Effect of molybdenum coatings on the accelerating cavity quality factor: A numerical study

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Physics and Applications of High Brightness Beams

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Contents

Introduction

❖ State-of-art

- Normal conducting cavities for next generations of XFELs (e.g., LCLS [1]) and linacs (e.g., CLIC [2]), as well as room-scale applications [3], require higher gradients (E_{acc}).
- Breakdown as the main limitation to achieve higher E_{acc} [3–5]; presenting multifactorial dependencies: E_{pk}, B_{pk}, pulse surface heating, material hardness, etc.
- Cryogenics greatly lowers breakdown rates (BDR); which points to crystal mobility caused by thermal stresses as origin [5].

[1] P. Emma *et al.*, *Nat. Photonics* **4**, 641 (2010)
[2] M. Aicheler *et al.*, *CERN Technical Report* **CERN-2012-007** (2012)
[3] A.D. Cahill *et al.*, *Phys. Rev. Accel. Beams* **21**, 102002 (2018)
[4] A.D. Cahill *et al.*, *Phys. Rev. Accel. Beams* **21**, 061301 (2018)
[5] F. Wang *et al.*, *Phys. Rev. ST Accel. Beams* **14**, 010401 (2011)

Introduction

- State-of-art
  - On the other hand, both the presence and magnitude of dark currents are correlated with Q_0 degradation [4].
  - Higher frequency devices are planned for the next generation of photoinjectors [6,7], as they reduce the filling and so the BDR. Thus, mitigation of non freq. dependent phenomena (i.e., understandings on the field enhancement factor in the *Fowler-Nordheim* emission) would unblock higher gradients.

[6] J. B. Rosenzweig *et al.*, *Phys. Rev. Accel. Beams* **22**, 023403 (2019)
[7] B. Spataro *et al.*, *Eur. Phys. J. Plus* **137**, 769 (2022)

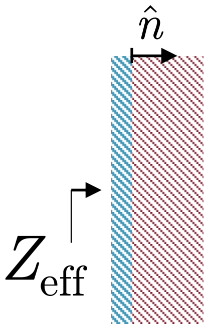
Motivation

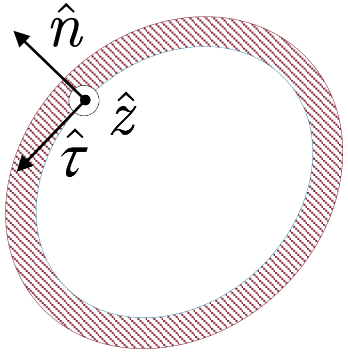
- Molybdenum oxide coatings
  - Molybdenum oxide films on copper [8] proposed to push the limits of next gen. of high brightness sources as:
    - Hardness ($H_{MoO_3} \sim 1.32$ - $1.47\,\mathrm{GPa}$) is comparable with Cu ($H_{CuO} \sim 1.43\,\mathrm{GPa}$).
    - Work function greater than Cu ($\Phi_{MoO_3} - \Phi_{Cu} \approx 1.8\,\mathrm{eV}$).
  - MoO3-on-Cu films of thickness 30-300 nm showing metallic behavior while performing at wide range of resistivities motivates **the study of the impact of the coating and its variability on the cavity performance**.

[8] S. Macis *et al.*, *Journal of Vacuum Science & Technology A* **37**, 021513 (2019)

Analysis : Electromagnetics

- RF accelerating cavities
  - Axially (z) symmetric TM (acc. mode) .
  - Perturbation theory predicts little corrections on Dirichlet BVP when the mode is held in bulk (good) conductors [9].
  - In coated conductors, the mode remains unchanged as long as $|Z_{\text{eff}}| \sim |Z_{s,\text{cond}}|$ (our hypothesis to be checked) .





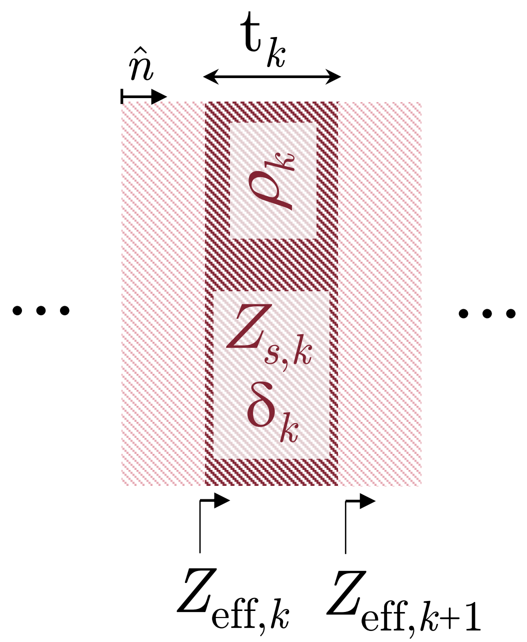
[9] J.D. Jackson, *Classical Electrodynamics* (1962)

Analysis : Electromagnetics

- Effective surface impedance, Z_{eff}
  - Multilayered conductors : wave impedance (imp. and refl.) :

$$Z_{\text{eff},k} = Z_{s,k}\,\frac{Z_{\text{eff},k+1} + Z_{s,k}\tanh[(1+\mathrm{i})t_k/\delta_k]}{Z_{s,k} + Z_{\text{eff},k+1}\tanh[(1+\mathrm{i})t_k/\delta_k]}\ ;$$

