

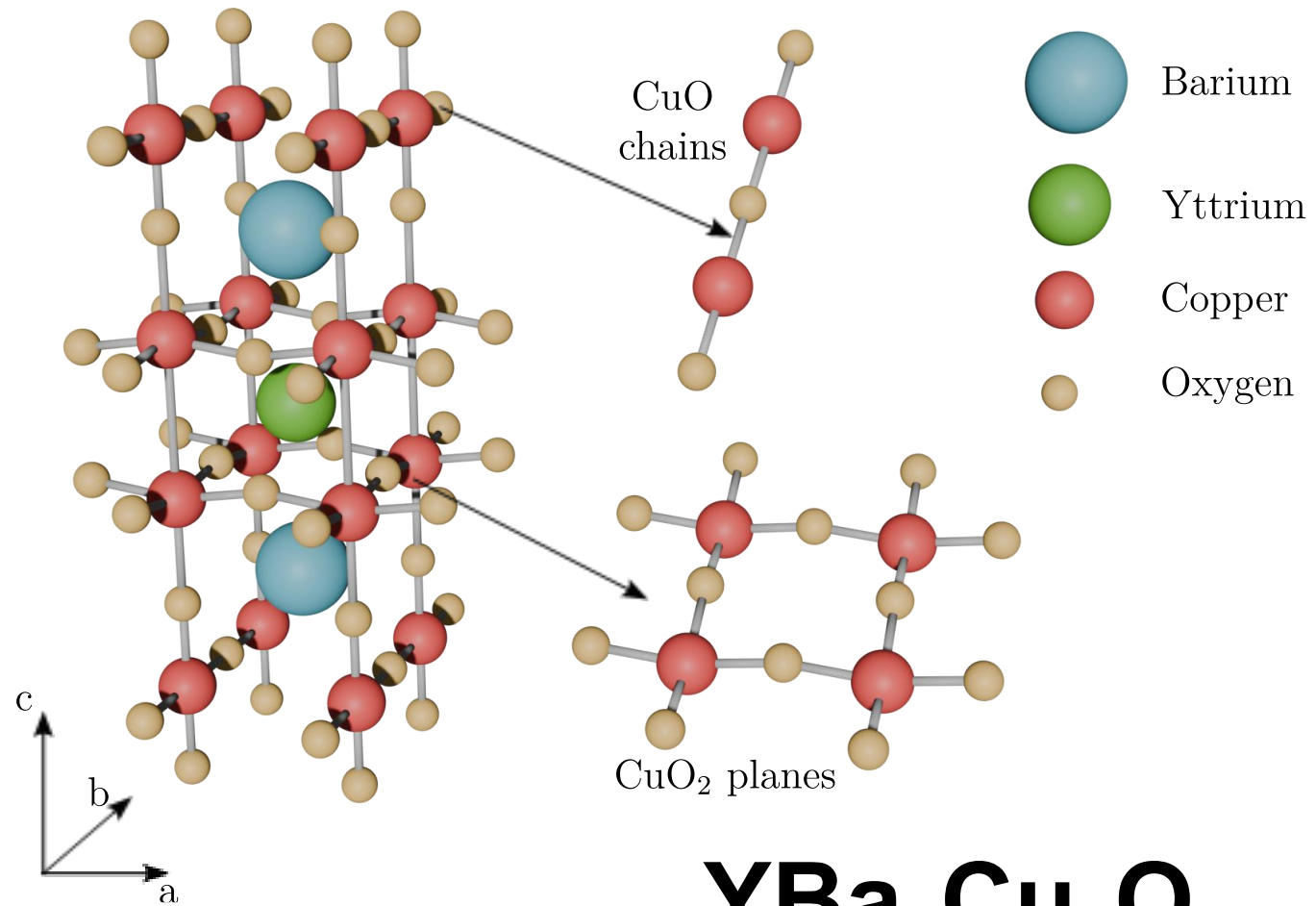
Controlling oxygen migration in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ with short current pulses and device geometry

D. Stoffels, C. C. Quaglio-Gomes, F. Egyenes, N. Lejeune, E. Fourneau, B. Aichner,
A. Palau, W. Lang, M. Motta, A. V. Silhanek

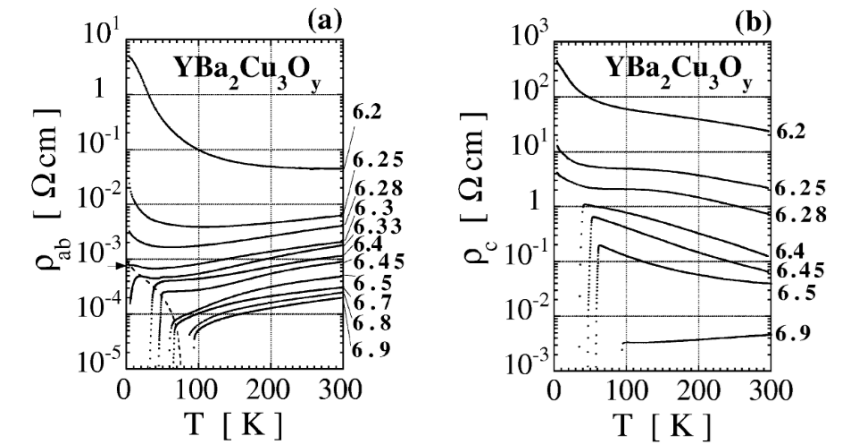
*Q-MAT, Experimental Physics of Nanostructured Materials,
Department of Physics, University of Liège,
Liège, Belgium*



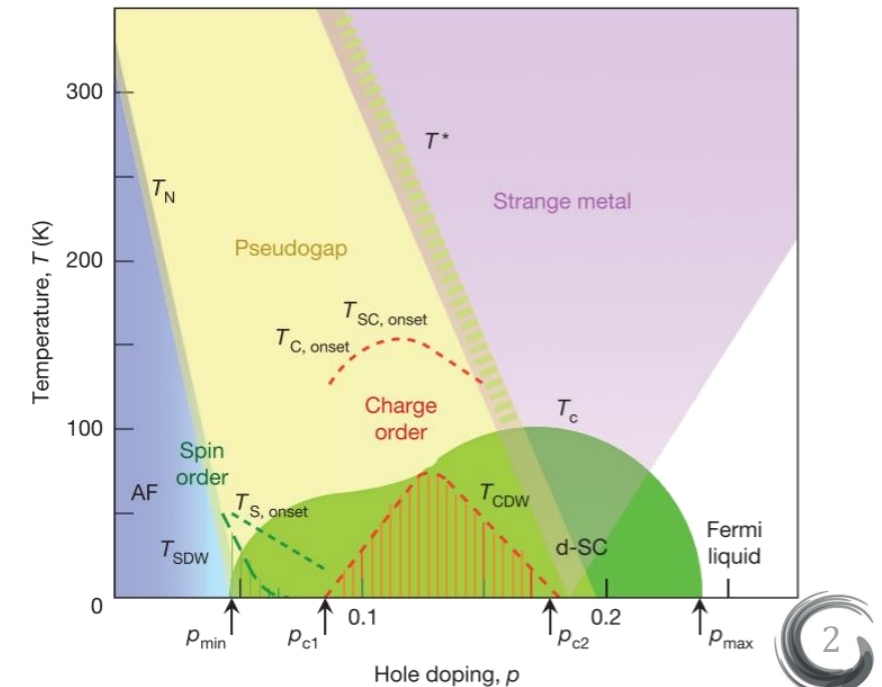
The role of oxygen in YBCO



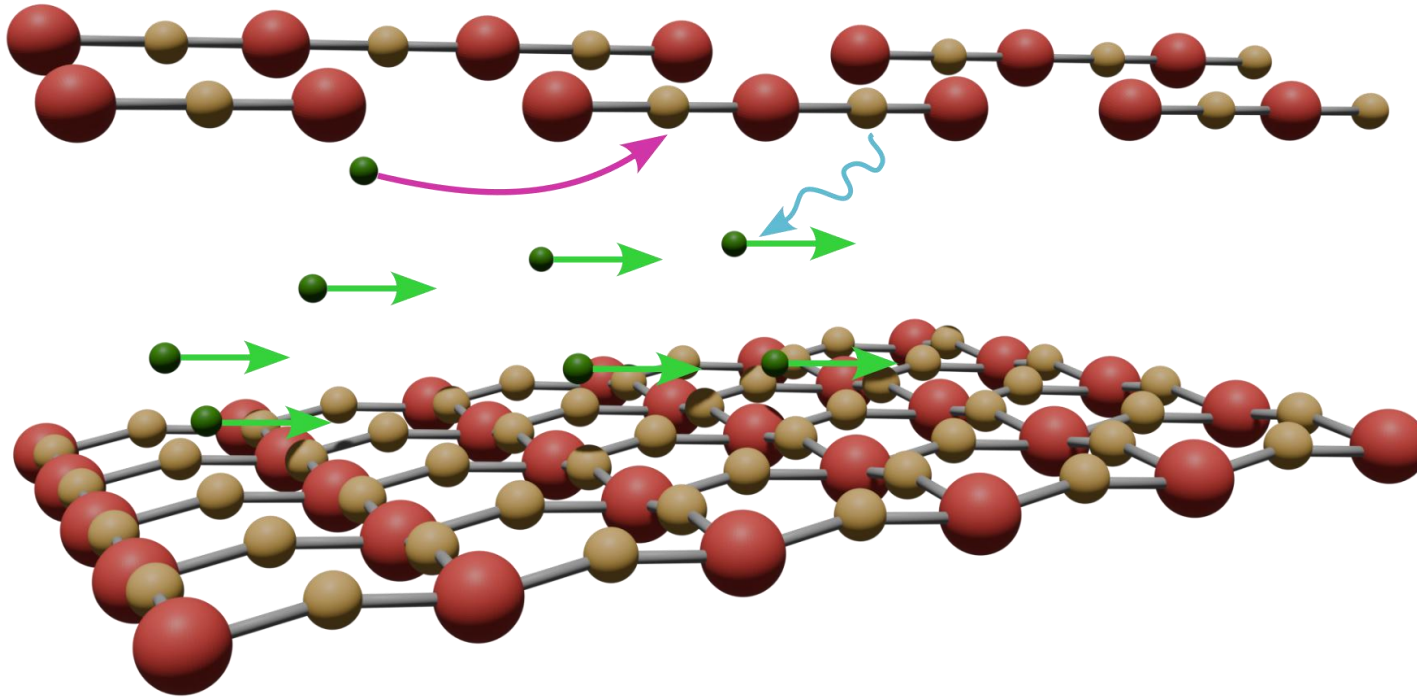
K. Semba and A. Matsuda,
Physical Review Letters **86**, 496 (2001).



