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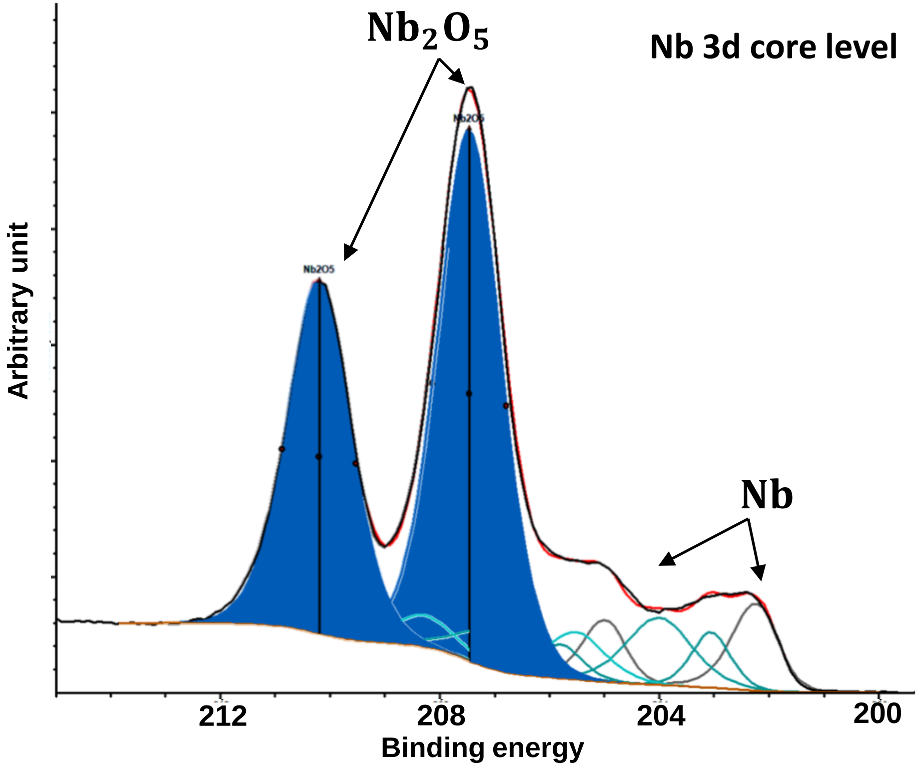
# Interstitial oxygen tailoring by various surface treatments and how it impacts $Q_0$

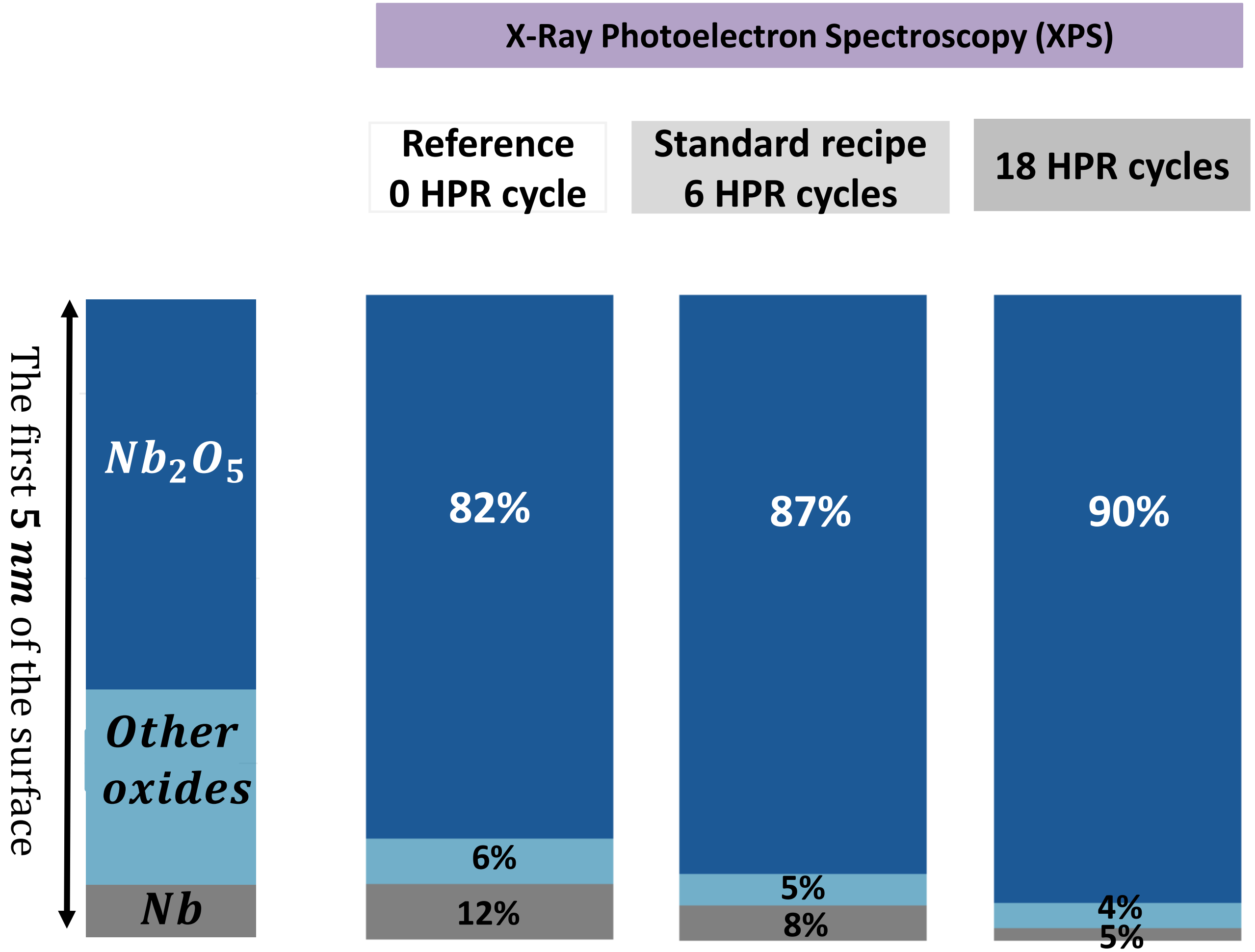
Rezvan Ghanbari, Marc Wenskat – on behalf of the UHH SRF R&D Team

# Extensive HPR

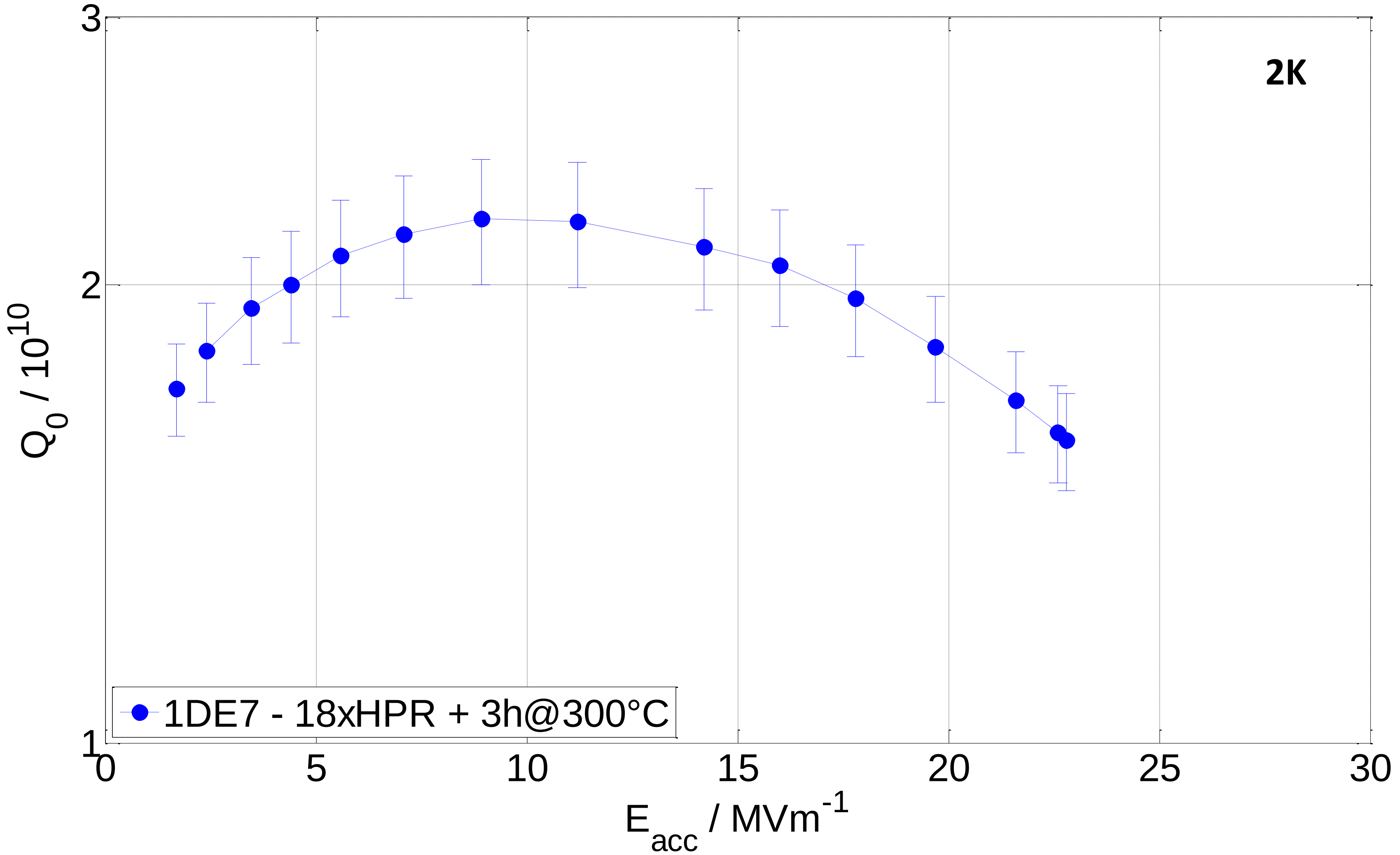
[Ghanbari, R. TTC Workshop 2022, Aomori]