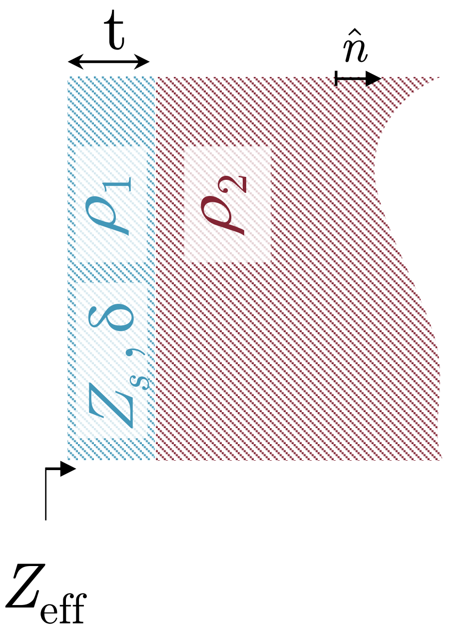
with $\delta_k \simeq \left[\frac{2\rho_k}{\omega\mu_0}\right]^{\frac{1}{2}},\ Z_{s,k} \simeq (1+\mathrm{i})\left[\frac{\omega\mu_0\rho_k}{2}\right]^{\frac{1}{2}}.$



Analysis : Parametrization

- Effective surface impedance, Z_{eff}
  - In particular, a metallic layer ($Z_{s,1}$) with finite thickness ($\mathrm{t} \equiv \mathrm{t}_1$) deposited on a bulk substrate :

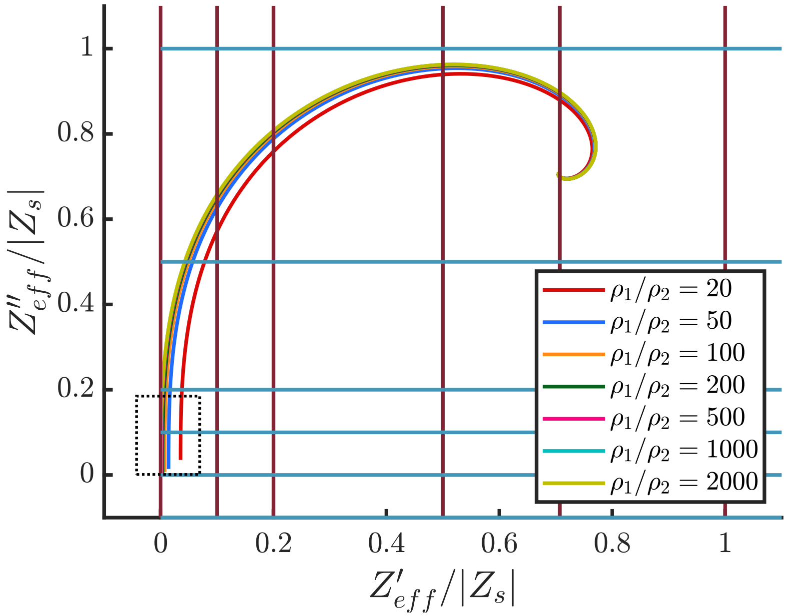
$$\frac{Z_{\mathrm{eff}}}{|Z_s|} \equiv \frac{Z_{\mathrm{eff},1}}{|Z_{s,1}|} = e^{\mathrm{i}\frac{\pi}{4}} \frac{1 + \left[\frac{\rho_1}{\rho_2}\right]^{\frac{1}{2}} \tanh\left[(1+\mathrm{i})\frac{\mathrm{t}}{\delta}\right]}{\left[\frac{\rho_1}{\rho_2}\right]^{\frac{1}{2}} + \tanh\left[(1+\mathrm{i})\frac{\mathrm{t}}{\delta}\right]} .$$

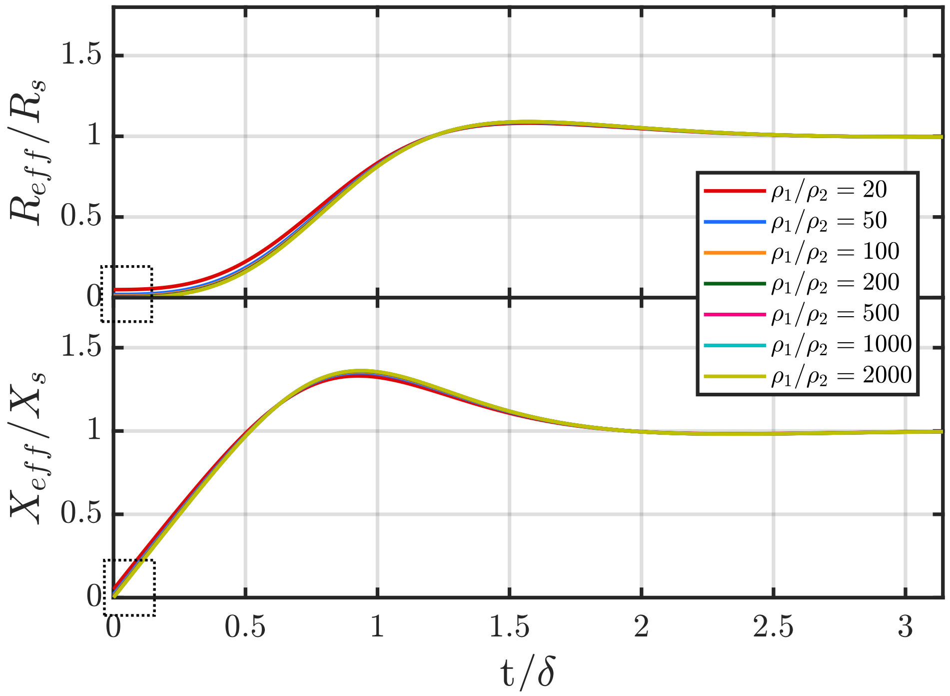


Parameterizations : $\frac{\rho_1}{\rho_2}, \frac{\mathrm{t}}{\delta}$.