B. Keimer *et al.*, Nature **518**, 179 (2015).



Selective electromigration: Moving oxygen by current



Oxygen dynamics

$$\frac{\partial C_o}{\partial t} = \nabla \cdot D(T) \left(\nabla C_o - \frac{C_o e \rho}{k_B T} z^* \mathbf{J} \right)$$

Diffusion coefficient

$$D(T) = D_0 \exp \left(-E_a / (k_B T) \right)$$

Joule heating

$$\mathcal{P}_{Joule} = \rho j^2$$

Linear resistance dependance

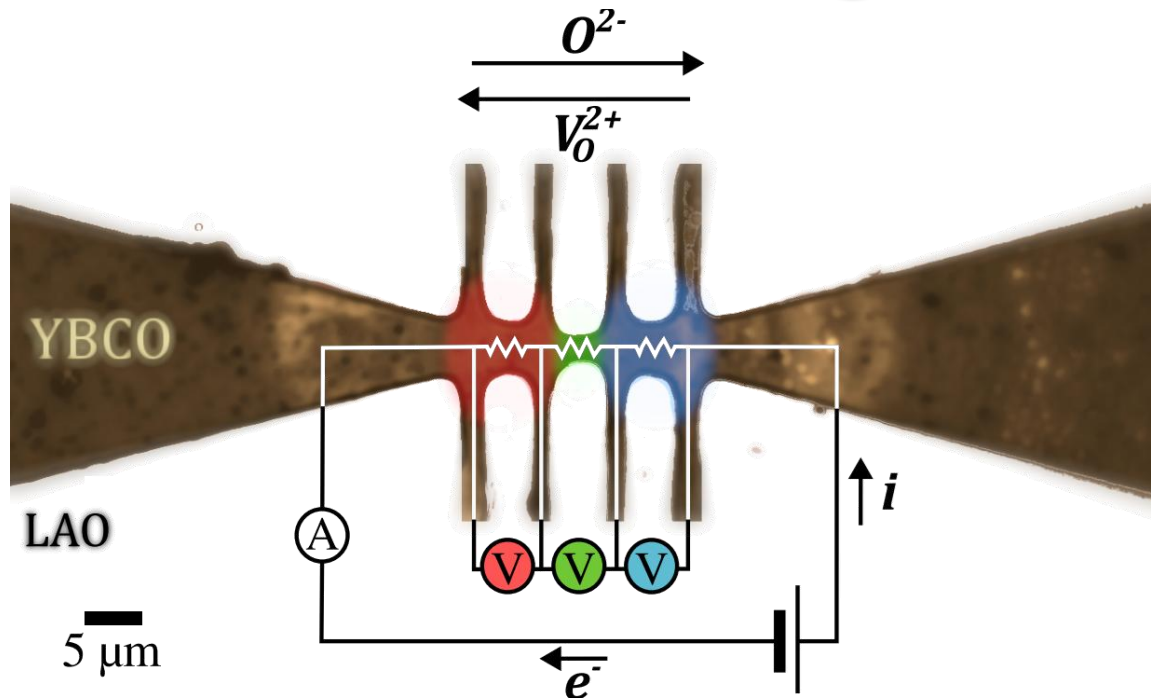
$$R(T) = R_0 (1 + \alpha \Delta T)$$

Material laws

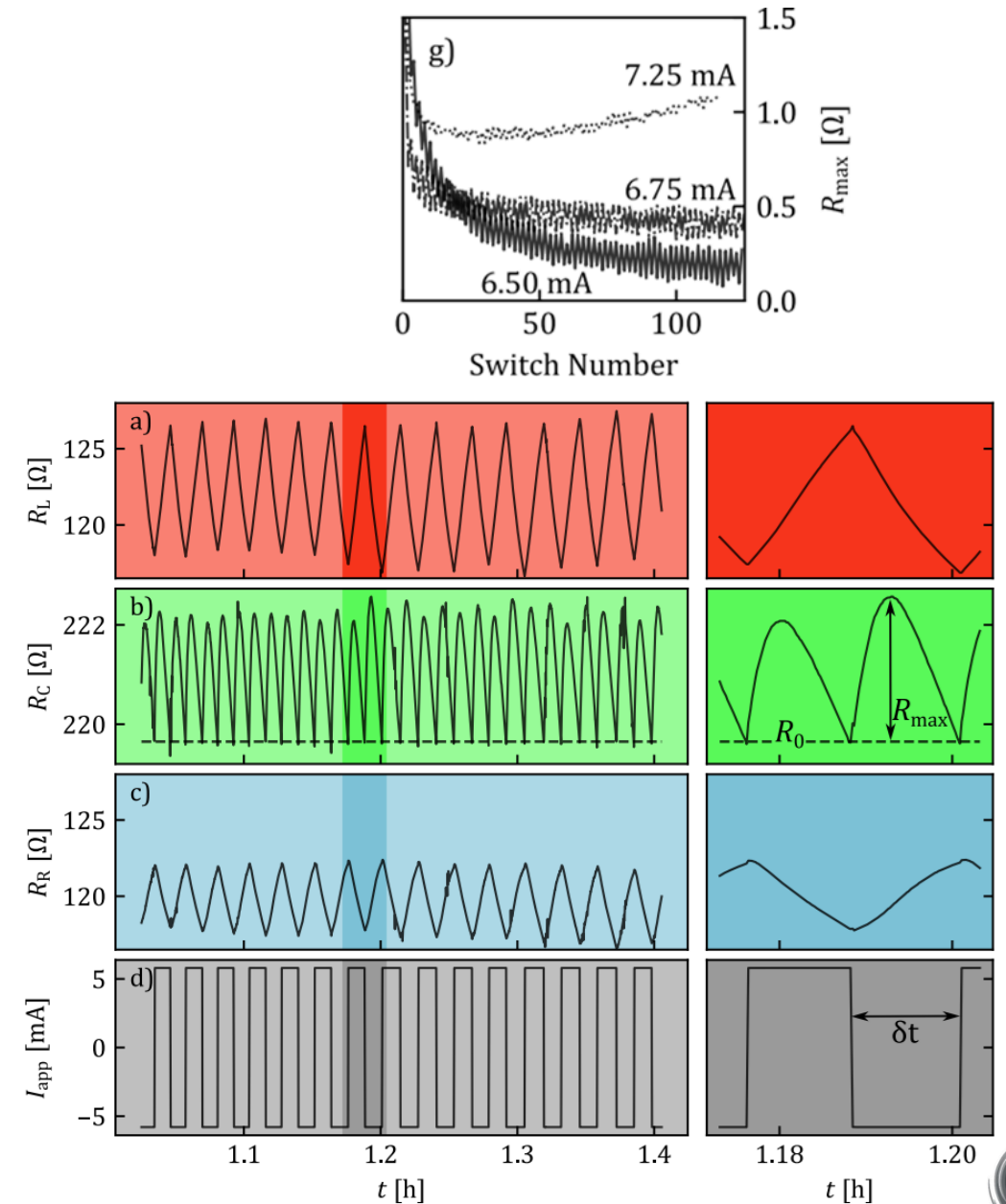
$$\rho(C_o)$$

“Momentum transfer between charge carriers and lattice atoms leads to atom displacement.”

