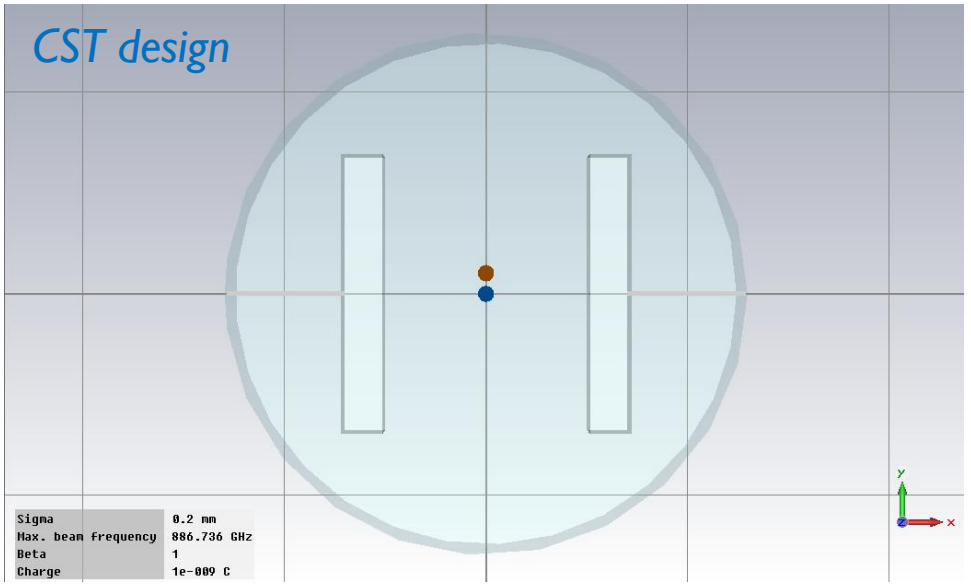
Parameters	Design (flat electrodes)	CST
Beam pipe radius	25mm	25mm
Electrodes height	20mm	27mm
Edges	5mm length, 45°	Included in the electrodes height
Electrodes thickness	4mm	4mm
Aperture (distance between electrodes)	20mm	20mm
Bunch length		0.2mm
Kickers length	1.7m	100mm

Stripline kickers



Original design

- Calculate the wake potential
- Insert the wake table in HEADTAIL
- Simulate this effect of this kick



Summary

- 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
- 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.
- 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)

Acknowledgements

- F. Antoniou
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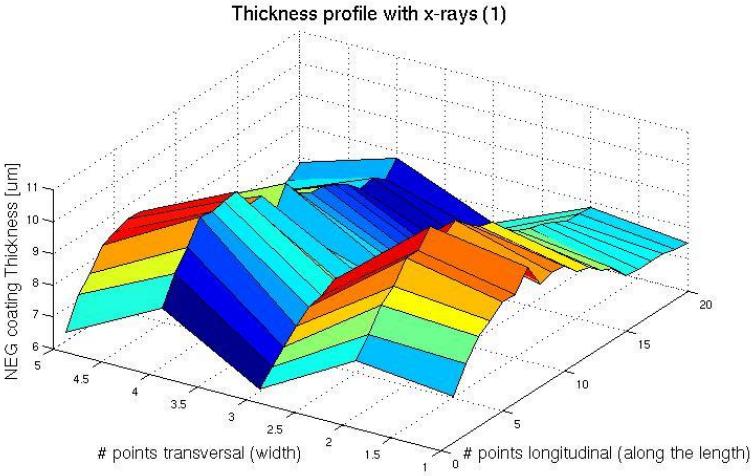
M. Malabaila
P. Costa Pinto
M. Taborelli

Thank you for your attention!