Analysis : Parametrization

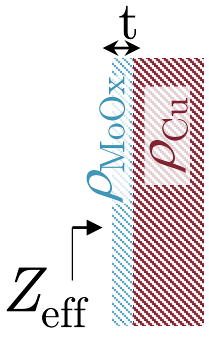
- Effective surface impedance, Z_{eff}
  - Chance : $R_{\text{eff}}/R_s \to 0$, as $t/\delta \ll 1$ and $\rho_1/\rho_2 \gg 1$!





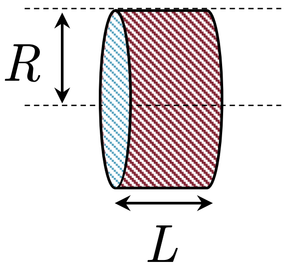
Analysis: Case study

- Molybdenum oxides (MoO_x) deposited on Cu [8]:
  - $20 \lesssim \rho_{MoOx}/\rho_{Cu} \lesssim 2000$;
  - $t_{min} \sim 30$ nm ($10^{-3}\delta \lesssim t_{min} \lesssim 10^{-2}\delta$ @10GHz).



- Pill-box cavity [9]:
  - TM_{010}: $G \equiv G_{010} \approx 258\,\Omega$ ($\beta = 1$);
  - $f_0 = \{11; 36\}^*$ GHz, $R \approx \{10.43; 3.188\}$ mm, $L \approx \{13.63; 4.164\}$ mm.

- Parameters [9]:
  - $Q_0 \equiv \dfrac{G}{R_{eff}}$; • $\dfrac{|\Delta f_0|}{f_0} = \dfrac{f_0 - f_{0,PEC}}{f_0} \equiv \dfrac{X_{eff}}{2G}$.

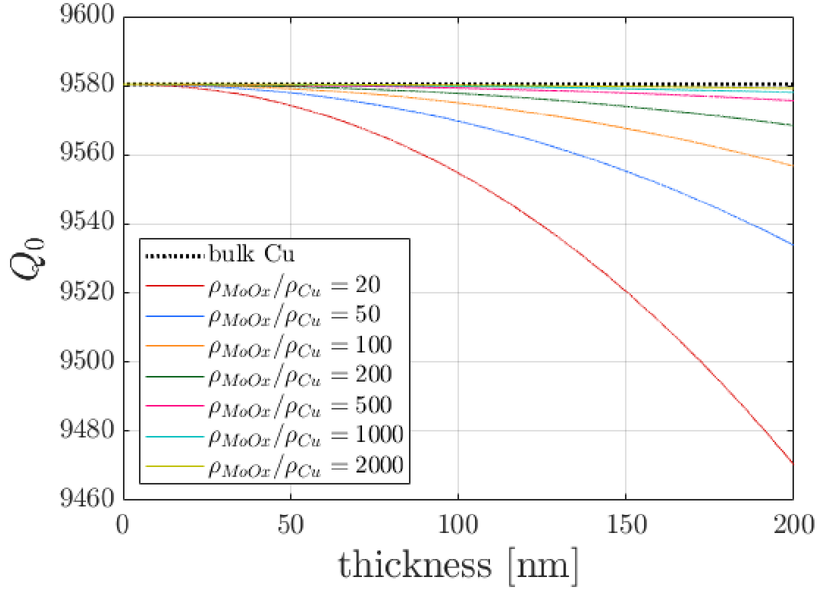


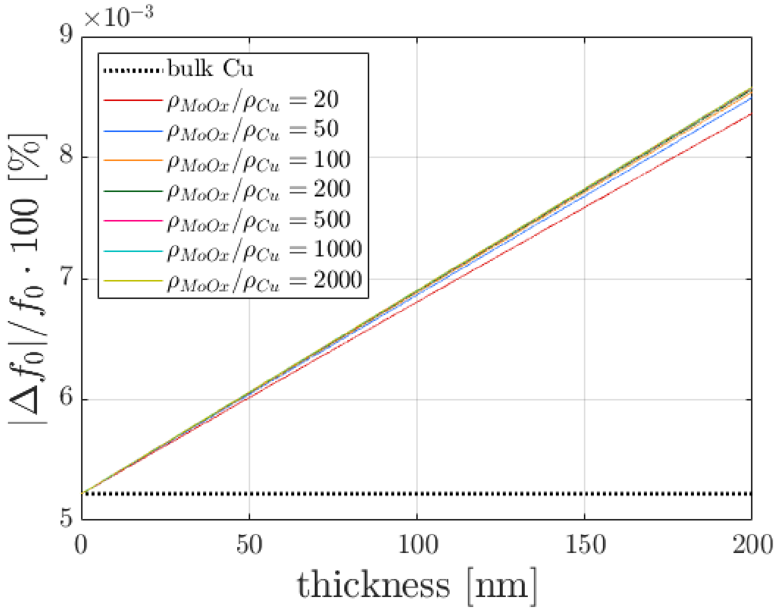
* Cryo-Cu-SLAC- #2 [3] : $f_0 \approx 11.43$ GHz
Compact Light XLS project Ka-band e-gun [7] : $f_0 \approx 36$ GHz