$$\frac{\text{component doublet peaks area}}{\text{total Nb 3d peak area}}$$

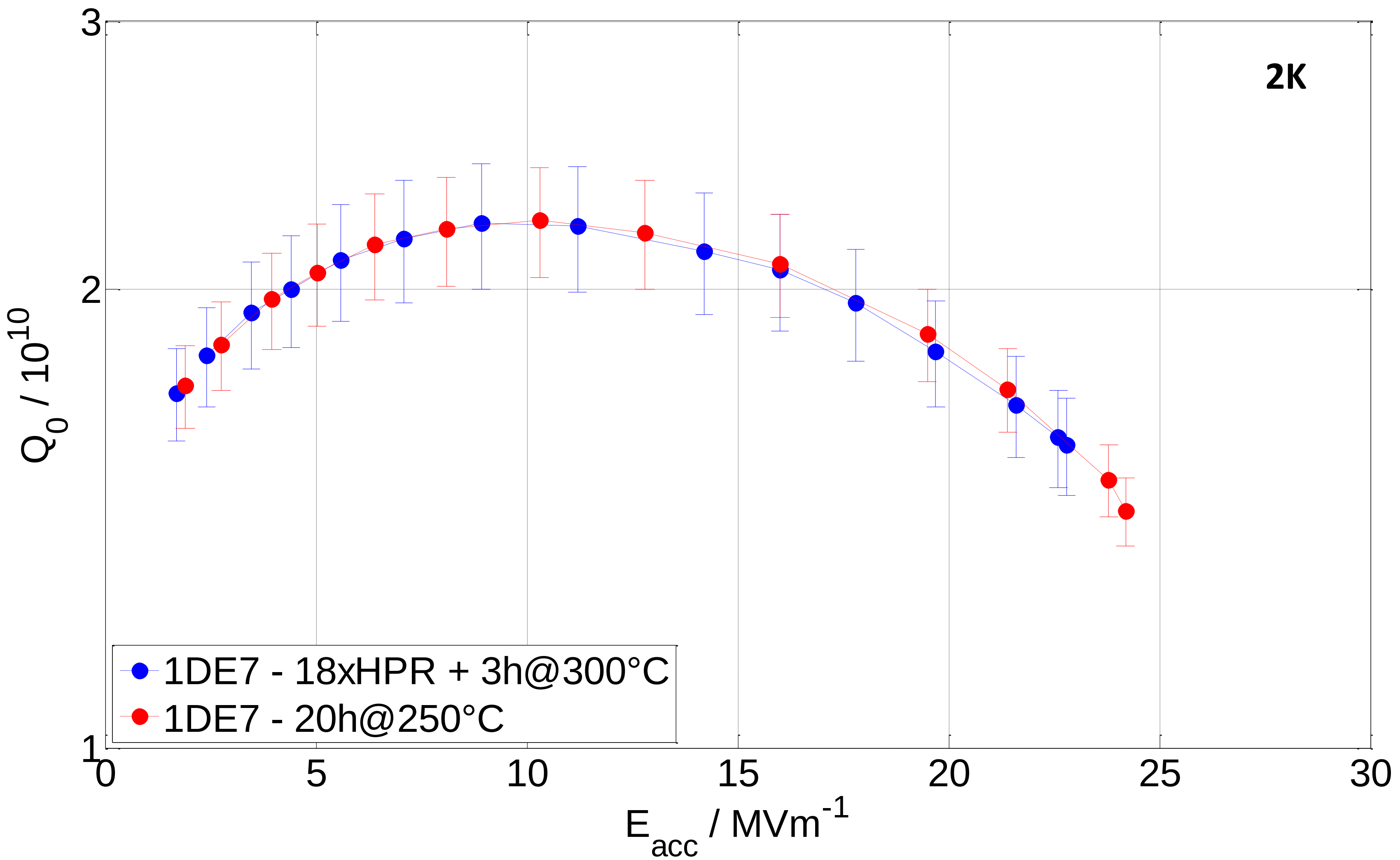


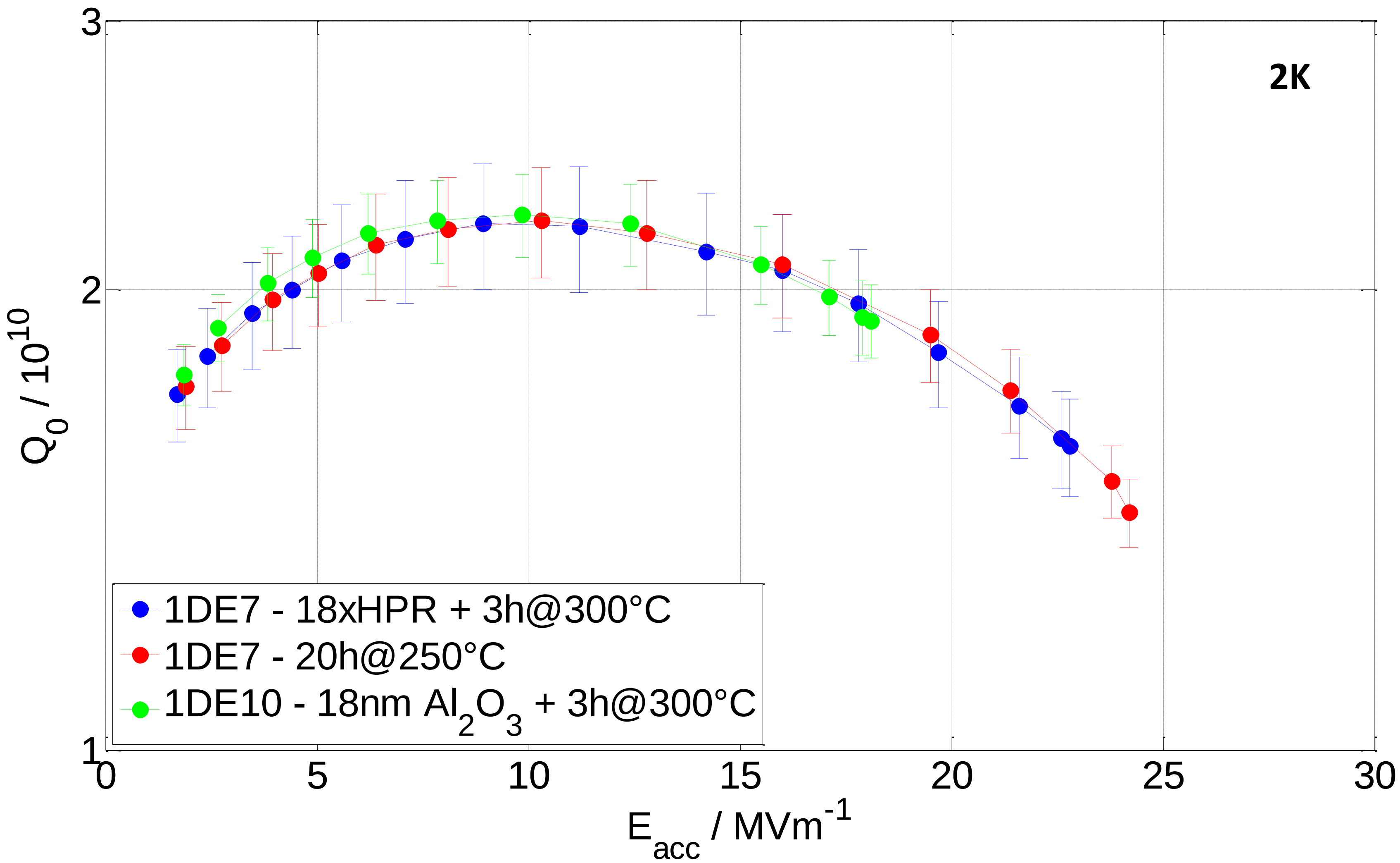
# 18x HPR is not beneficial for $Q_0$



# Different treatments – same rf behaviour

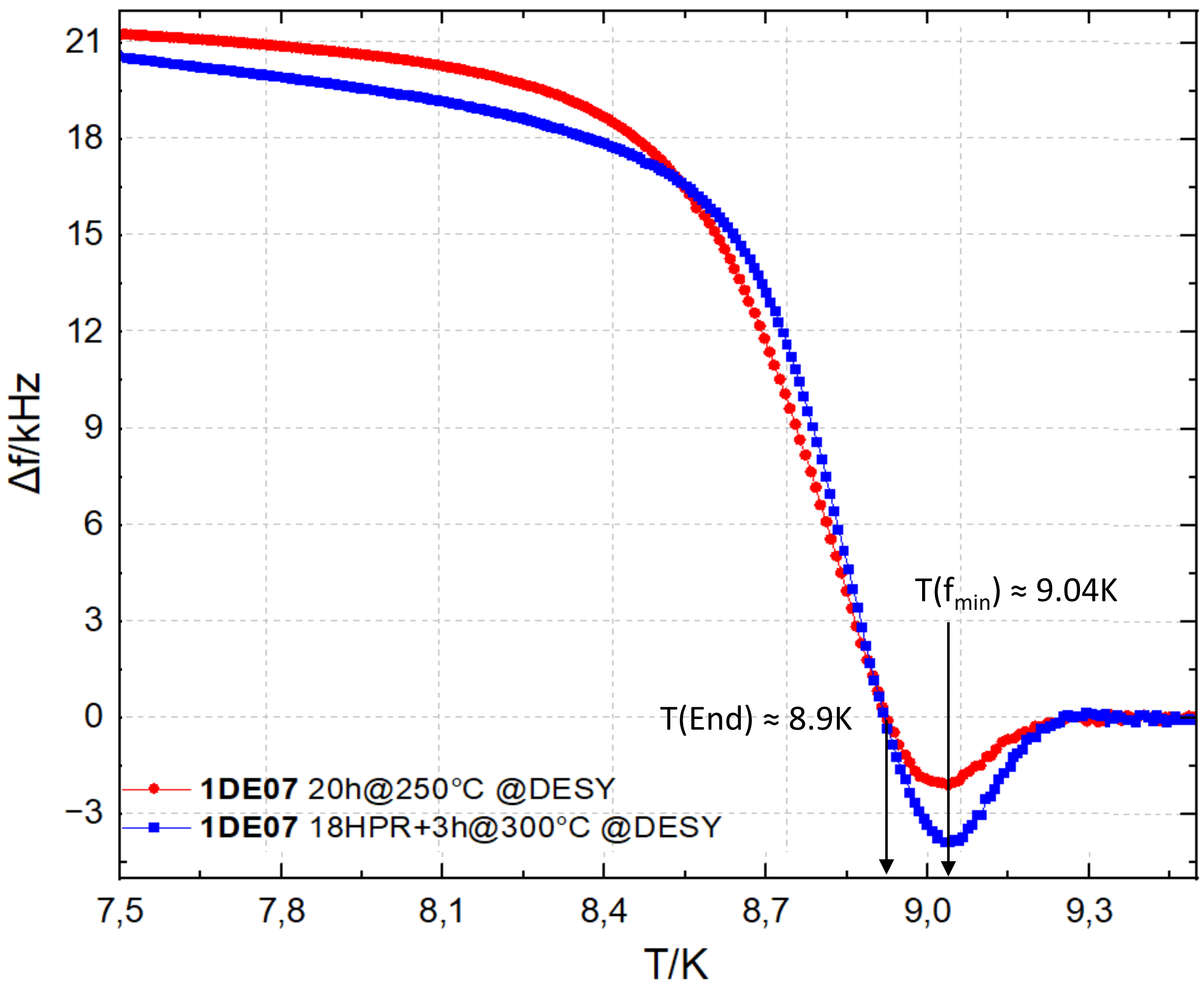


# It's not the cavity!



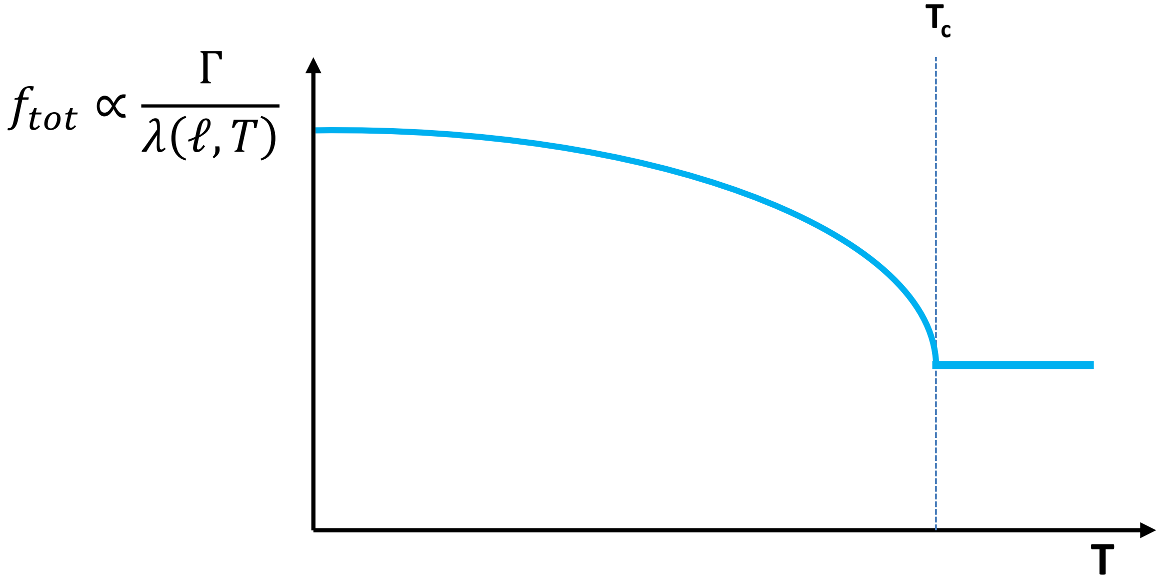

20µm EP between black and red