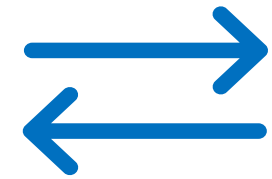
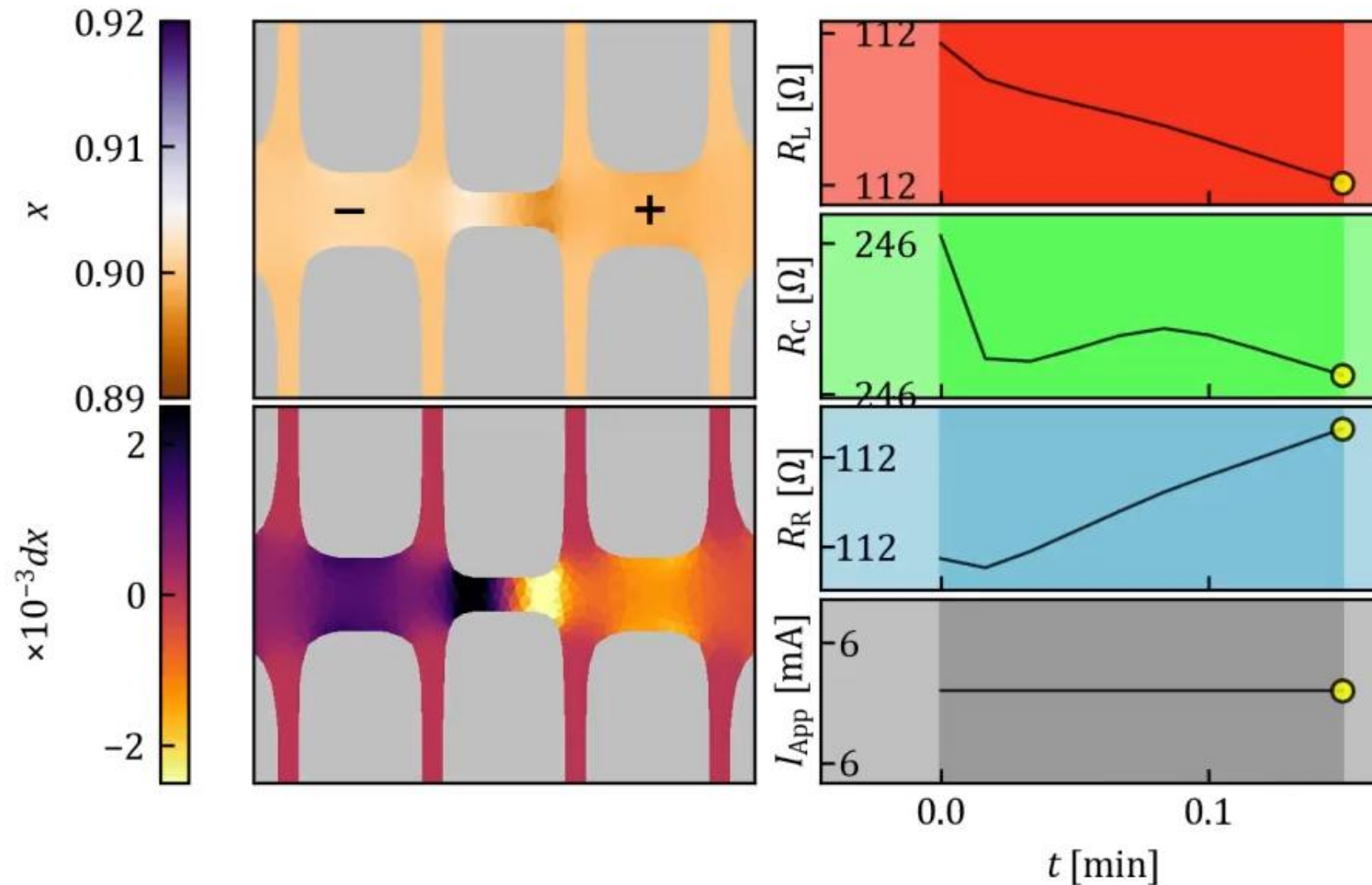
Reversible switching



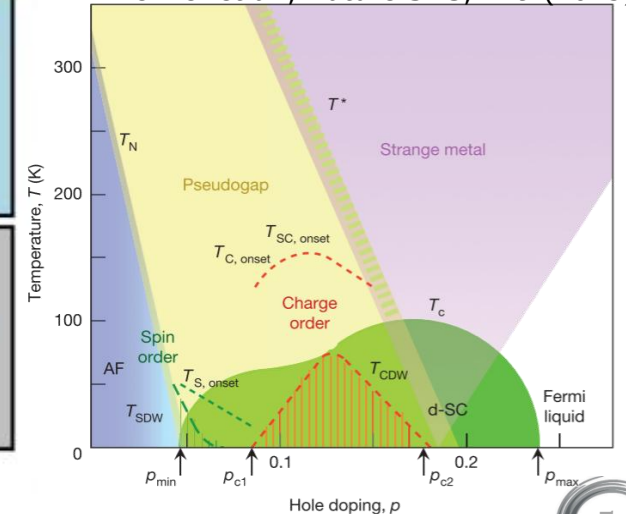
50 nm YBCO via PLD
Substrate: LAO
Center constriction 3x5 μm



FEM insights into reversible oxygen movement



B. Keimer et al., Nature **518**, 179 (2015).



Interplay between j and T

Oxygen movement is reversible, **but what determines I_{EM}** ?



Only current density, j



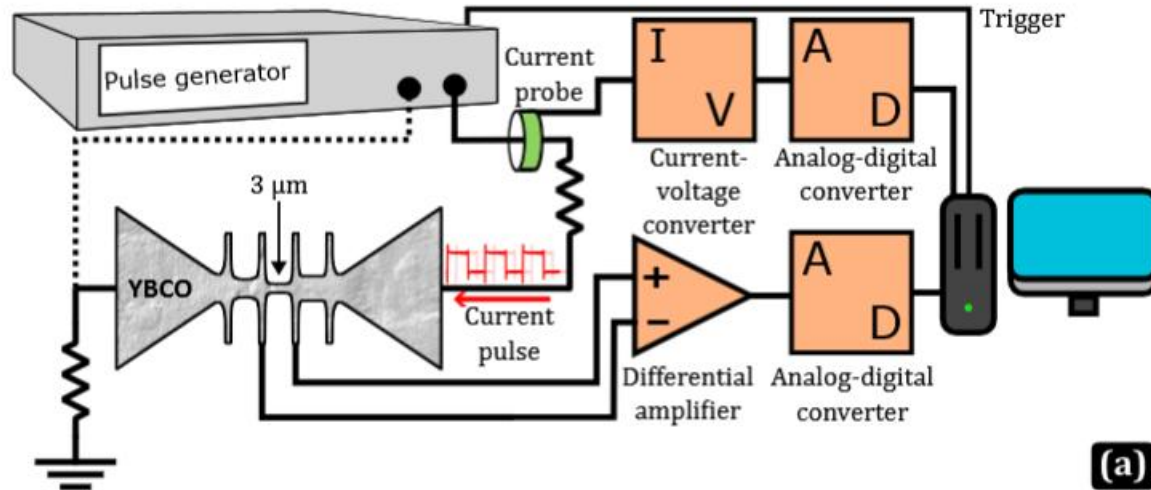
Or also Joule effect, $\mathcal{P}_{Joule} = \rho j^2$
resulting in heating

How to **decouple** them?



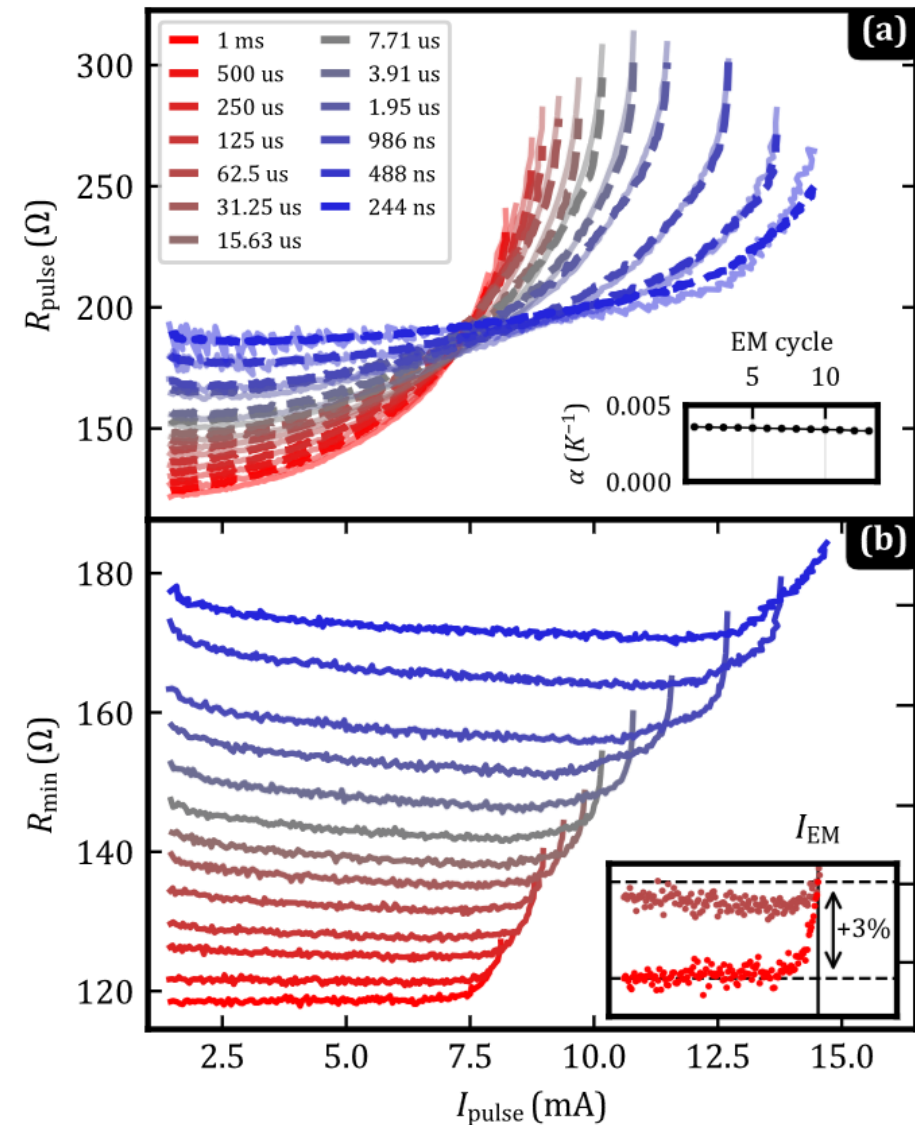
Use current pulses instead of continuous current