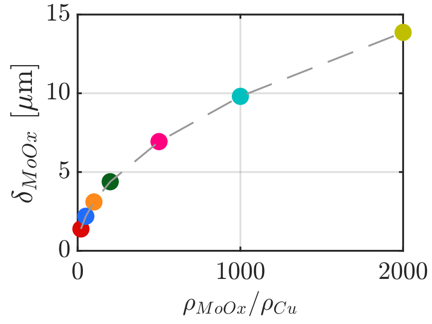
Analysis : Case study

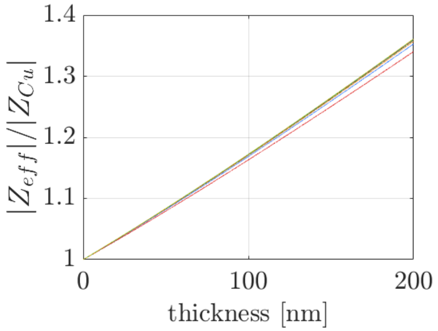
❖ Pill-box cavity at $f_0 = 11\,\mathrm{GHz}$:

- ❑ Low sensitivity to inhomogeneities of both t and ρ_{MoOx} ;
- ❑ $\uparrow \rho_{\mathrm{MoOx}}/\rho_{\mathrm{Cu}} \Rightarrow \uparrow Q_0$ (homogeneous), $|\Delta f_0|/f_0$ practically invariant .