40µm EP between red and blue

# Dip is deeper for 18xHPR – $\Delta f_{tot}$ similar




| Cavity | Treatment | $\Delta f_{dip}$/kHz |
|---|---|---|
| 1DE19 | 4.5h @ 335°C | 1.1 |
| 1AC02 | 3.25h @ 335°C | 1.4 |
| 1RI04 | 3h @ 250°C | 0.9 |
| 1DE07 | 20h @ 250°C | 2.0 |
| 1DE79 | 18xHPR + 3h @ 300°C | 3.9 |

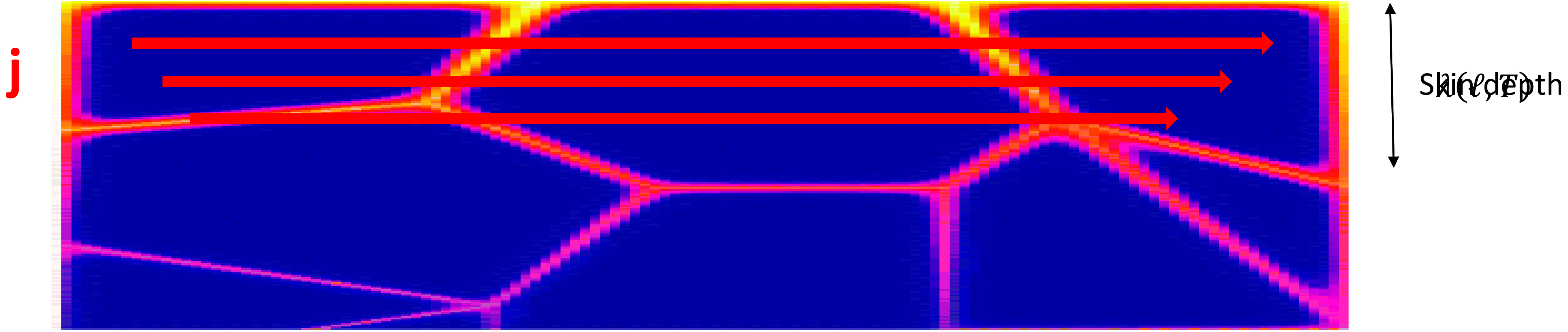
# What information is encoded in f vs. T?