Pulsed electromigration of multibridges

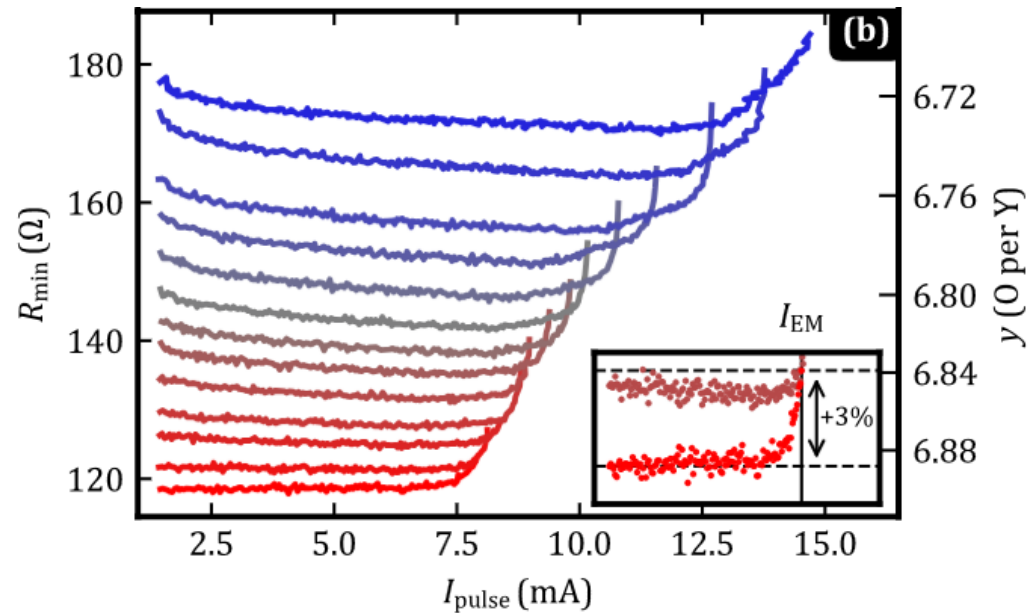


Protocol:

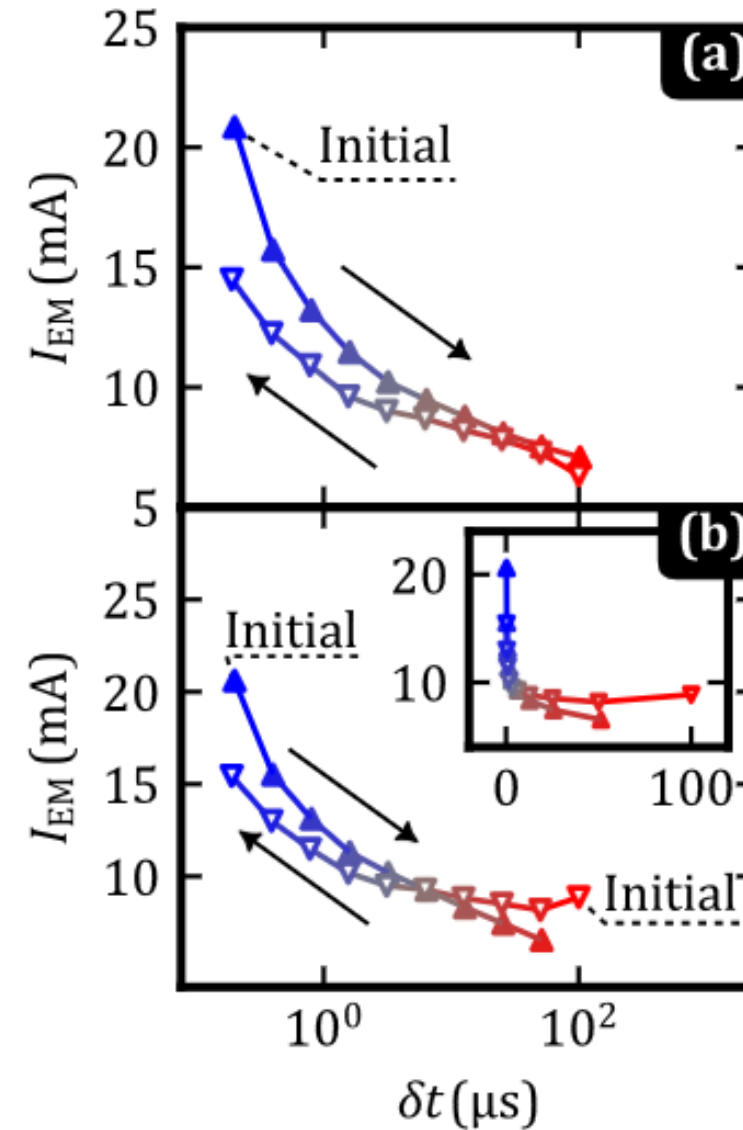
- Monitor
 - R_{max} during pulse (hot)
 - R_{min} after pulse (cold)
- Increase I_{pulse} until R_{min} has increased by 3%
- Then, decrease the pulse width, δt and start over
- (same sample)



Link between I_{EM} and δt



- Possibility to translate it to average oxygen content
- Influence of sample history
- Influence of scanning direction
- Sharp increase of I_{EM} around 10 μs (less thermal assistance?)