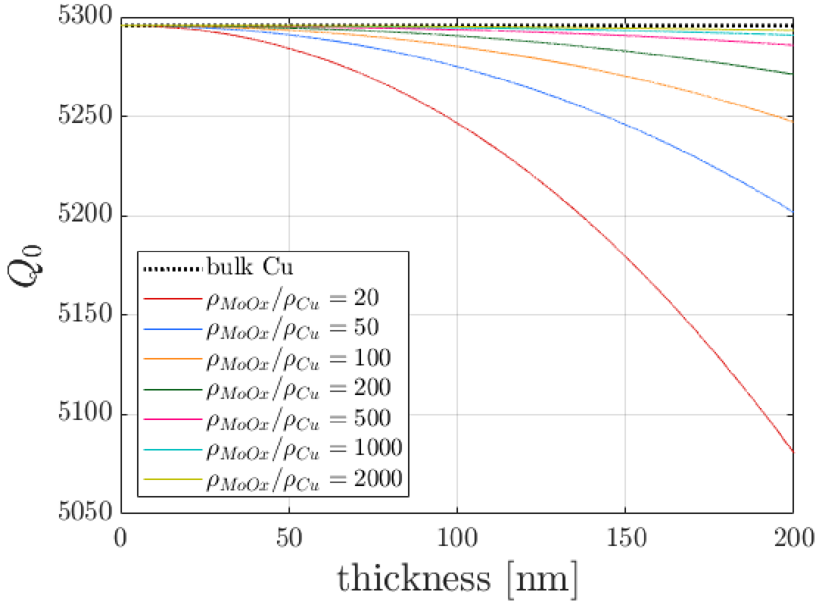


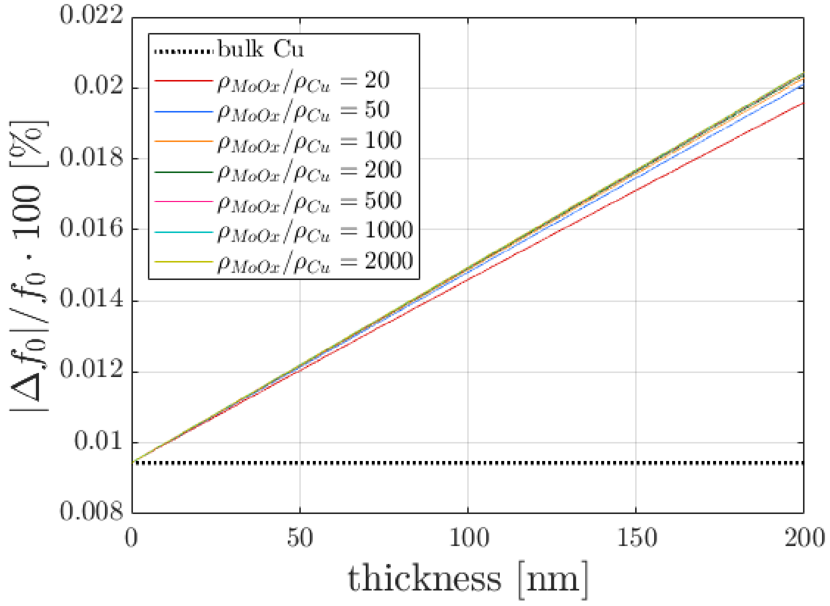


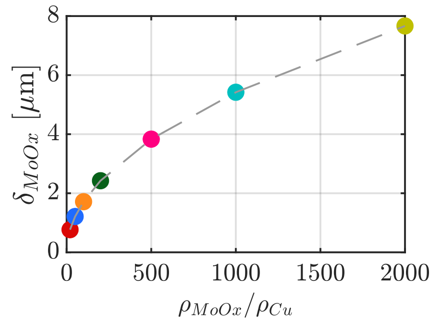


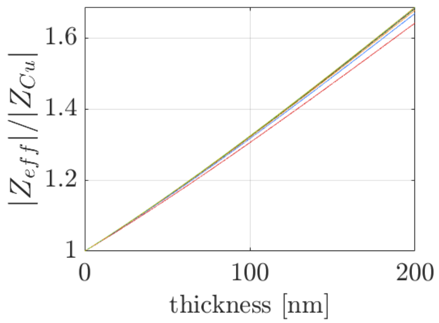
Analysis : Case study

- ❖ Pill-box cavity at $f_0 = 36\,\text{GHz}$:
  - ❑ At higher frequencies, the MoO_x film is relatively less robust against inhomog. Nevertheless, $\uparrow \rho_{MoOx}/\rho_{Cu}$ still mitigates them.