- Frequency shift is sensitive to interstitial concentration

$$\lambda(\ell,T) = \lambda_L(T)\sqrt{1+\frac{\xi_0}{\ell}}$$ (equation valid for dirty limit)

- $\Delta f_{tot}$ for EXFEL type cavities is typcially 5-6 kHz
- Mid-T: more interstitials → larger Δf, but yet no dip



# Microscopic model for disordered superconductor

- An increased oxygen concentration reduces $T_c$ of Nb by 0.93K per 1 at.% [Desorbo, W. *Phys. Rev.* 132 (1963): 107.]

  - to have a dip minimum at 9.1K we would need ≈ 0.2 at.%
  - „end of dip“ around 8.9K ≈ 0.3 at.%

- Solubility limit of O in Nb is 1 at.% @ 500°C and 0.33 at.% at 145°C [Benvenuti, C., et al. 10th *SRF* (2001): p441.] [Kolchin, O.P., et al. *Soviet Atomic Energy 45 (4) (1978): p999*.]

- We have shown that C diffusion speed in Nb along GB vary with GB orientation, increasing disorder by spatially varying concentration [Dangwal Pandey, A., et al. *Appl. Phys. Lett. 119(2021): 194102*]

  → Assume same is true for O: not homogenous distributed within the rf layer, but clusters with uneven O-concentration

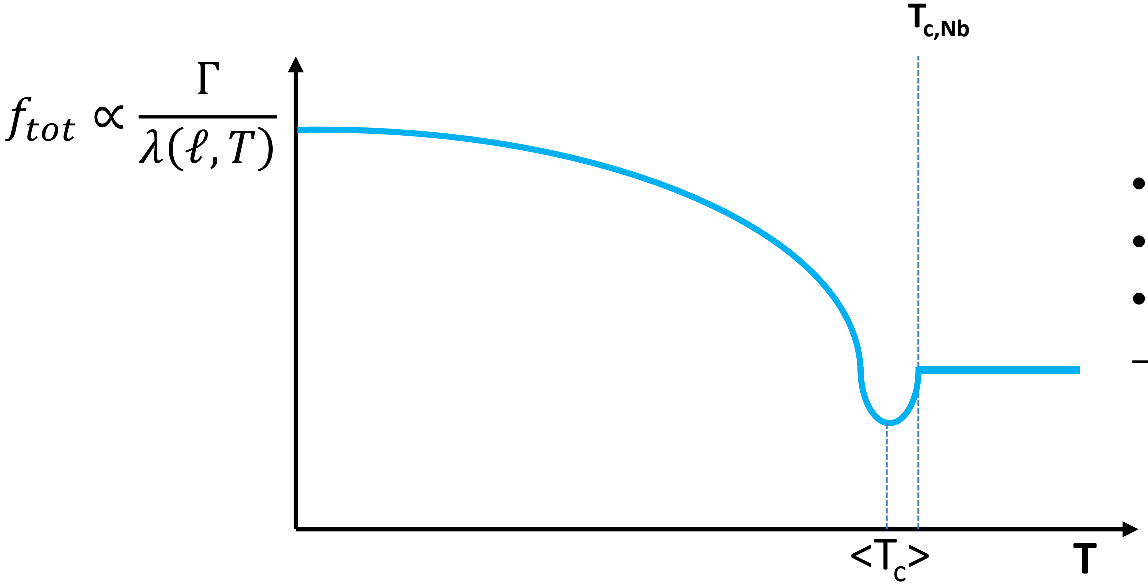
→ Expect non-constant (gaussian shaped) $T_c$ reduction

→ Lowest $T_c$ equal to the max. at.% concentration at RT (≈ 0.33 at.%)

→ Only locally saturated – not globally. If SIMS spot size ≈ multiple grains, obtained $c_O$ below saturation limit

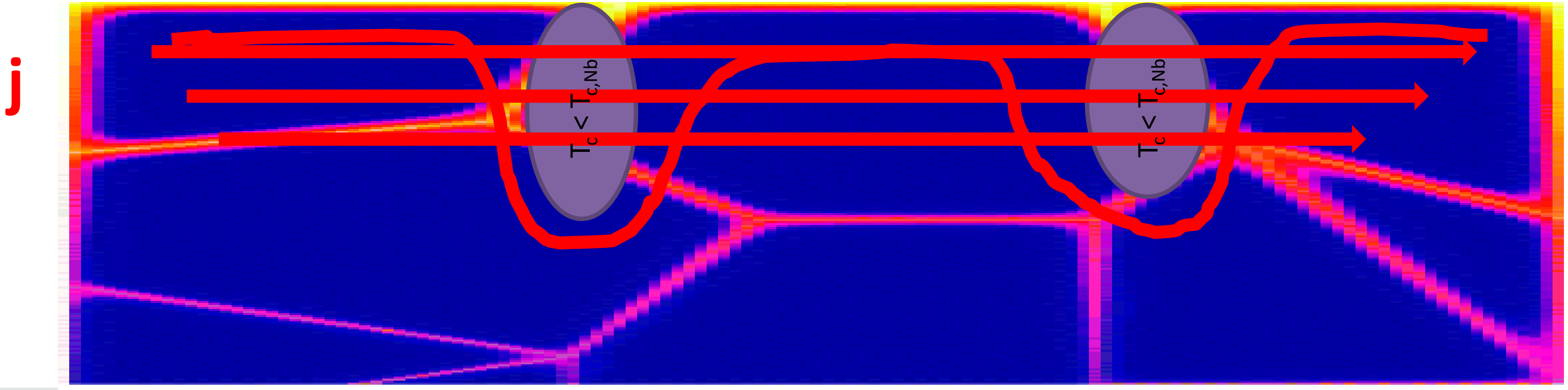
# Disordered superconductor show dip

[Barra, M., et al. *SUST* 18.3 (2005): 271.]