Cu waveguide coating measurements

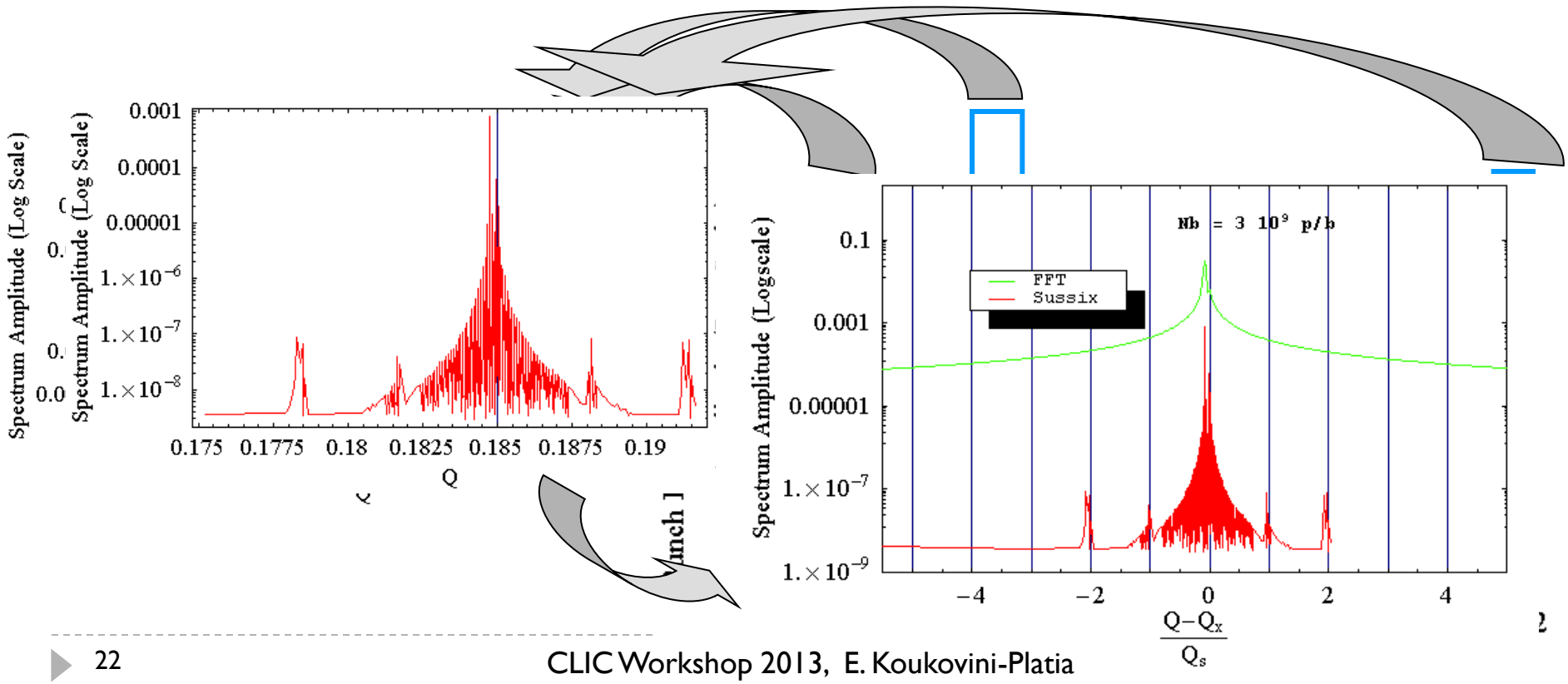
- Challenges
  - Manufacture of the small waveguide
  - Coating technique
  - Profile measurements
- Simulation
  - Non-uniform coating



Backup slides

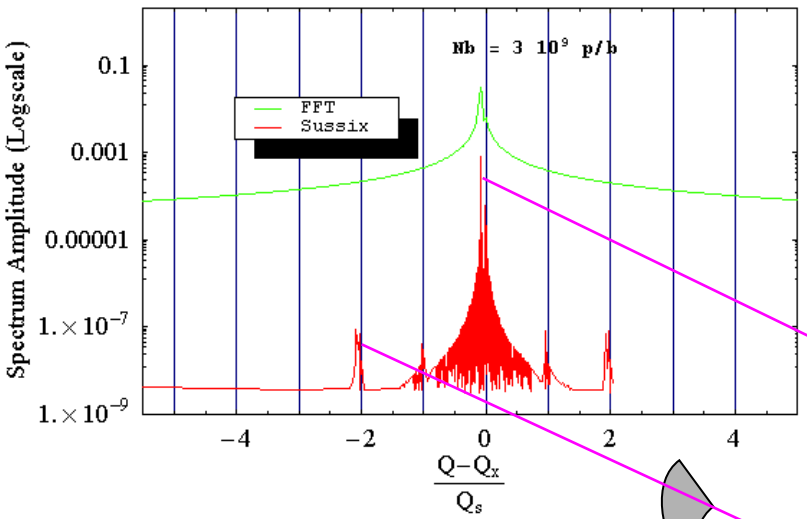
Methods : *What to do with HEADTAIL outputs ?*