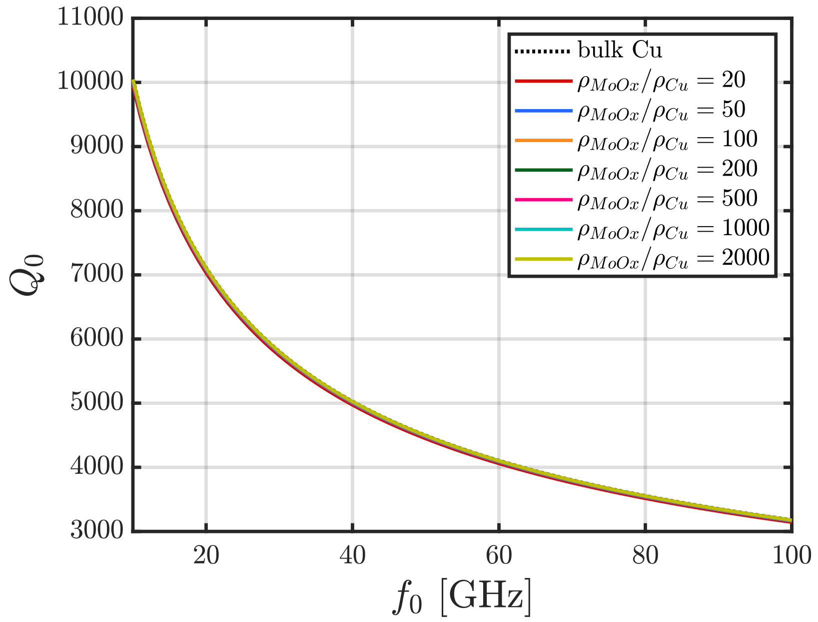


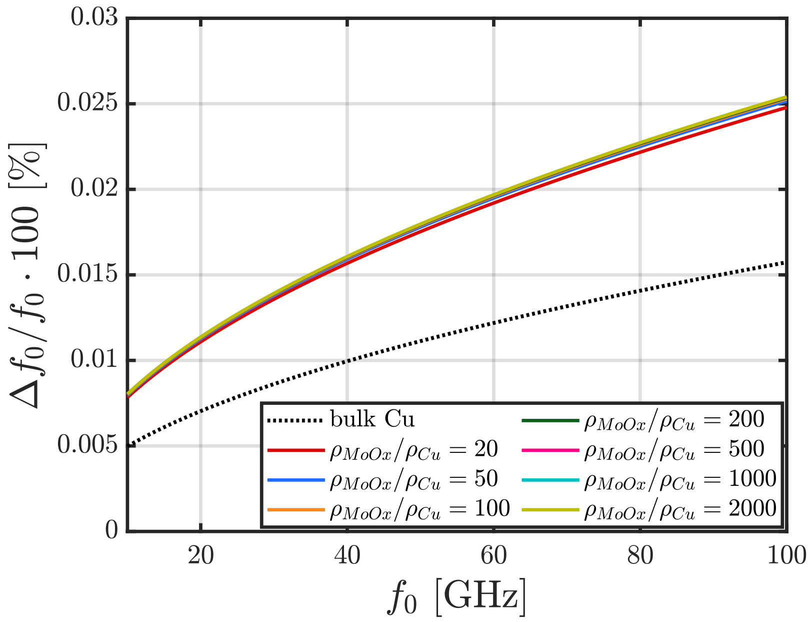




Analysis: Case study

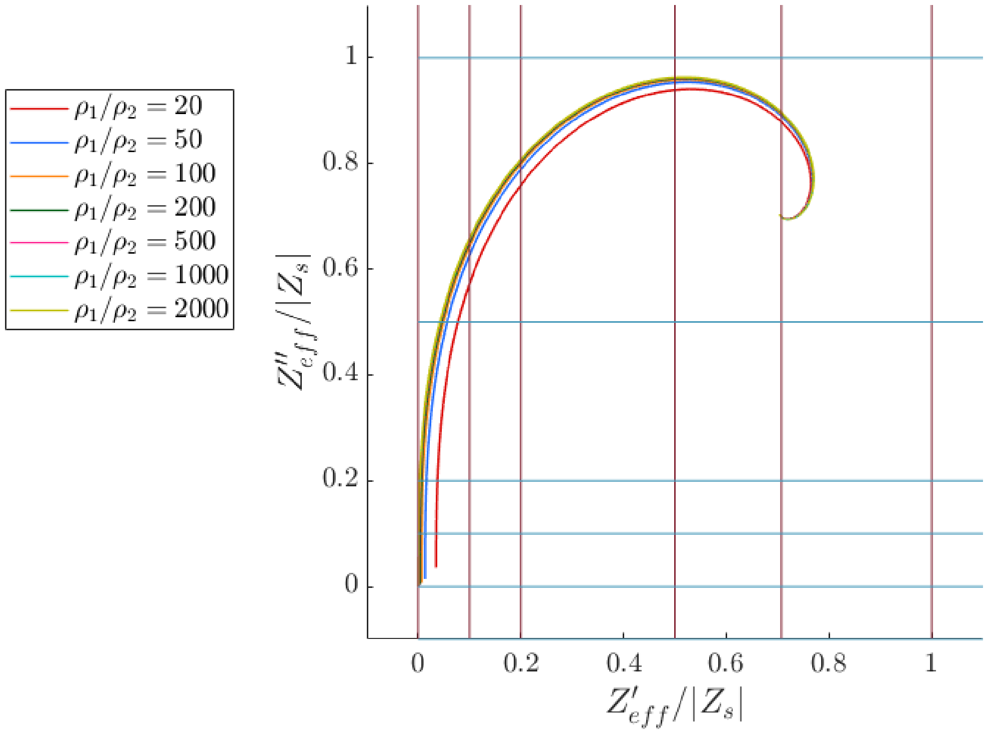
- Pill-box cavity with t = 200 nm:
  - The coating performs close to the bulk at even higher freq.

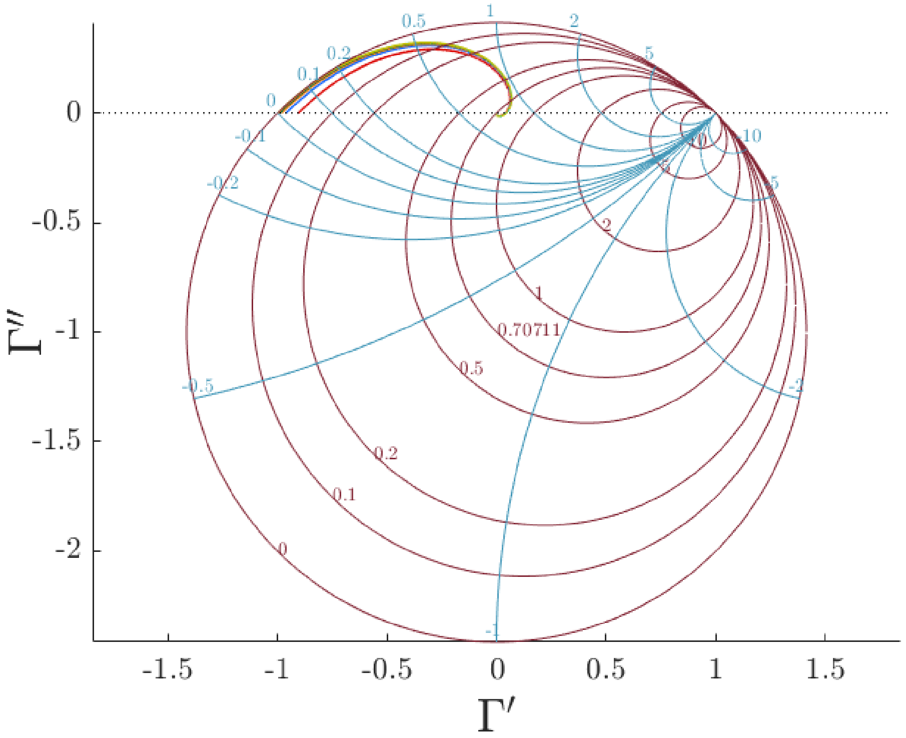




Analysis : Generalization

- Effective surface impedance, Z_{eff}
  - $\left[\frac{R_{\text{eff}}}{|Z_s|}, \frac{X_{\text{eff}}}{|Z_s|}\right] \leftrightarrow \Gamma[\mathrm{t}/\delta; \rho_1/\rho_2]$.