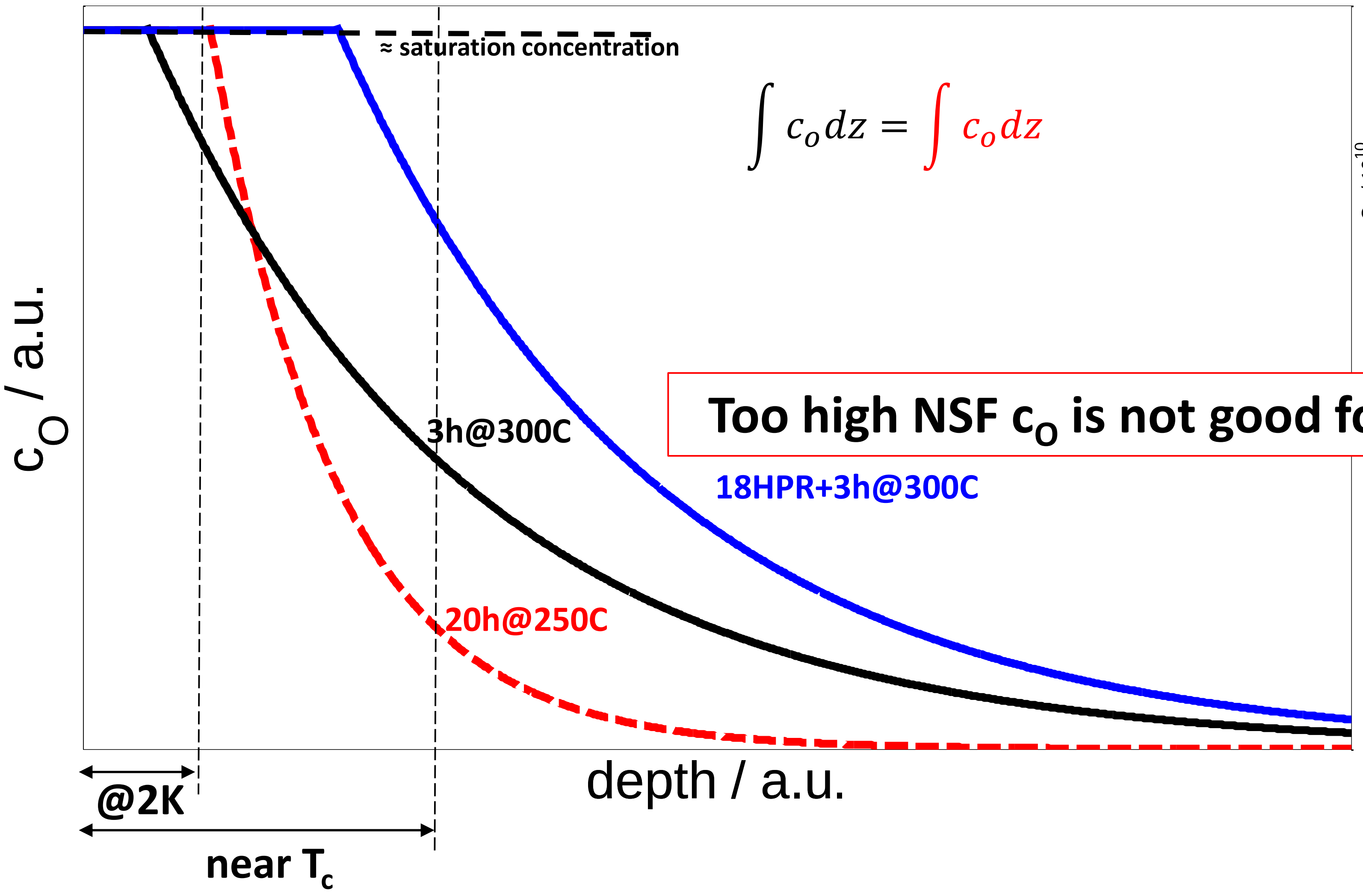


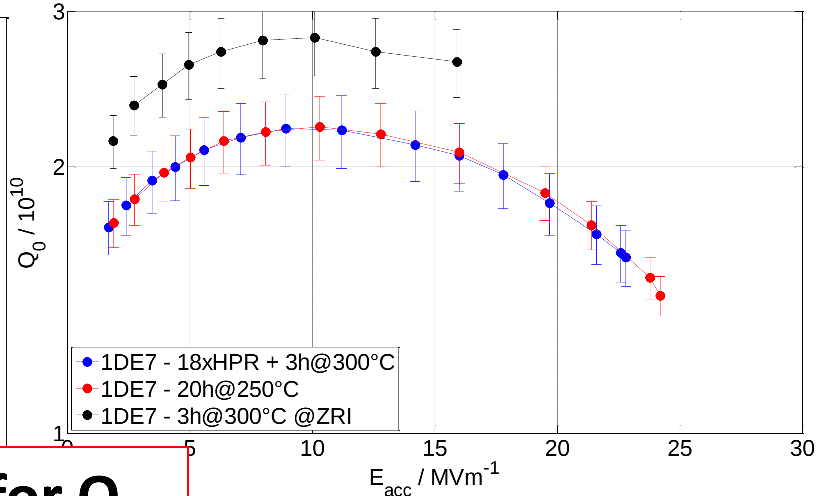

- Mathematically speaking, the geomtery constant Γ is not constant
- Dip properties ∝ cluster distribution causing current redistribution
- Observed: Q vs. T still increases at 9.27K

→ Dip caused by clusters and not homogenous O-enriched Nb-layer

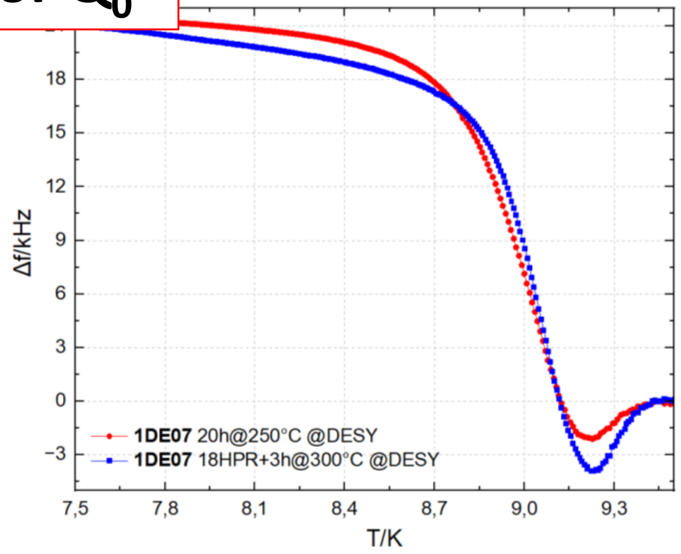


# If it acts the same – is it the same?



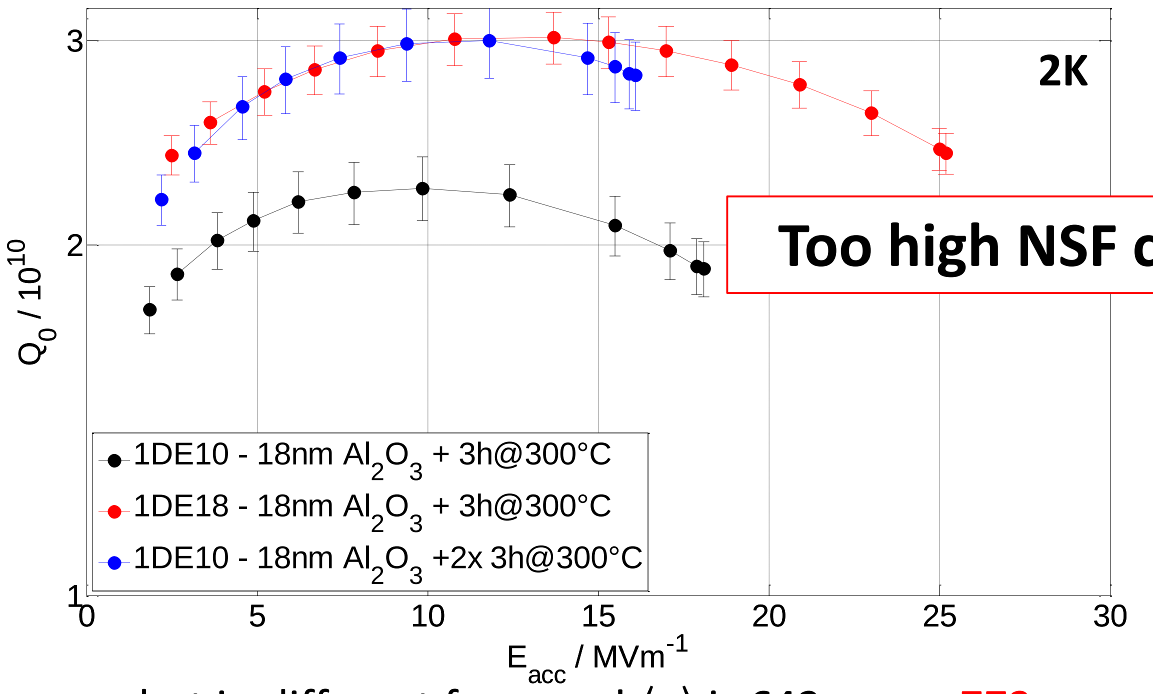

**Too high NSF $c_O$ is not good for $Q_0$**

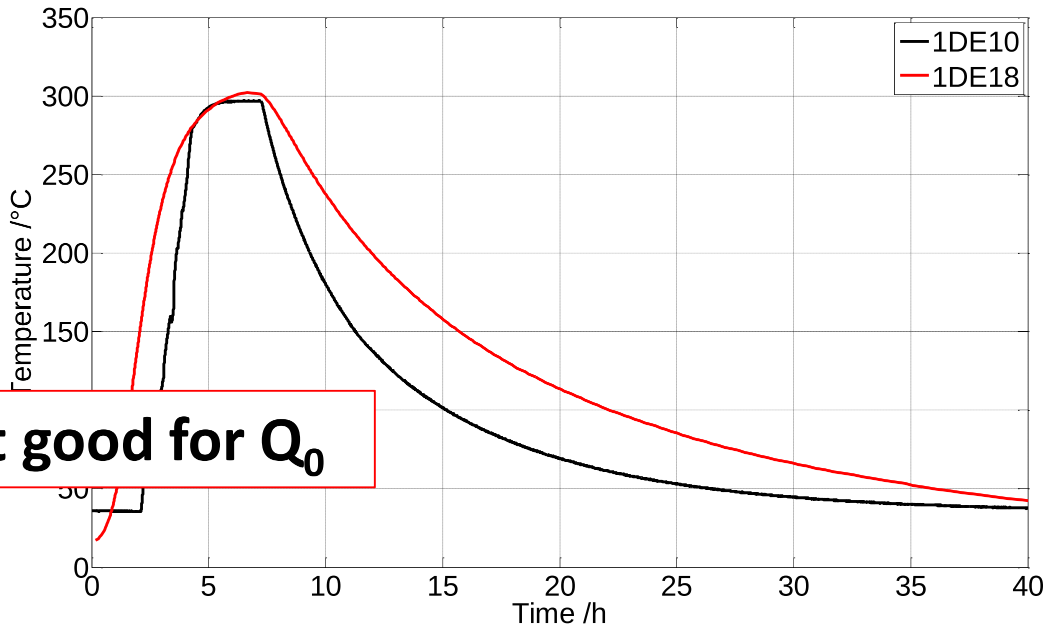


# 3h@300°C ≠ 3h@300°C

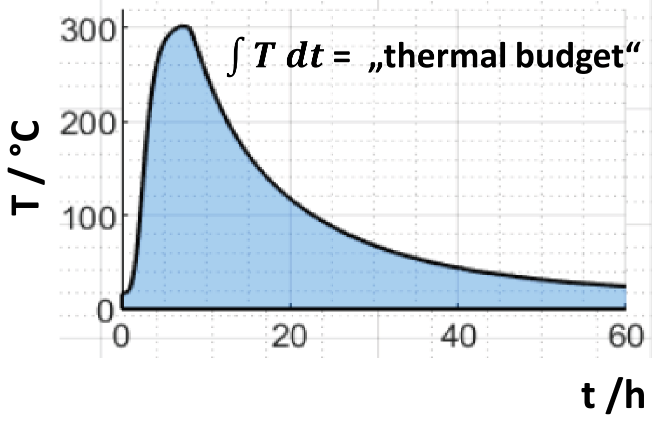
[Wenskat, M., et al SRF2023 TUIBA02.]
[Wenskat, M., et al Supercond. Sci. Technol. 36 (2023) 015010 (11pp).]

