Electromagnetic characterization of materials for the CLIC Damping Rings and high frequency issues

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Acknowledgements
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Outline

- Introduction
- Motivation
- Experimental method- simulations
- First results- testing simulations
- Conclusions- future planning- challenges
Introduction (I)  
CLIC: a future multi-TeV $e^+e^-$ collider

- Compact Linear Collider (CLIC)
- Allows the exploration of a new energy regime, in the multi-TeV range beyond the capabilities of today's particle accelerators

- DR will deliver the desired ultra low emittances
- EDR - PDR
Introduction (II)

**Damping Rings**

- **CLIC DR parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CLIC@3TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>2.86</td>
</tr>
<tr>
<td>Circumference [m]</td>
<td>427.5</td>
</tr>
<tr>
<td>Energy loss/turn [MeV]</td>
<td>4.0</td>
</tr>
<tr>
<td>RF voltage [MV]</td>
<td>5.1</td>
</tr>
<tr>
<td>Stationary phase [°]</td>
<td>51</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>1.3e-4</td>
</tr>
<tr>
<td>Damping time x/s [ms]</td>
<td>2/1</td>
</tr>
<tr>
<td>Number of dipoles/wigglers</td>
<td>100/52</td>
</tr>
<tr>
<td>Dipole/wigglar field [T]</td>
<td>1.0/2.5</td>
</tr>
<tr>
<td>Bend gradient [1/m²]</td>
<td>1.1</td>
</tr>
<tr>
<td>Bunch population [10⁹]</td>
<td>4.1</td>
</tr>
<tr>
<td>Horizontal normalized emittance [nm.rad]</td>
<td>456</td>
</tr>
<tr>
<td>Vertical normalized emittance [nm.rad]</td>
<td>4.8</td>
</tr>
<tr>
<td>Bunch length [mm]</td>
<td>1.8</td>
</tr>
<tr>
<td>Longitudinal normalized emittance [keV.m]</td>
<td>6.0</td>
</tr>
</tbody>
</table>

- **Small emittance, short bunch length and high current**
- **Rise to collective effects which can degrade the beam quality**
Introduction (III)  
Collective effects

- Represent phenomena describing the evolution of a particle beam under the effect of self-induced forces
- Could lead to instabilities, tune shift, beam loss and emittance growth
- Determine the performance of an accelerator (by limiting the beam intensity or degrading beam quality)
- Study to ensure safe operation under nominal conditions
- Focus on impedance

To suppress some of those effects, coating will be used

- **Positron Damping Ring (PDR):** electron-cloud effects $\rightarrow$ amorphous carbon (aC)
- **Electron Damping Ring (EDR):** fast ion instabilities $\rightarrow$ need for ultra-low vacuum pressure $\rightarrow$ Non-Evaporable Getter (NEG)
Introduction (IV)
Tools

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

- ImpedanceWake2D
  - Computes the longitudinal and transverse wake functions of multilayer structures, cylindrical or flat

- CST Microwave Studio
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
Single bunch simulations to define the instability thresholds

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

For zero chromaticity, the impedance budget is estimated at 7 MΩ/m
Estimating the machine impedance budget with a 4-kick approximation

- A uniform coating of NEG, 2μm thickness, ($\sigma=10^6$ S/m) 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 $\rightarrow$ broadband resonator ($S_{\text{kick}}=1$ m)

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

9 mm round

FODO

6 mm flat

Wiggler

Wiggler

QF

QD

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

4 kick $\rightarrow$ rest of the FODO (L=53.3 m, 9 mm, round, $<bx>=5.665$ m, $<by>=8.582$ m, $S_{\text{kick}}=39.2$ m)
Estimating the machine impedance budget with a 4-kick approximation

- A uniform coating of NEG, 2μm thickness, ($\sigma=10^6$ S/m) was assumed around the ring made from stainless steel.

Straight section:
- 13 FODO cells
- ARC (9mm round): DS1-14 TME cells-DS2
- 3 kick $\rightarrow$ wigglers (L=104m, 6mm, flat, $<bx>=4.200m, <by>=9.839m, Skick=41.3m)
- 4 kick $\rightarrow$ rest of the FODO (L=53.3m, 9mm, round, $<bx>=5.665m, <by>=8.582m, Skick=39.2m)

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

Need to characterize the properties of NEG.
Motivation

- Need to characterize the properties of the coating materials at high frequencies (CLIC), i.e. 500 GHz
- Characterize the electrical conductivity of NEG
- Combination of experimental method and EM simulations

**EM properties of NEG and aC** → **Code calculating wake fields/impedances** → **Instabilities studies for the CLIC DR**

*TiZrV coating*
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 $S_{21}$

![Experimental setup](image1)

*X band Cu waveguide of 50 cm length*
Copper waveguide

- First test: a pure copper (Cu) X band waveguide
- Measure the $S_{21}$ from 9-12 GHz

Signals traveling in the waveguide experience loss due to the conductor resistance.