Analysis : Generalization

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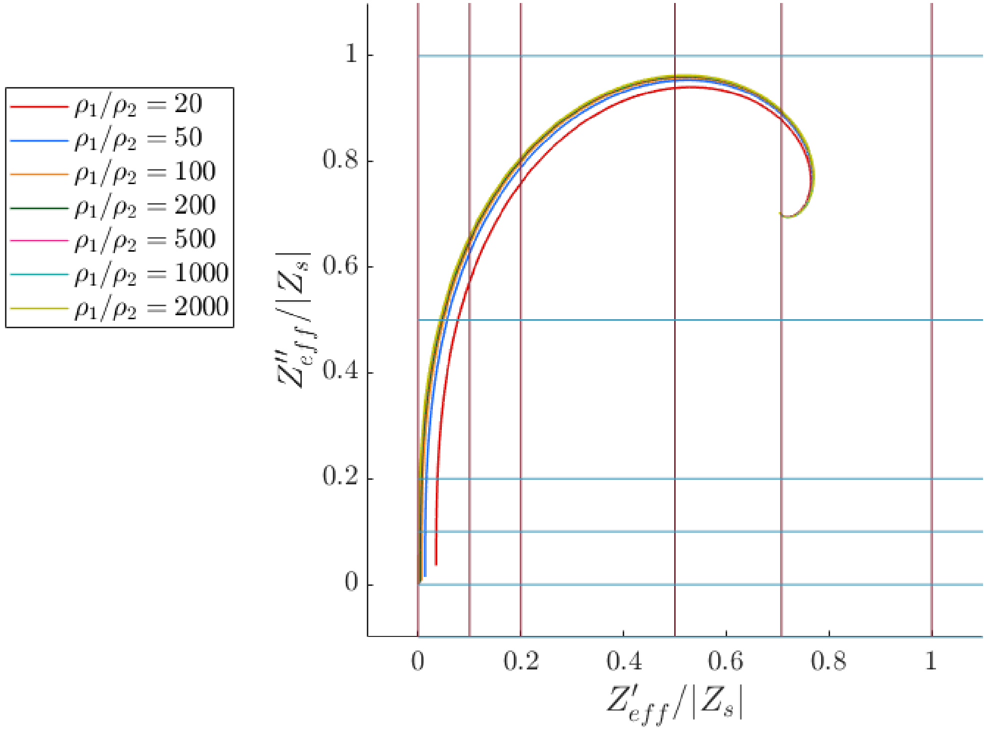

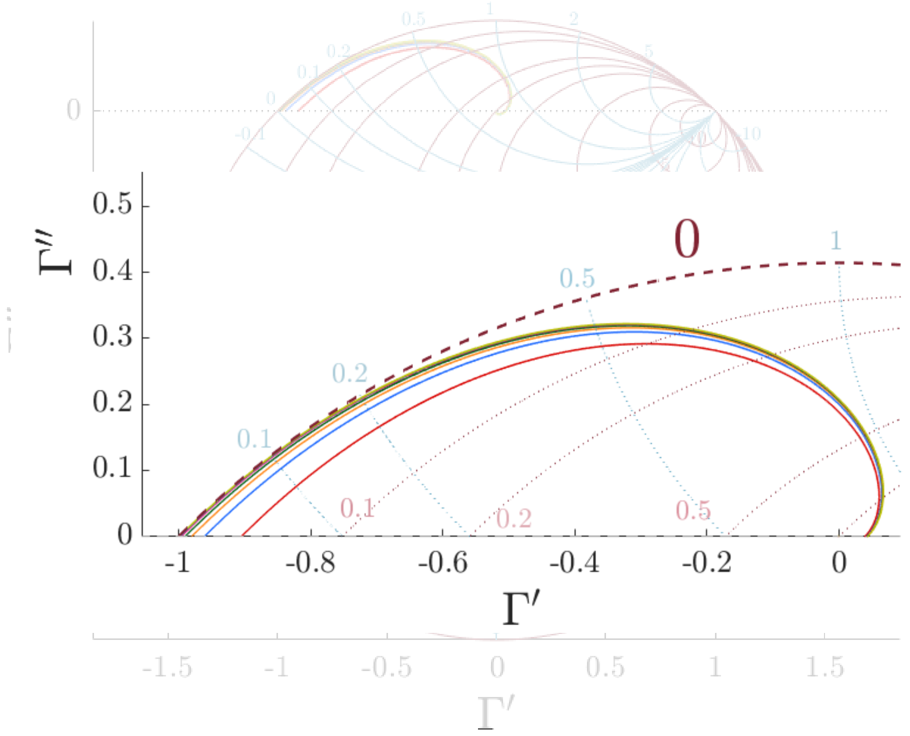

Analysis : Generalization

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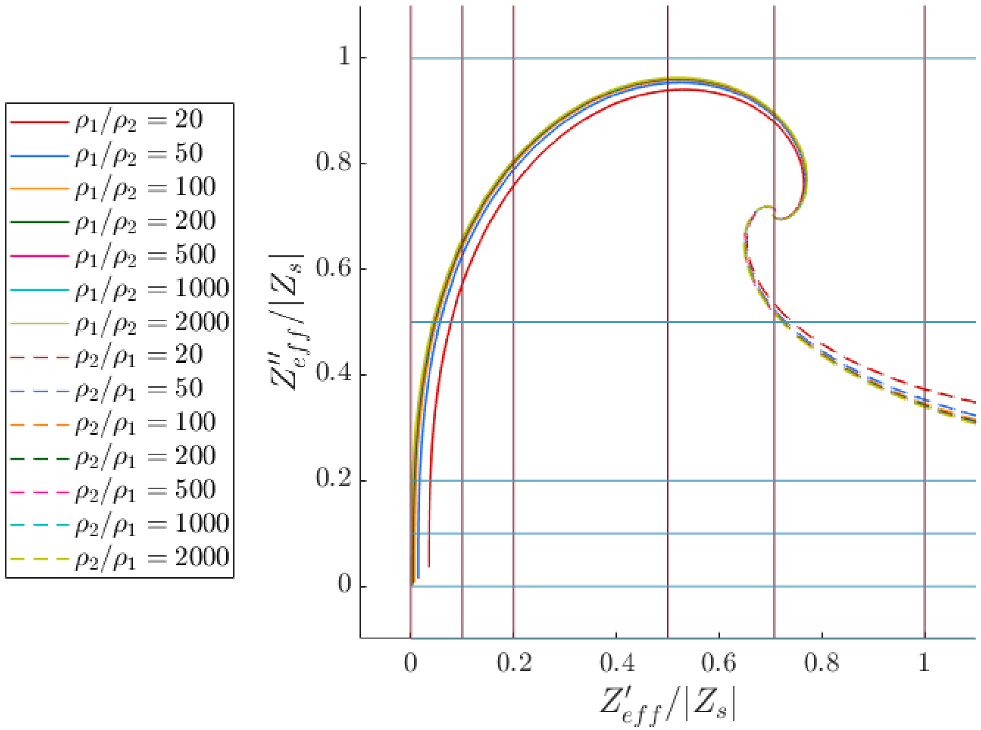

