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Atomic Growth Modes of Metal Coatings on Nb for SRF Cavities

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Steven Sibener Group at
The University of Chicago

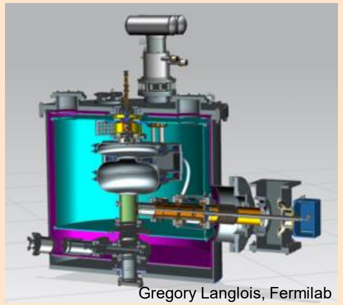
July 9, 2026

SRF Cavities Efficiently Accelerate Particles

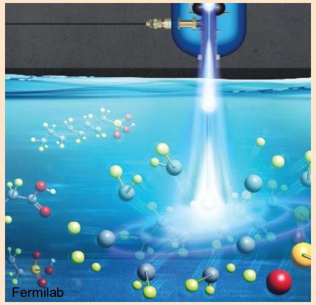
Radio-frequency cavities are the most common and efficient method for accelerating charged particles at high energy.

Applications

Medical Sterilization

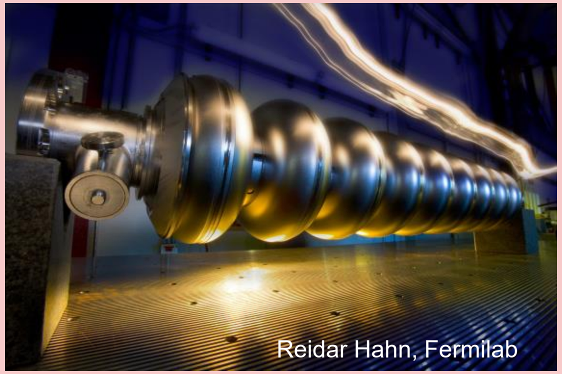


Degradation of PFAS



Current Operation

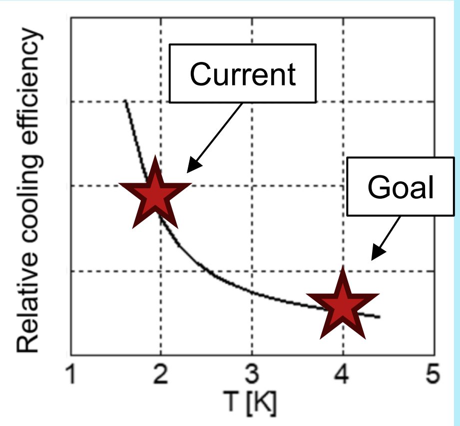
Nb SRF Cavity



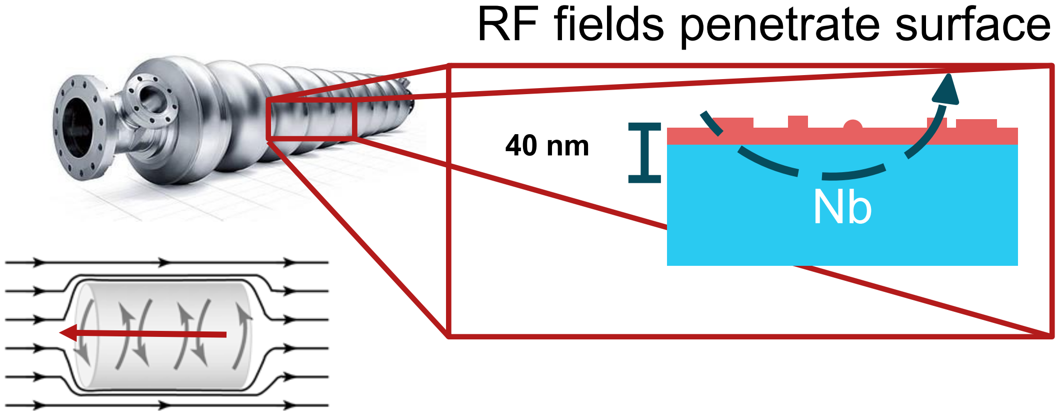
- High-purity Nb cavities
- Operate at 2 K
- $Q \approx 10^{10}$

Our Goal

Increase operating temperature while reducing cooling requirements



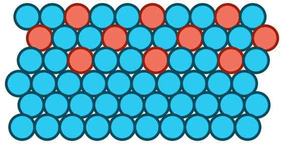
Why the Surface Matters



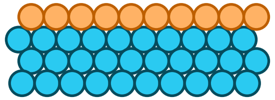
RF fields penetrate only the first ~40 nm of the Nb surface, making this region critical to cavity performance.