$S_{21}$ is related to the loss suffered in the transmission from one port to the other.

Cu is a very good conductor and the losses are small.

$S_{21}$ is related to the material conductivity.
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)
3D EM Simulations and measurements (I)

- X band Cu waveguide, $\varepsilon_r=\mu_r=1$, $\sigma$ is the (unknown) scanned parameter
- For each frequency from 9-12 GHz, the output result is the $S_{21}$ coefficient as a function of conductivity
- Combine with the measurement results $\rightarrow \sigma$ as a function of frequency

Example at 10 GHz
Intersection of the simulation results with the measurement $\rightarrow$ point of intersection defines the conductivity

Value of conductivity
**3D EM Simulations and measurements (II) Conductivity of Cu**

- Result from the intersection of measurements with CST MWS simulations

![Graph showing conductivity of Cu](image)

- Cu conductivity was estimated within the same order of magnitude with the known value
- Average is $5.91 \times 10^7$ S/m
- Good agreement with the known value of $5.8 \times 10^7$ S/m
- The attenuation is very sensitive to the errors because of the small losses (high conductivity of Cu)
- Despite this, the results were encouraging to continue with a coated waveguide
Experimental Method (III)

- **NEG coated Cu waveguide**
  - Same Cu waveguide used before is now coated with NEG

- **Coating procedure**
  - Elemental wires intertwined 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)
Experimental Method (IV)

- **NEG coated Cu waveguide**
  - Measure the $S_{21}$ from 9-12 GHz

![Graph showing $S_{21}$ vs Frequency]

- $S_{21}$ results indicate that the skin depth is small enough compared to the coating thickness
- Allows the EM interaction with the NEG
3D EM Simulations and measurements (III)
Conductivity of NEG

- Real thickness profile $\rightarrow$ unknown
- First indication from x-rays
- 2 scenarios
  - skin depth $<<$ thickness $\rightarrow$ losses only from NEG $\rightarrow$ $\sigma_{\text{NEG}}$
    - simulation: infinite thickness of NEG $\rightarrow$ upper limit
  - skin depth $\sim$ thickness $\rightarrow$ losses from NEG and Cu $\rightarrow$ $\sigma_{\text{NEG}}$
    - simulation: NEG-coated (9µm) Cu waveguide
3D EM Simulations and measurements (IV)
Conductivity of NEG

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

- Errors
  - Experimental method (stainless steel waveguide)
  - Benchmark CST MWS coating simulations
First tests of the CST MWS simulations (I)

- Check the results reliability of coating simulations
- First tests

Compare simulations
1. A Cu waveguide NEG coated of 100 µm (2 materials)
   - Assuming $\sigma_{NEG} = 2 \times 10^6$ S/m, the skin depth is varying from 3.9-3.2 µm for 8-12 GHz
   - $\delta = \sqrt{\frac{2}{\mu \omega \sigma}} \approx 503 \sqrt{\frac{1}{\mu_r f \sigma}}$
   - skin depth $<< 100$ µm thickness $\rightarrow$ EM interaction only with NEG
2. A waveguide from NEG (1 material)
First tests of the CST MWS simulations (II)

- Compare the results from simulations for the 2 cases

The results are in a very good agreement, 1% error
First tests of the CST MWS simulations (III)

• Simulate different values of NEG thickness and check the output of simulations
  - From 8-12 GHz, skin depth varies from 3.9-3.2 µm ($\sigma_{\text{NEG}} = 2 \times 10^6$ S/m)
  - Simulate thickness from 1-20 µm
First tests of the CST MWS simulations (IV)

- Compare results for different NEG thickness from 1-20 µm

- For small values, 1-4 µm, the skin depth is larger or comparable to the thickness → small losses due to Cu
- For 10-20 µm, the skin depth << thickness → higher losses due to NEG

The results are in agreement with the expected ones
Summary

⇒ NEG (Non Evaporable Getter)/ aC (amorphous Carbon) coating is necessary for good vacuum and to fight e⁻ cloud in the EDR and PDR of CLIC

⇒ Unknown material properties at high frequencies

⇒ Combine experimental results with CST simulations

⇒ Powerful tool for this kind of measurements

50 cm Cu wg
9-12 GHz

Material properties
σ, ε, μ

Calculation of the wake fields

Study of instabilities with HEADTAIL

S21(σ)

Intersection

(f, S21)
Conclusions- Future work

- The waveguide method combined with CST EM simulations was tested at frequencies from 9-12 GHz for a Cu NEG coated waveguide
- The results were encouraging
- Upper limit for the NEG conductivity at this frequency range
- Measurements for a stainless steel waveguide will take place (error of the method)
- CST MWS simulations will be benchmarked (error of simulations)
- Measurements on a different coating? aC?
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
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