- 1DE18 and 1DE10 performed similar before and after coating
- Coating was done with same parameters
- Both cavities underwent 3h@300°C …



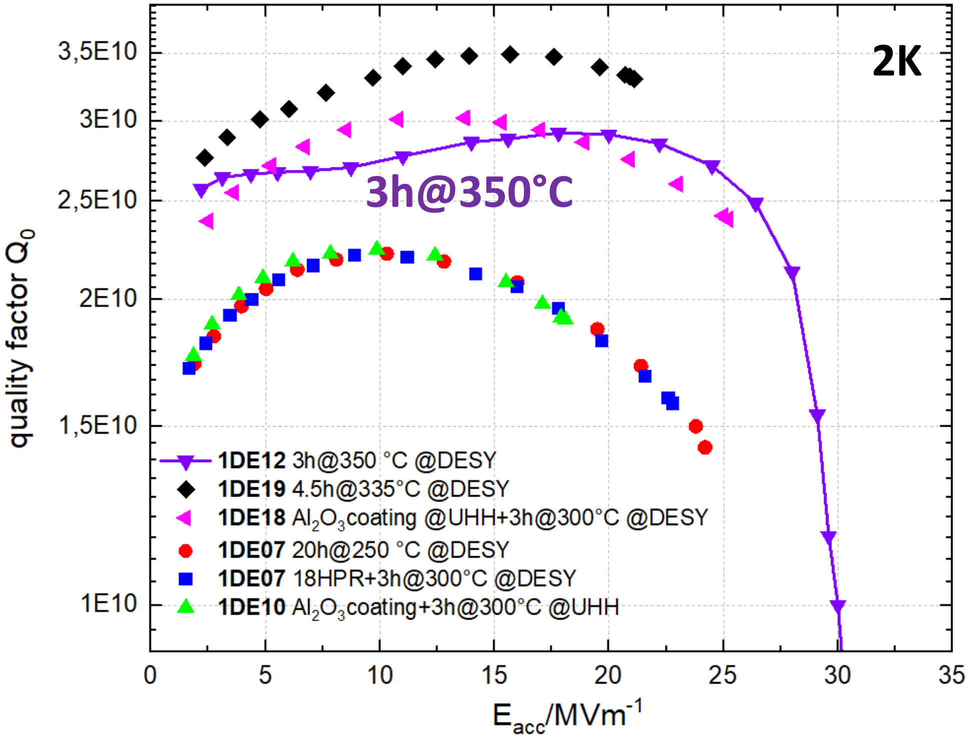



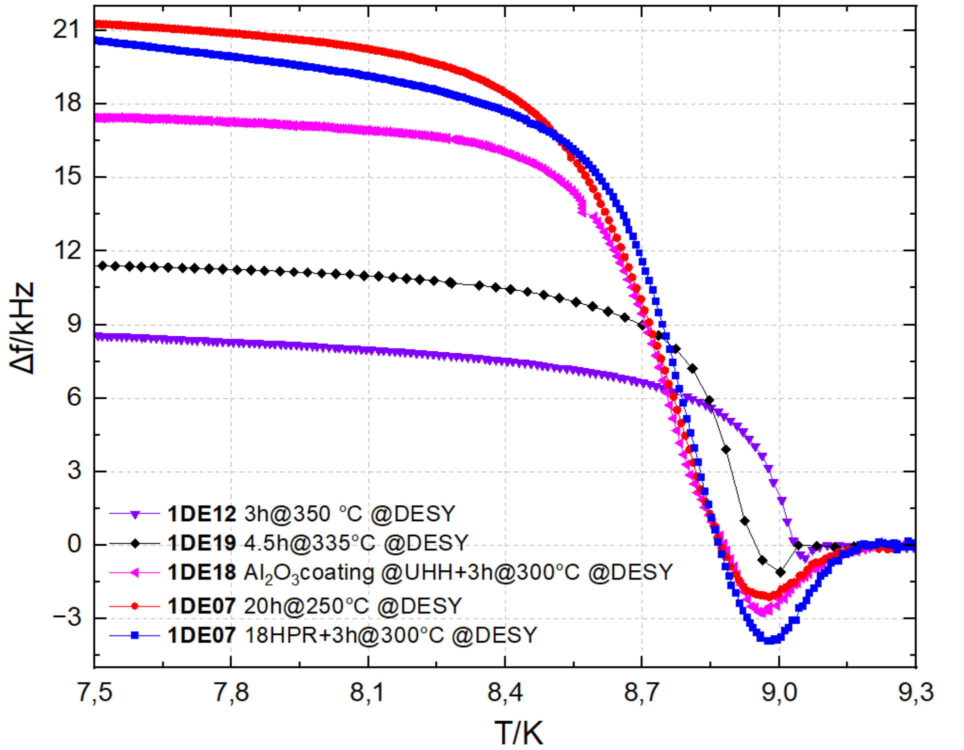

**Too high NSF $c_O$ is not good for $Q_0$**




- … but in different furnaces! $\langle z \rangle$ is 642nm vs. 773nm
- Since both cavities are coated, no Nb-oxide regrowth
- Annealed 1DE10 a second time to diffuse more O away from SF w/o source on top
  → **$Q_0$ improved**

# High thermal budget



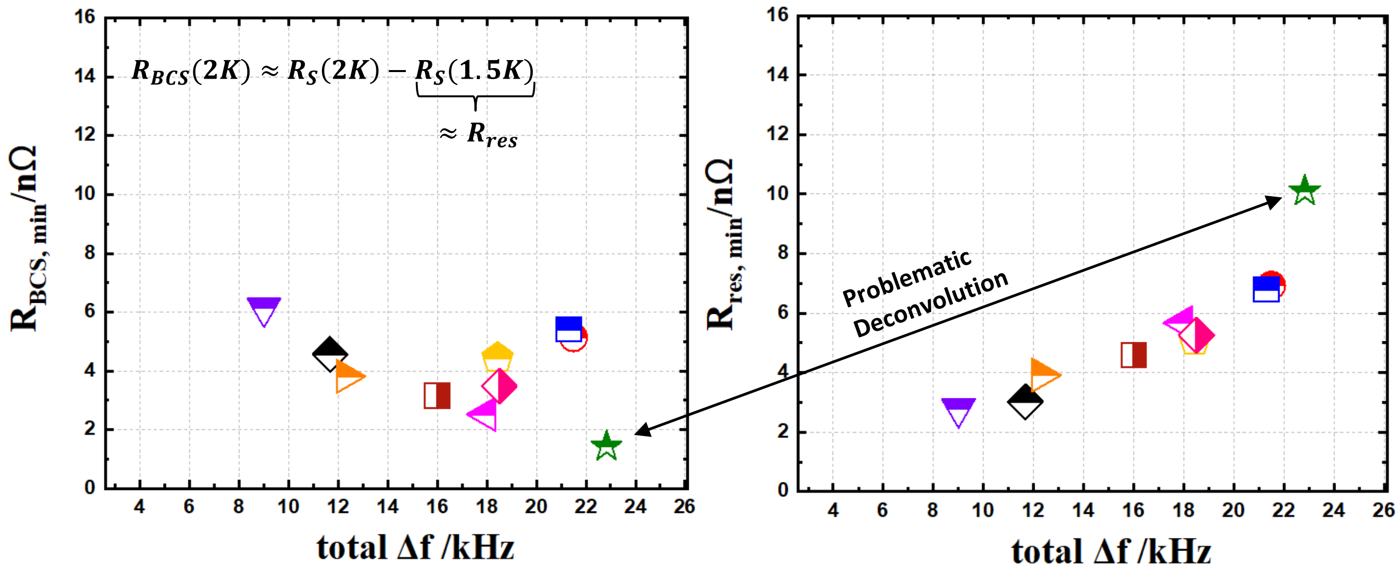

| Cavity | Treatment | $\Delta f_{tot}$/kHz | $\Delta f_{dip}$/kHz |
|---|---|---|---|
| 1DE19 | 4.5h @ 335°C | 11.7 | 1.1 |
| 1AC02 | 3.25h @ 335°C | 12.3 | 1.4 |
| 1RI04 | 3h @ 250°C | 18.4 | 0.9 |
| **1DE12** | **3h @350°C** | **8.3** | **0.52** |