Same sample for δt up and down

Different sample for δt up and down

Thermal modelling

Heat balance

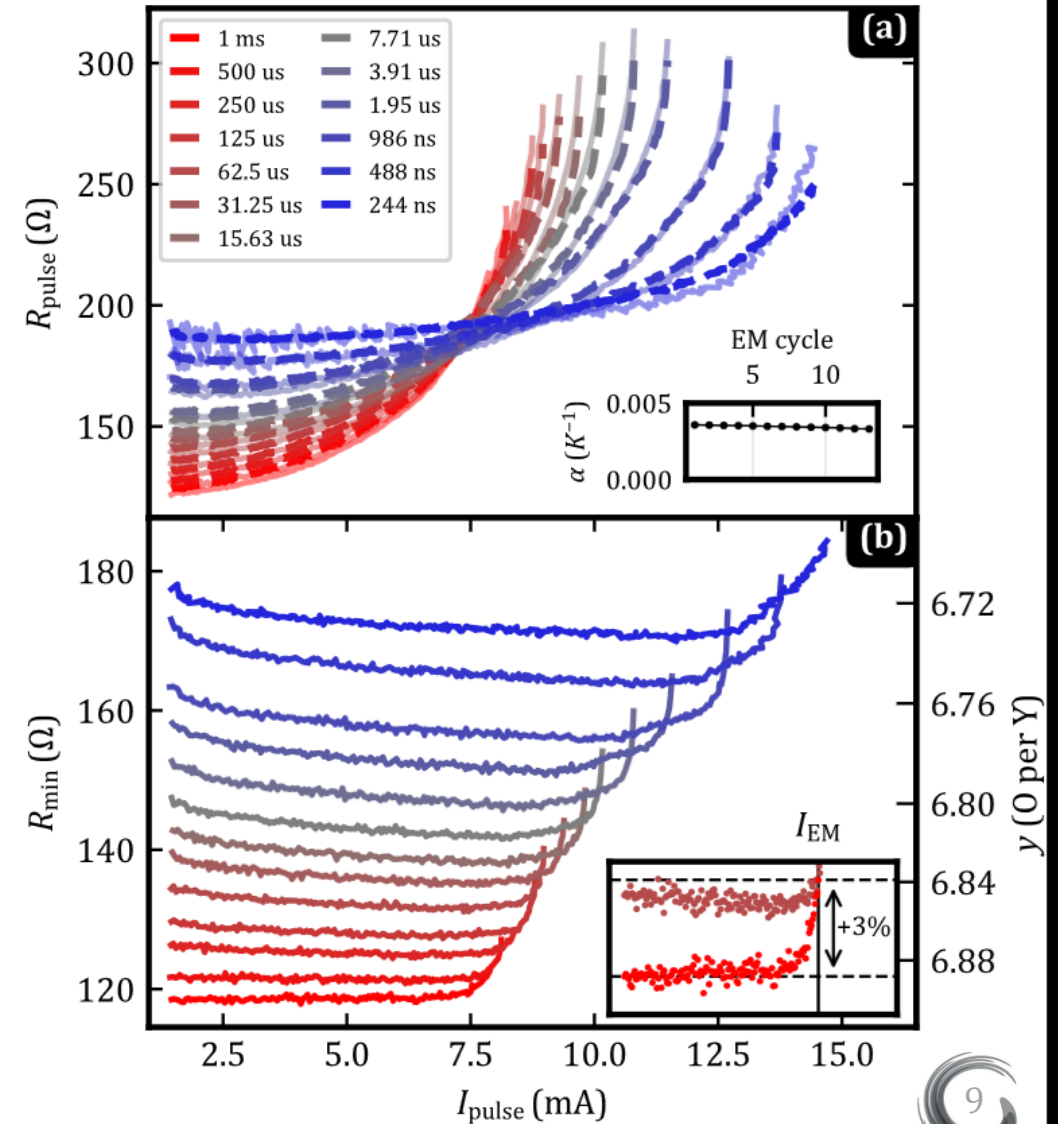
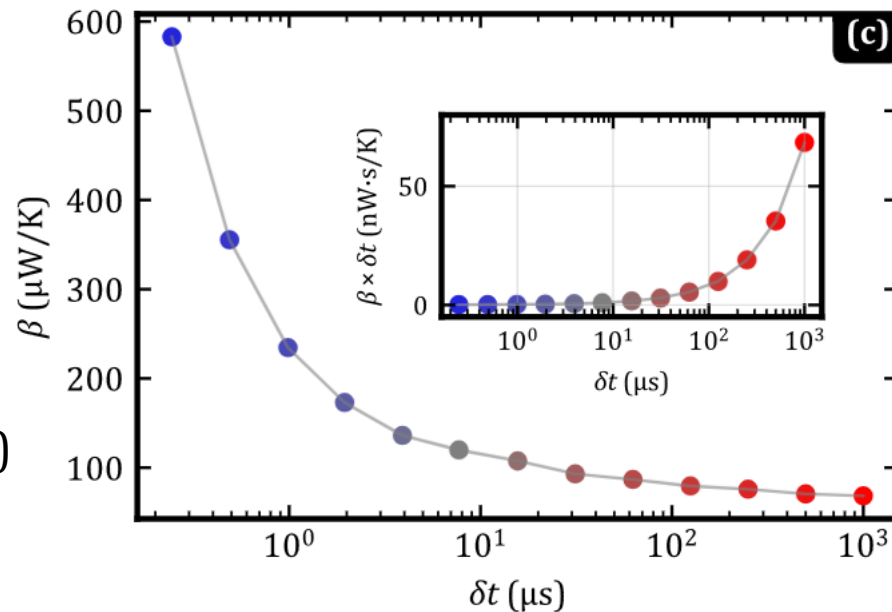
$$R_{\text{pulse}} I_{\text{pulse}}^2 = \beta \Delta T$$

Linearized resistivity

$$R(T) = R_0(1 + \alpha \Delta T)$$

$$R_{\text{pulse}}(I_{\text{pulse}}) = R_0 \left(1 + \frac{\alpha R_0 I_{\text{pulse}}^2}{\beta - \alpha R_0 I_{\text{pulse}}^2} \right)$$

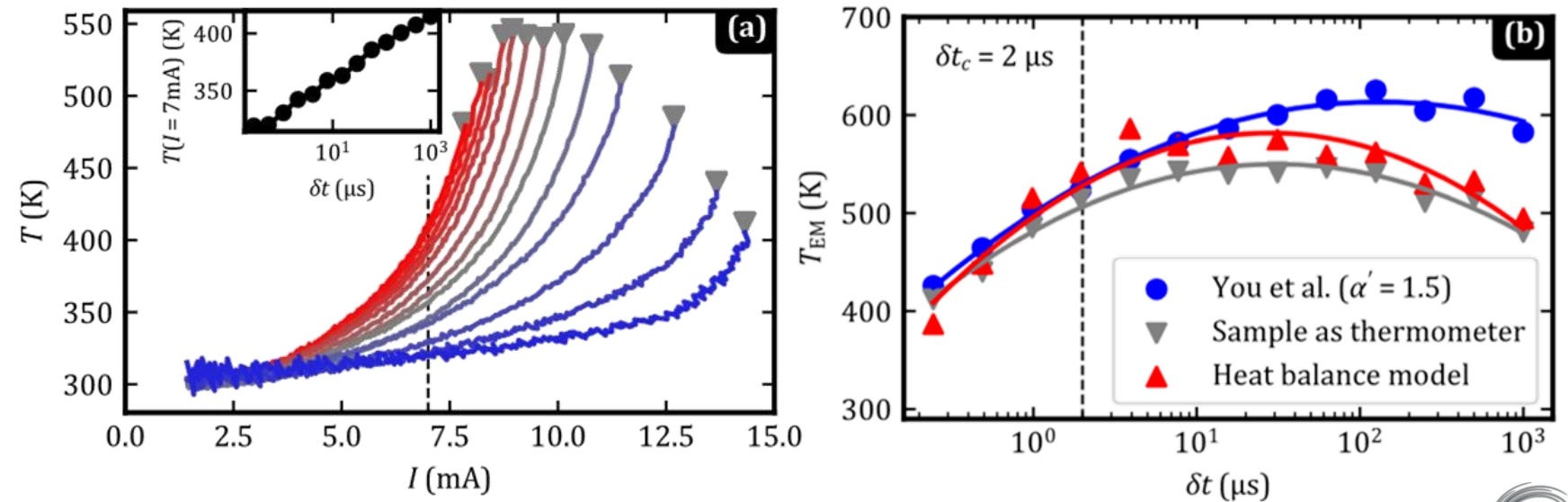
- α roughly **invariant**
- β as fitting parameter:
Captures heat transfer
(see dotted lines)
- Not in thermal steady state



Estimations of T_{EM}

Heat balance fitting	Linearized resistivity	<i>You et al.</i>
$T_{EM} = T_0 + \frac{R_0 I_{EM}^2}{\beta - \alpha R_0 I_{EM}^2}$	$T_{EM} = T_0 + \frac{R_{\text{pulse}} - R_{\text{min}}}{\alpha R_{\text{min}}}$	$T_{EM} = T_0 + \frac{R_{\text{pulse}} I_{EM}^2}{\pi l k} \operatorname{arcsinh} \left(\frac{2\sqrt{k\delta t/\rho_m C}}{\alpha' w} \right)$