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

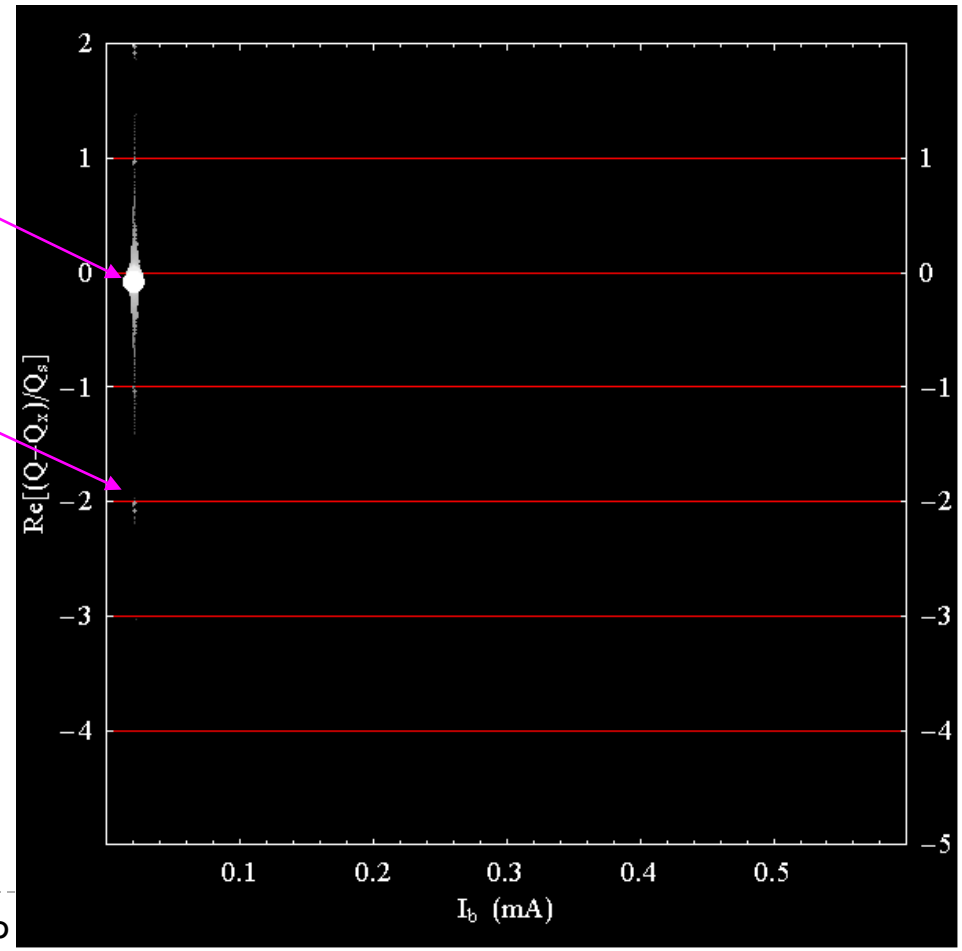


Another visualization of the tune spectrum

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

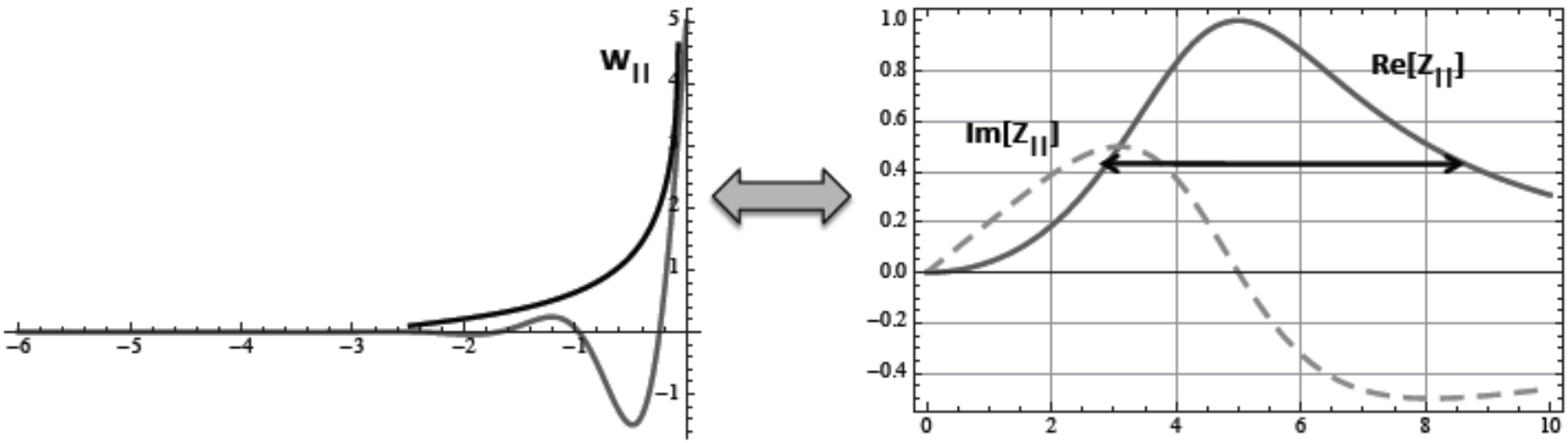


Displaying the Sussix spectrum on one line per bunch intensity



The dots are brighter and bigger if the amplitude is larger