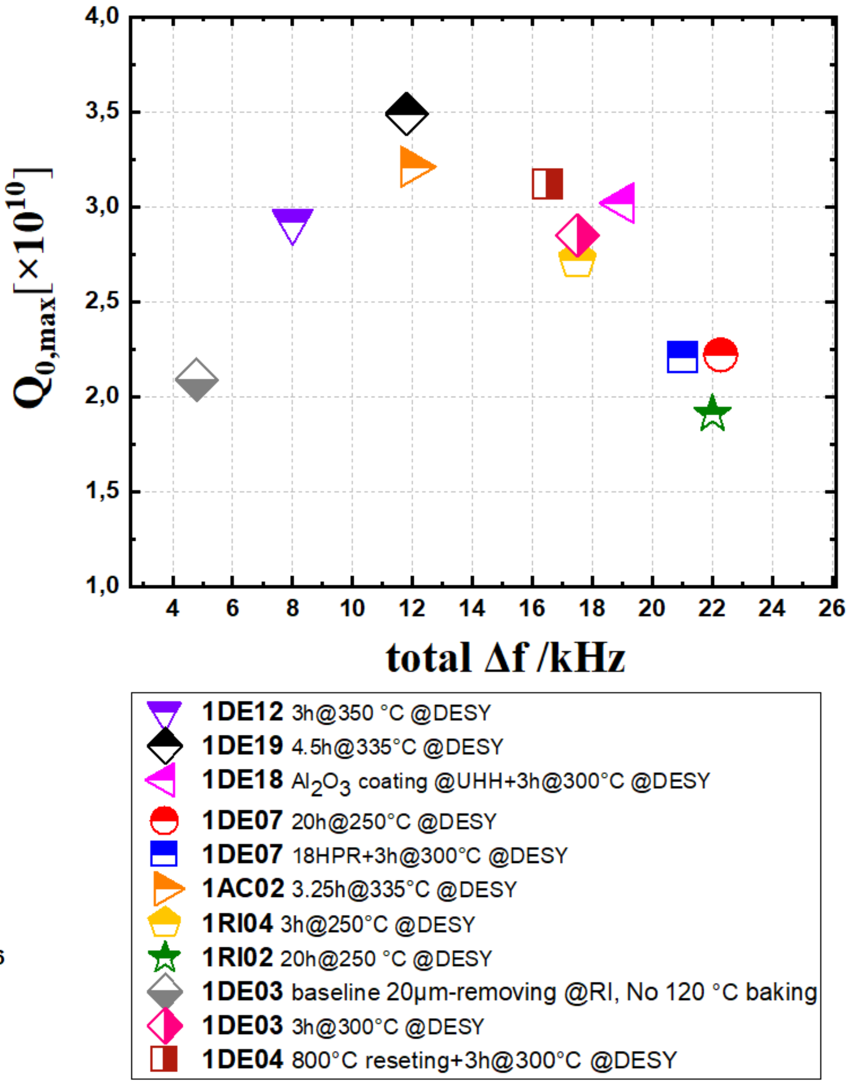
- Diffuse O out of RF layer
  → HFQS reappears and $\Delta f_{tot}$ / $\Delta f_{dip}$ decreases again

# Is there an optimal O-concentration?

- Too high NSF $c_O$ is not good for $Q_0$ (1DE7 / 1DE10)
- Too low NSF $c_O$ causes HFQS again (1DE12 / 800°C reset)
- Is there a sweet spot?
- Need a substitute: assuming $\Delta f_{tot}$ depends on $c_O$ …
- … look for correlation between $Q_0$ and $\Delta f_{tot}$

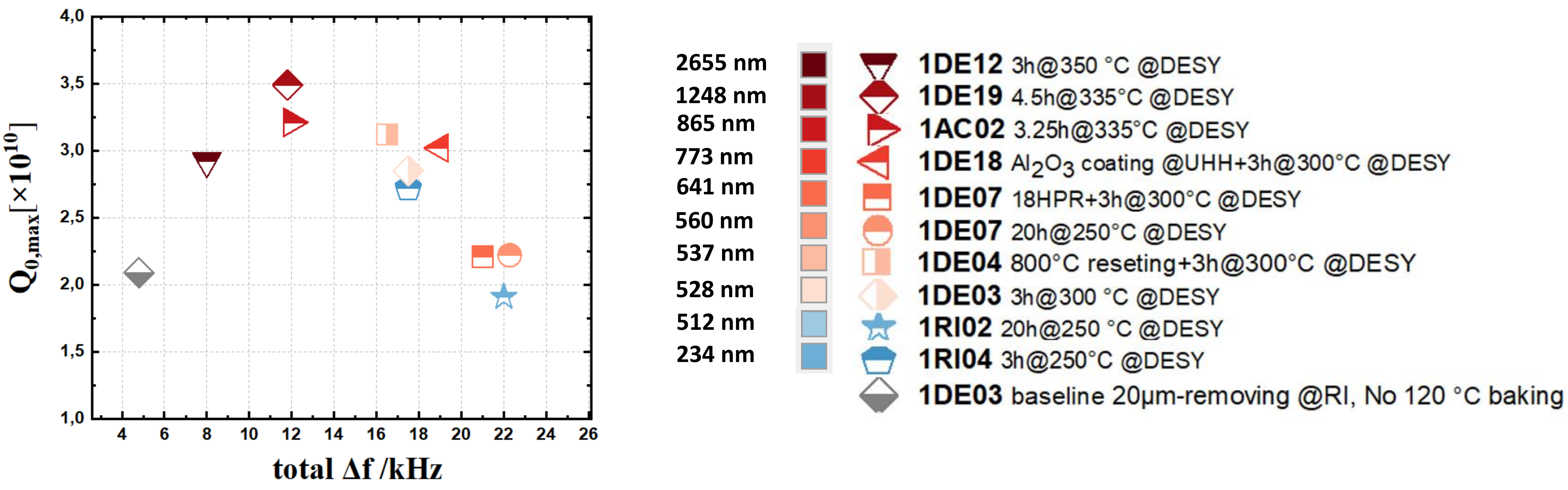
$Q_{0,max}$ @ 2K
$\Delta f = f(7K) - f(T>T_c)$



# Correlation with thermal budget?

Assumed Δf is depends $c_O$ …
and we know that NSF $c_O$ goes down with larger thermal budget / larger $\langle z \rangle$ …
some correlation of $Q_0$ with $\langle z \rangle$ expected as well – yet weaker as Fick's law does not accomodate uneven GB diffusion / saturation effects



# Conclusion

- Too high $c_O$ near the surface is not good
  - 18xHPR before midT of 1DE7
  - 1xmidT vs. 2xmidT of 1DE10

- Too low $c_O$ leads to HFQS again
  - 1DE12 or every 800°C reset

- Optimal recipe depends on furnace – „thermal budget“
  - 1DE10 vs. 1DE18

- Sweet spot for $Q_0$ seems to exist – right amount of disorder ?
  - continue investigation & model building ($\Delta f_{tot}$ vs. $\Delta f_{dip}$, $E_{acc}$, grain mapping)

# Thanks…

- to **DESY** for the cavity measurements
- to **you** for listening
- to the **conveners** for the opportunity to present this work

**Questions?**

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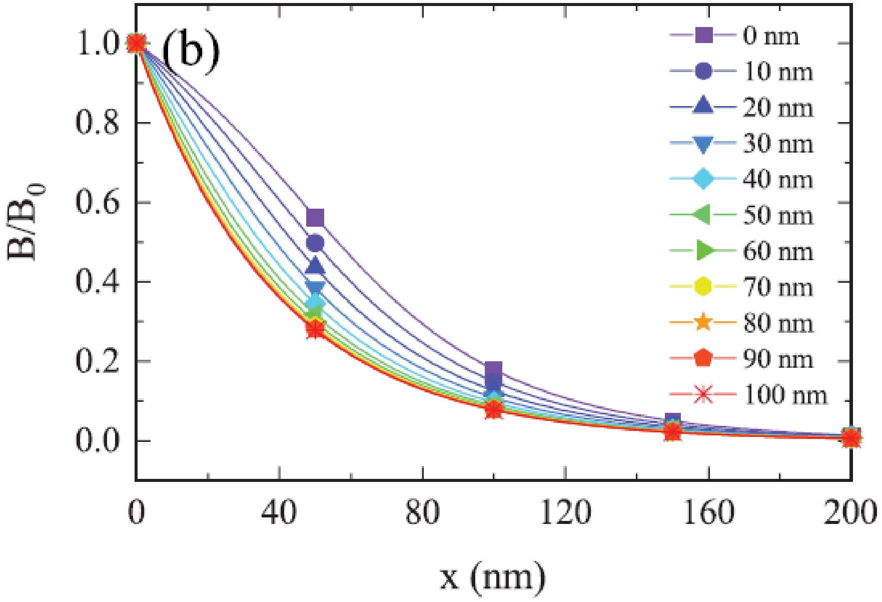
# Back Up