- *You et al.* breaks down for large δt
- Highest T_{EM} for intermediate δt



Black-inspired model

$$MTF = Ae^{U/k_BT}J^{-n}$$

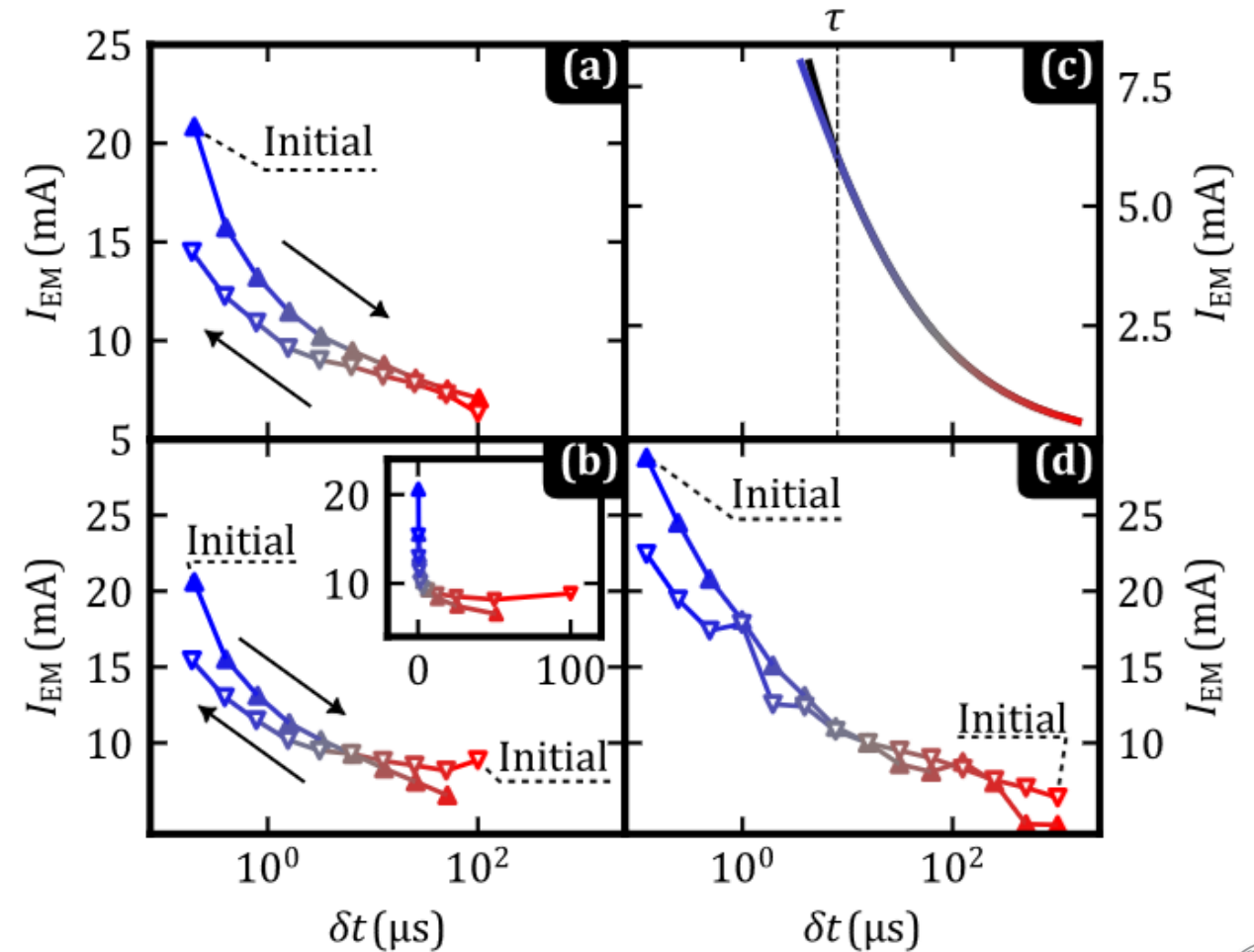
$$J = I_{EM}/S$$

$$MTF = \delta t$$

$$n \approx 2$$

$$I_{EM}^2 = AS^2 \frac{e^{U/k_BT_{EM}}}{\delta t}$$

$$T_{EM} = T_0 + \frac{R_0 I_{EM}^2}{\beta - \alpha R_0 I_{EM}^2}$$



Interplay between j and T

Oxygen movement is reversible, **but what determines I_{EM}** ?



Only current density, j



Or also Joule effect, $\mathcal{P}_{Joule} = \rho j^2$
resulting in heating

Take home message:

Part 1



Oxygen electromigration is **reversible** (if low amplitude of modulation)



Strong **interplay** between threshold current and pulse durations



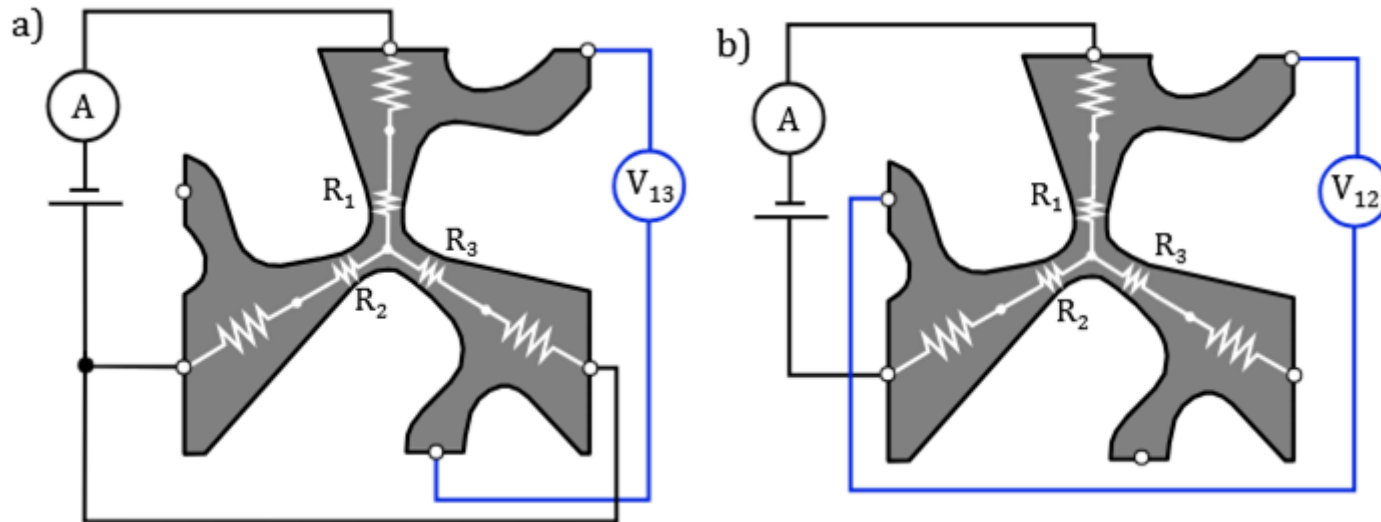
Non-trivial **heating** as a function of pulse duration

But what about spatial control?

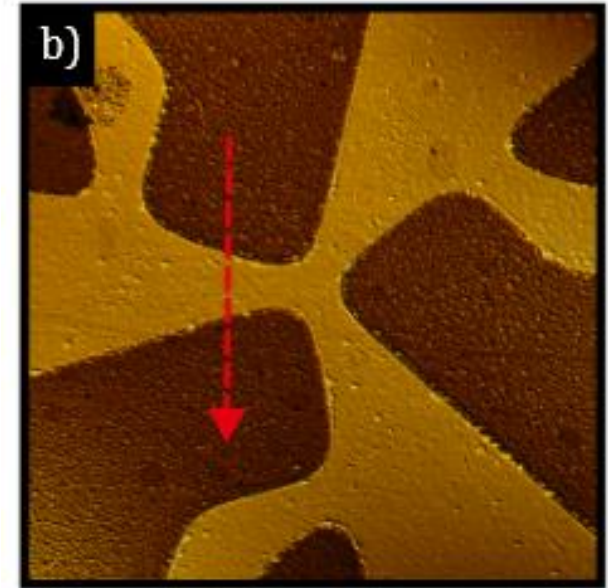
Spatially controlled oxygen modulation: Multiterminal devices

Idea: Can we move oxygen in one branch without strongly perturbing the others?

Wiring:



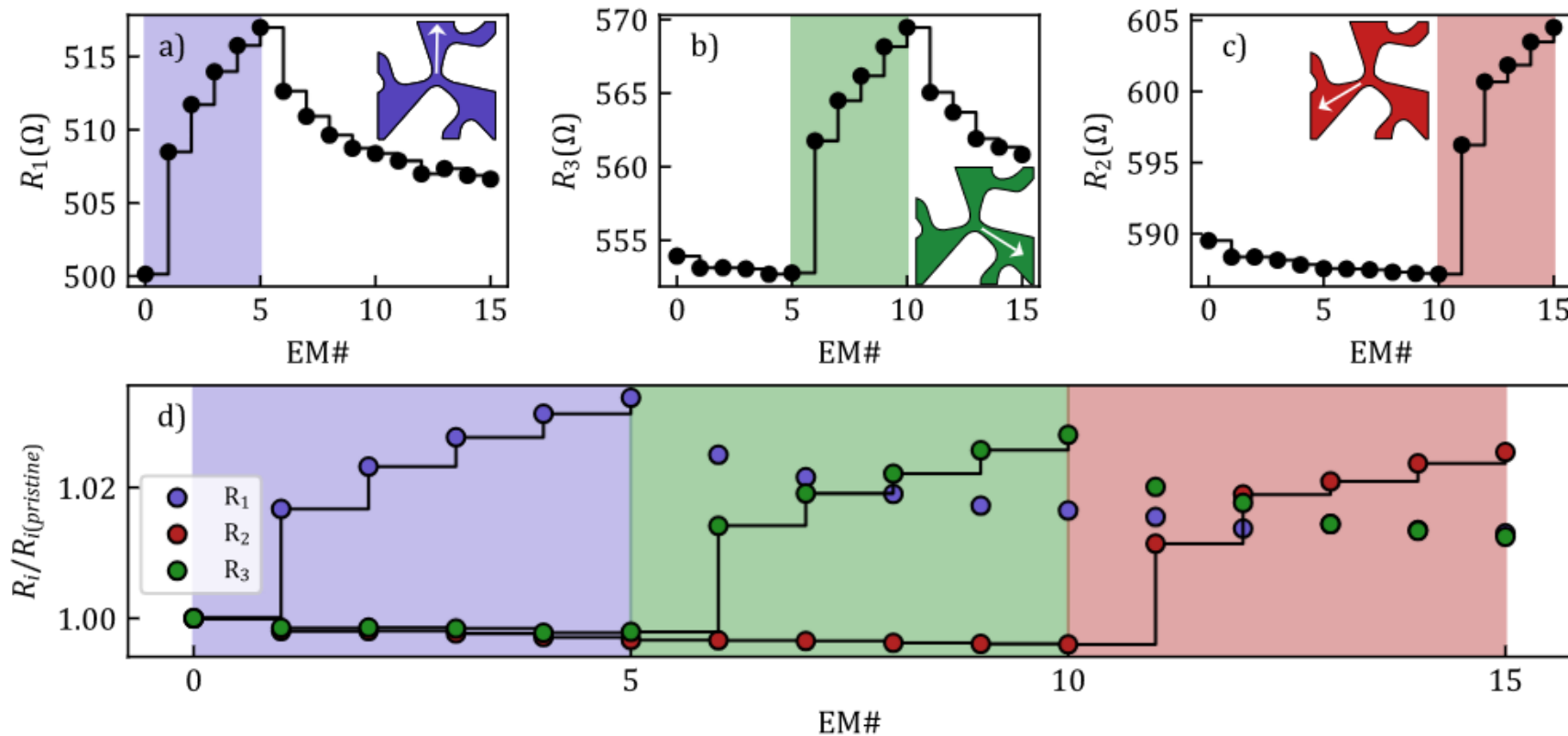
Solve a linear system to get the individual resistances: $R_{ij} = R_i + R_j$