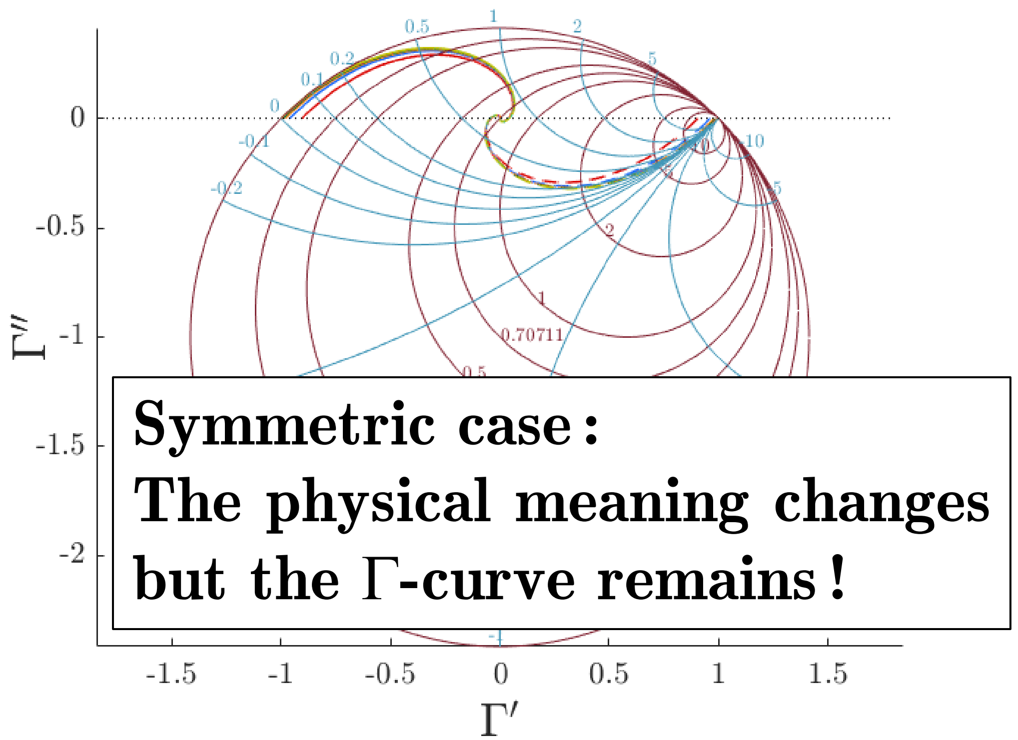

Symmetric case :
The physical meaning changes but the Γ-curve remains !

Wrap-up

- Summary
  - We checked the effect of MoO_3 coatings on the main cavity parameters (quality factor and frequency shifting) is negligible throughout a wide range of film thicknesses, conductivities and frequencies .
  - We indeed see that the highest resistivities of metallic MoO_3 coatings mitigate the Q_0 drop caused by possible inhomogeneities of thickness .

Wrap-up

- Conclusions
  - MoO_3 coatings result appropriate for the purpose of reducing dark currents due to its intrinsic higher work function while keeping unvaried the RF properties of the accelerating cavities used to produce high brightness beams.
  - We point out the generalized character of this study for the RF characterization of a wide range of metals, as well as its potential usefulness in analyzing multilayer hybrid structures.

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SAPIENZA UNIVERSITÀ DI ROMA

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Analysis : Electromagnetics

- RF accelerating cavities
  - Axially (z) symmetric TM (acc. mode) :
    - Dirichlet 2D–BVP : $E_{z,0} \equiv \Phi_0$, $\Phi_0[\mathbf{t} \in \partial S] = 0$;
      - $\boldsymbol{E}_{t,0} \propto \nabla_t \Phi_0$, $\boldsymbol{H}_{t,0} := Z_{mode}^{-1} [\hat{z} \times \boldsymbol{E}_{t,0}]$, $Z_{mode} = k(\omega \varepsilon_0)^{-1}$.
  - Perturbation : $\Phi \approx \Phi_0 + \varepsilon \Phi_1$.
    - In bulk good conductors with smooth surfaces [8] : $\Phi_1 \sim \Phi_0$; and $\varepsilon \equiv |Z_s| / Z_{mode}$. Thus, $\Phi \sim \Phi_0$ as long as $\varepsilon \ll 1$.
    - In deposited conductors : $|Z_{\text{eff}}| / Z_{mode} \ll 1$.
    - Thus, as long as $|Z_{\text{eff}}| \sim |Z_{\text{metal}}|$, Φ unperturbed .

[9] J.D. Jackson, *Classical Electrodynamics* (1962)