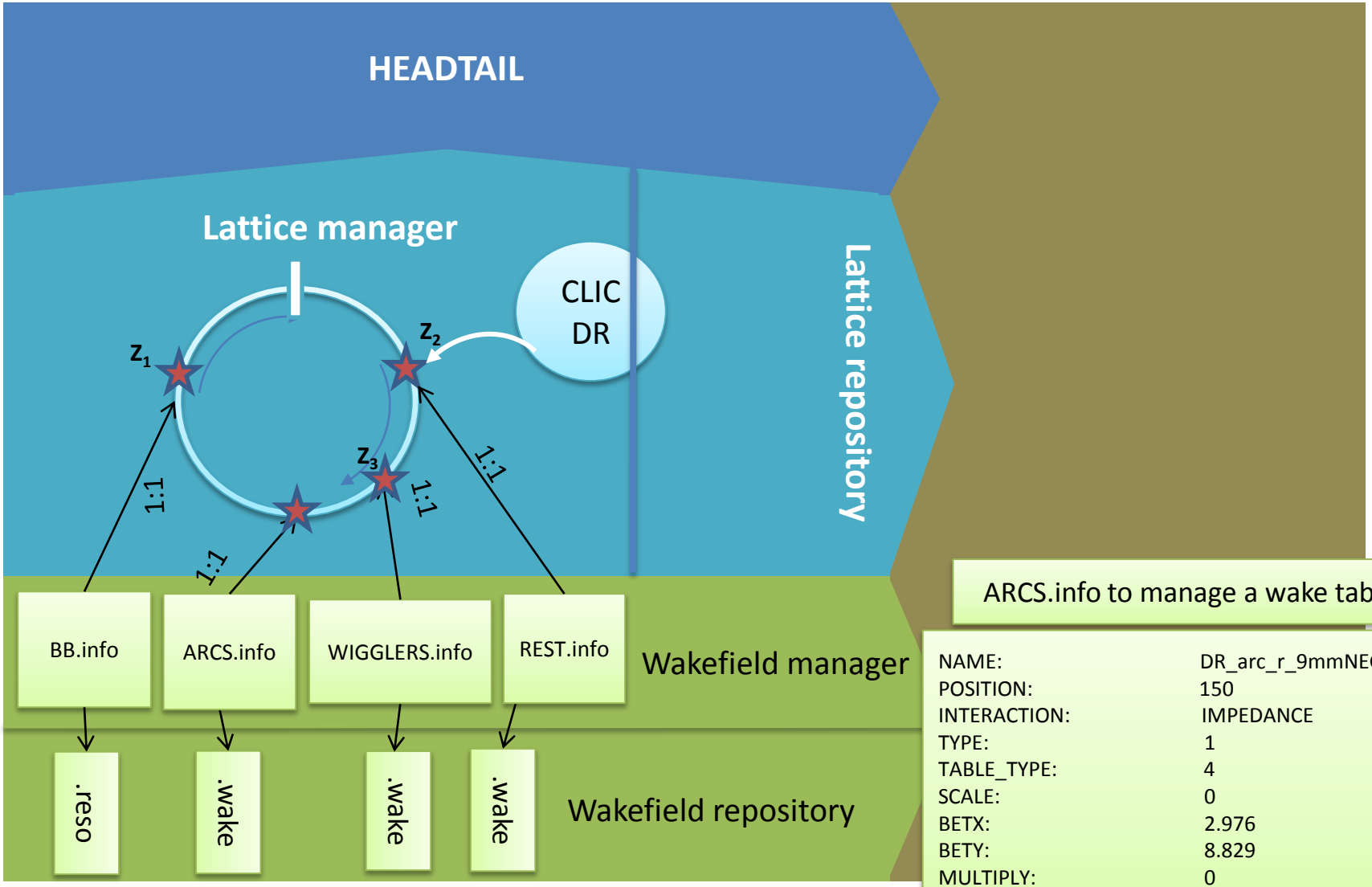
Broadband Resonator



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

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

NAME:	DR_arc_r_9mmNEG0p002ss
POSITION:	150
INTERACTION:	IMPEDANCE
TYPE:	1
TABLE_TYPE:	4
SCALE:	0
BETX:	2.976
BETY:	8.829
MULTIPLY:	0
MULTIPLY_COEFF:	1

Name of .wake