50 nm YBCO via PLD
Substrate: STO
Center constriction 2 μm

**Multimodal
characterization**

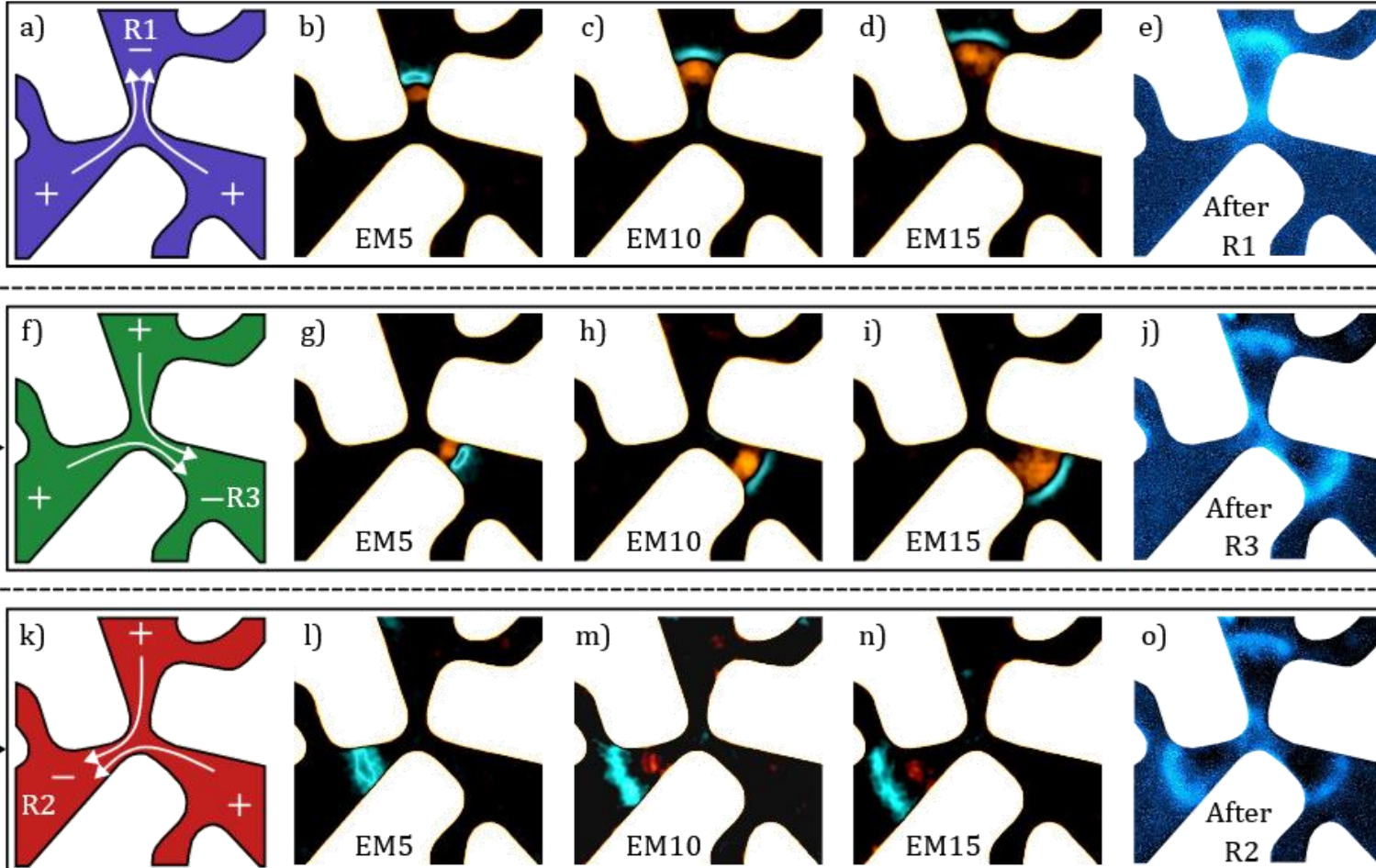
Spatially controlled oxygen modulation: Electrical behavior



Insight:

Targeted electrical modification possible,
but slight influence on the other terminals

Gathering evidence: Optical reflectivity

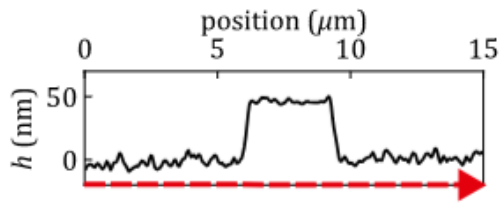


Insight:

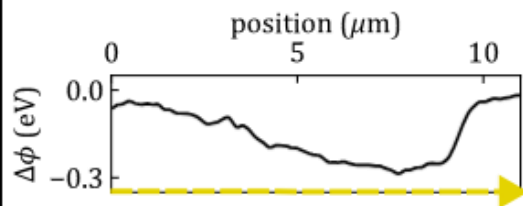
- Deoxygenation front propagating outwards
- Leaving a slightly less deoxygenated tail behind
- Deoxygenation remains when switching to another terminal

Gathering evidence: Kelvin probe force microscopy

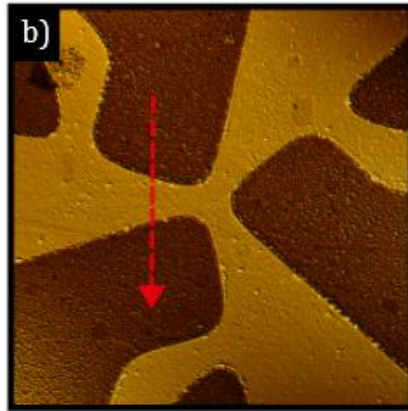
Topology AFM



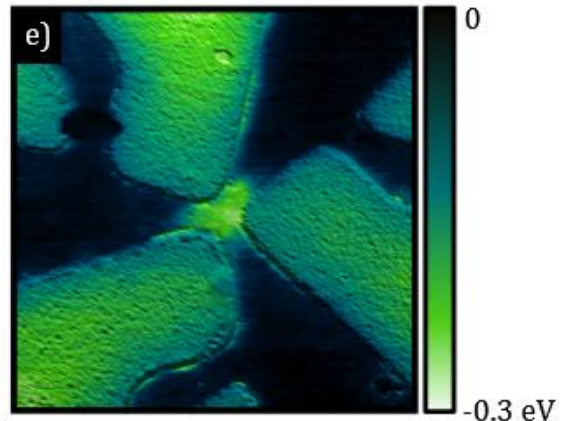
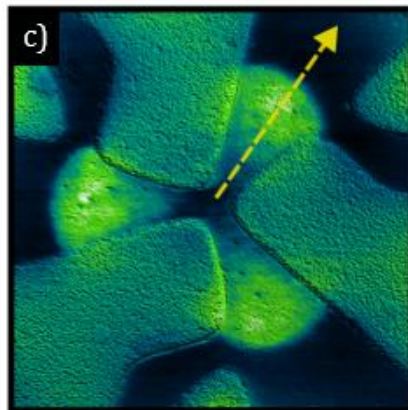
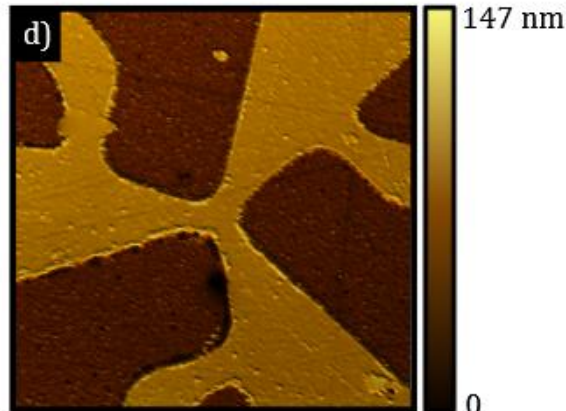
KPFM



Negative Polarity



Positive Polarity



Insight:

- No large structural damage/modifications
- Work function evolution confirms optical microscopy results (deoxygenation wave with slightly less deoxygenated tail)
- Reversing polarity does not push the wave far into the other terminals
- Limited reversibility (geometry)

Gathering evidence: Laser scanning microscopy

Physics:

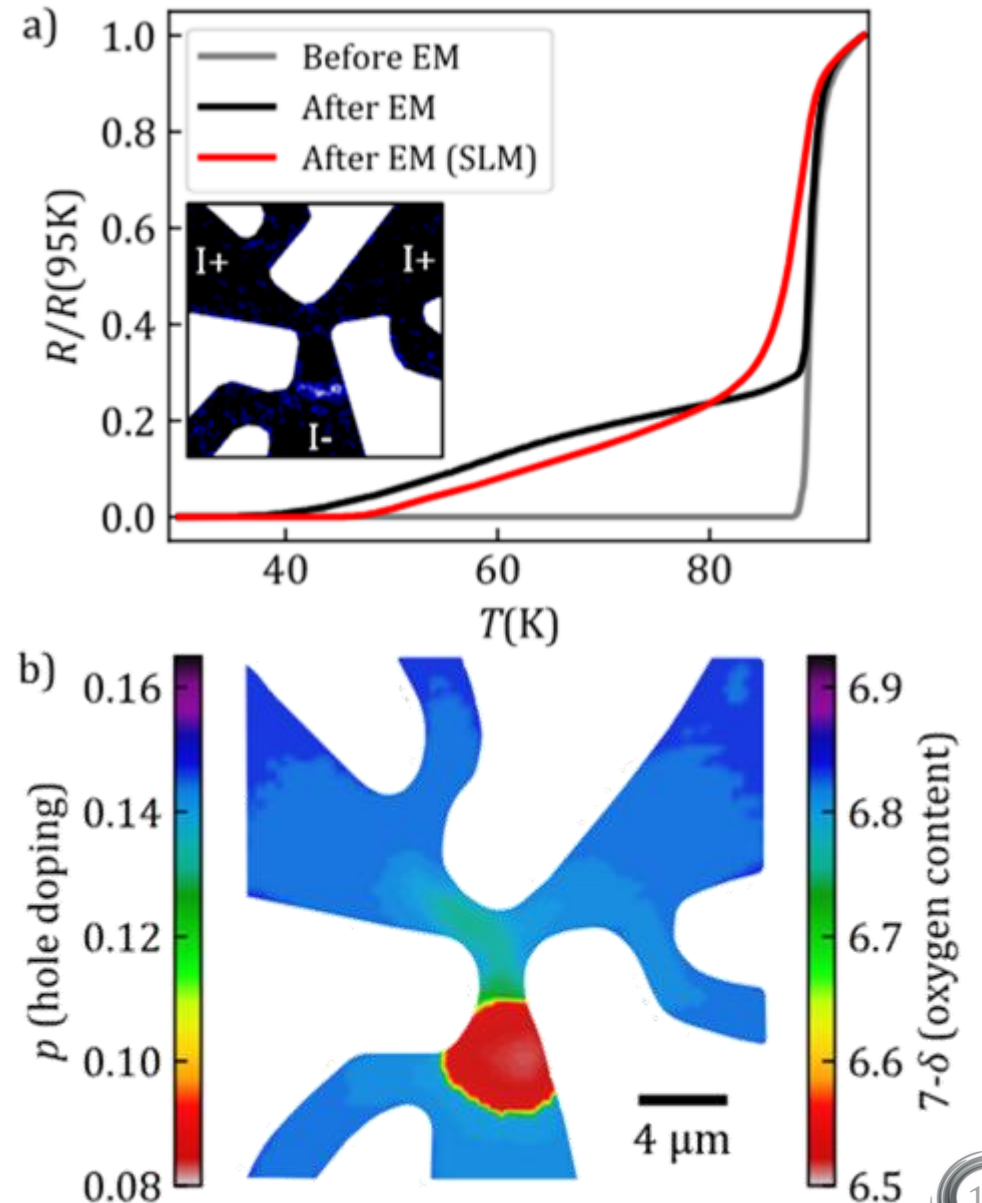
- Deoxygenation lowers T_c
- Laser heating can break superconductivity locally

Principle:

- Scanning a chopped laser (0.8 mW , $\Delta T \ll$)
- Lock-in detection of voltage if laser heating breaks superconductivity gives $\frac{dV}{dT} \Delta T$
- Measuring this at different sample temperatures

Insight:

- RT curve
- T_c map
- Doping map
- Oxygen content map

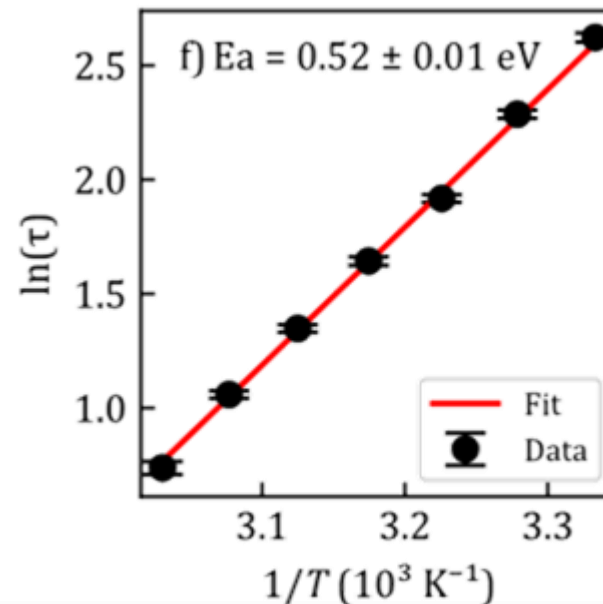
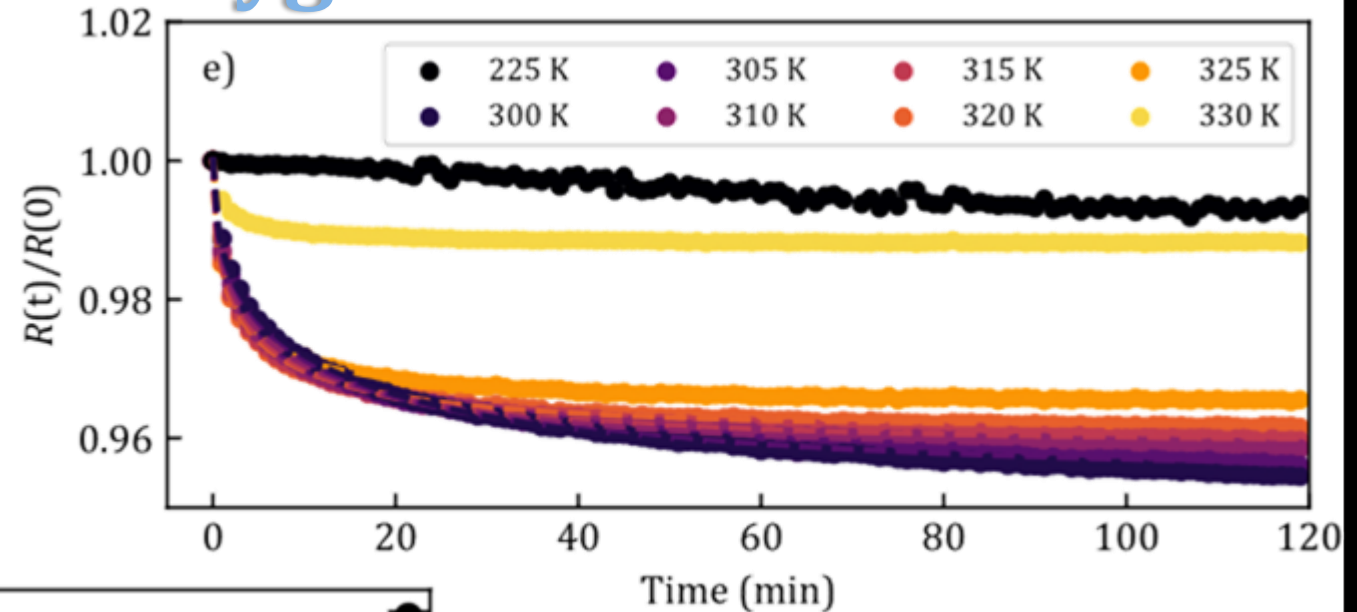


Diffusive relaxation of the oxygen modulation

- Resistance relaxation after electromigration

- $$R(t) = R_{\infty} + \Delta R \exp \left[- \left(\frac{t-t_0}{\tau} \right)^{\beta} \right]$$
$$\beta \approx 0.445$$

- Timescale τ depends on T
- $D(T) = D_0 \exp \left(-E_a / (k_B T) \right)$
with $E_a = 0.52$ eV
consistent with O diffusion
- What are the structural modifications responsible for this?



Take home message:

Part 2



Targeted modifications are possible



Not fully reversible



Slightly wave-like behaviour,
inconsistent with **bulk** (superconducting) response



Relaxation coherent with activation energies of atomic diffusion

Teamwork makes the dream work



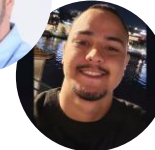
Dr. Anna Palau



Prof. Wolfgang Lang
Dr. Bernd Aichner



Dr. Fridrich Egyenes



Prof. Maycon Motta
Caio C. Quaglio-Gomes



Dr. Stefan Marinkovic



Prof. Alejandro V. Silhanek
Dr. Emile Fourneau
(soon Dr.) Nicolas Lejeune



Thank you for your attention
I'd be glad to answer your questions

Condensed Matter > Superconductivity

[Submitted on 16 Mar 2026]

Effect of pulse duration on current-induced selective oxygen migration in high-T_c superconductors

Fridrich Egyenes, Daniel Stoffels, Stefan Marinkovic, Bernd Aichner, Huidong Li, Anna Palau, Milan Tapajna, Wolfgang Lang, Alejandro V. Silhanek



LIÈGE université
EPNM

**Experimental Physics of
Nanostructured Materials**



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