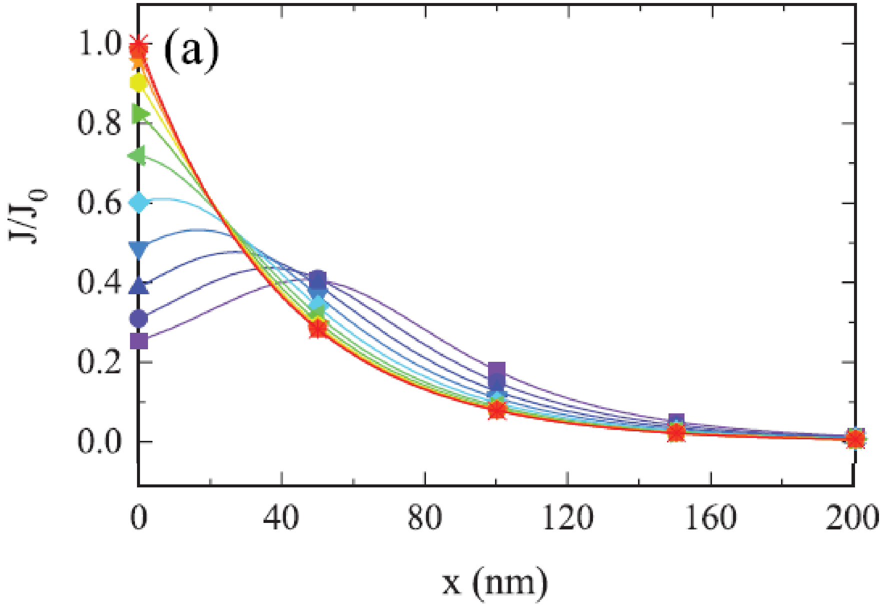
# Current Redistribution

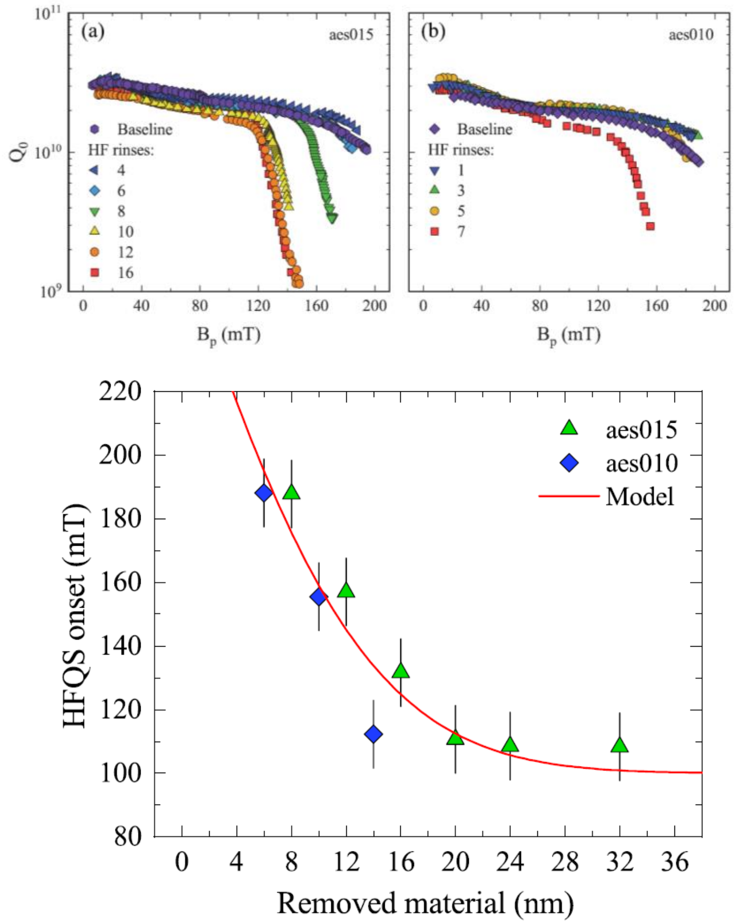
[Checchin, M. et al., Appl. Phys. Lett. 117, 032601 (2020)]
[Pambianchi, M. et al., Phys. Rev. B 50, 13659]

$$\lambda^2 B''(x) + 2\lambda\lambda' B'(x) - B(x) = 0.$$

$$\lambda(x) = (\lambda_s - \lambda_0)\mathrm{Erfc}\left[\frac{x}{\delta}\right] + \lambda_0,$$

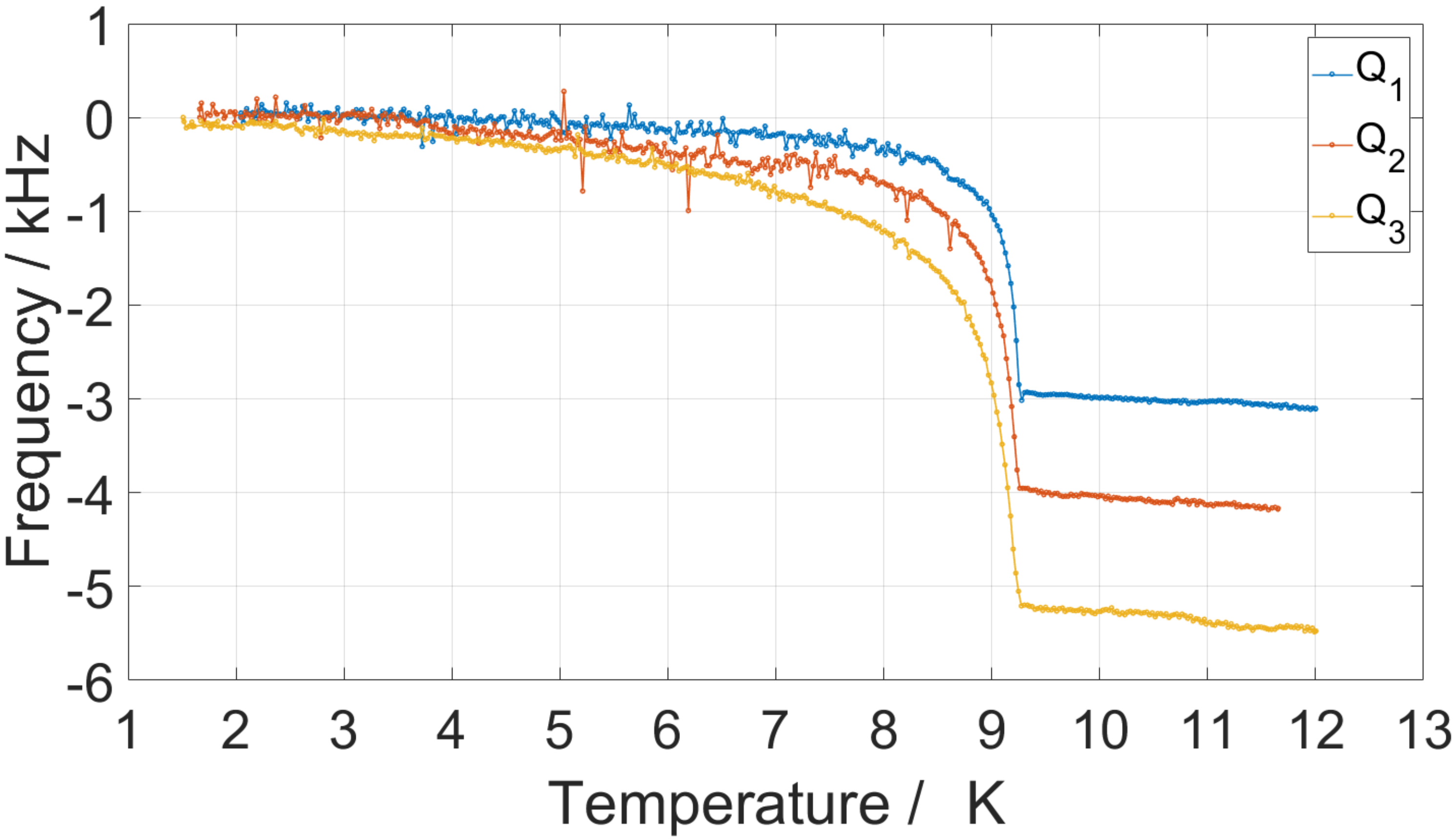



Consequence:
Currents shifted away from the surface where “lossy mechanism(s)” occur

# Frequency shift is frequency dependent




- $Q_n$ = n x 433MHz
- Lower frequency $f_{op}$ ⟶ lower $\Delta f_{tot}$
- That is because Γ is frequency dependent
- If the dip is caused by current redistribution ⟶ $\Delta f_{dip}$ should depend on $f_{op}$ as well