Surface Enhancement Strategies at CBB

Alloying Layers (Nb_3Sn, Zr-Nb)



Capping Layers (Au)

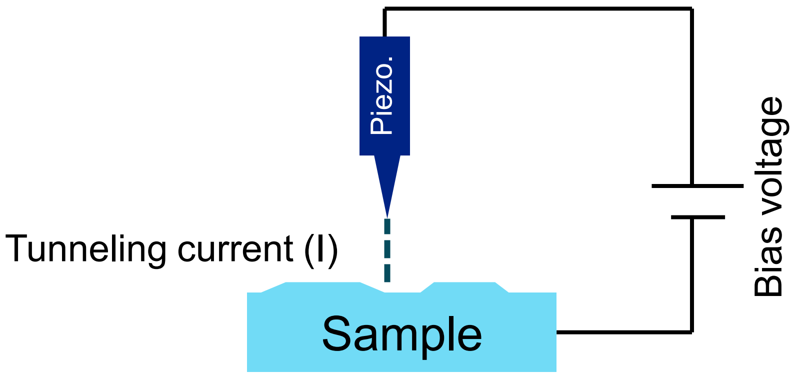


Rather than replacing the entire niobium cavity, we focus on engineering only the surface to produce coatings that reduce RF losses and enable higher-performance SRF cavities.

STM Shows Atomic Topography of Coatings

Understanding **how these metal films nucleate and grow** is essential for producing uniform, high-performance coatings.

$$I \propto V \rho_s(E_F) e^{-2\kappa z}$$



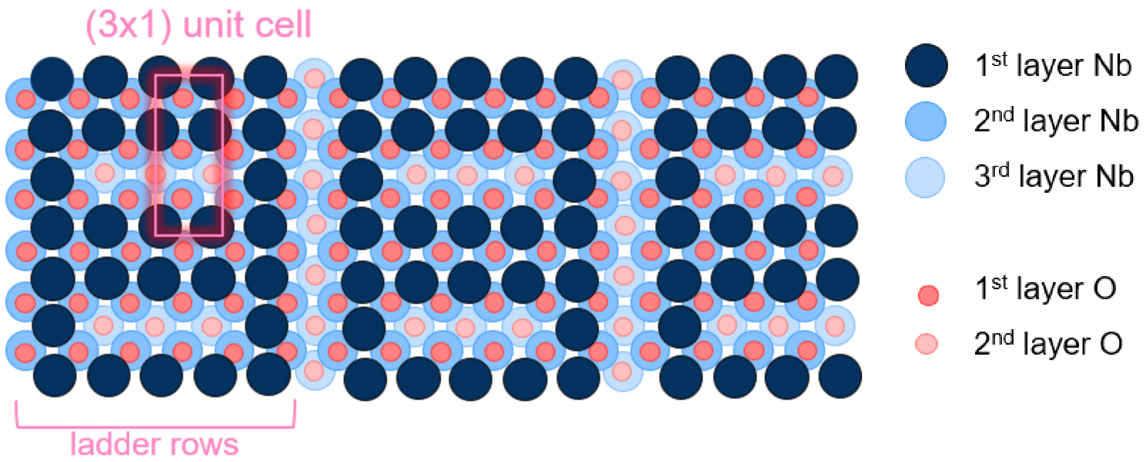
- Atomic-scale spatial resolution
- Sensitive **surface topography** and **electronic structure**
- Tunneling current (I) changes exponentially with tip height (z)

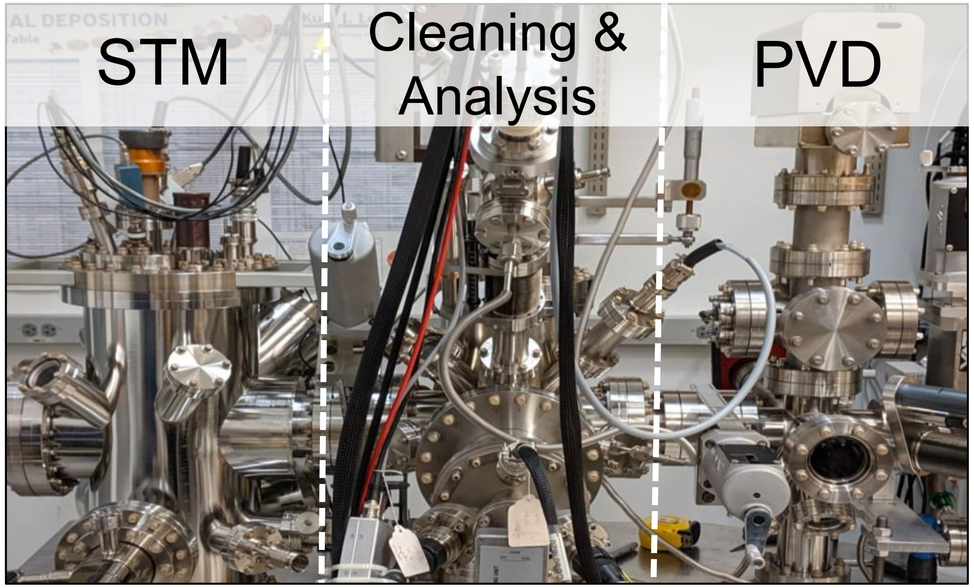
STM allows us to observe the **initial nucleation and growth** of metal coatings while simultaneously probing their local electronic properties.

Model System for Rapid Thin-Film Growth Studies

Model system of Nb(100) single crystal

- (3 x 1)-O/Nb(100) structure (NbO)
  - Highly ordered surface allows visualization of atomic surface changes
- UHV Chamber with STM, PVD, Chemical Analysis (XPS, UPS, AES)





Model System for Rapid Thin-Film Growth Studies

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- (3 × 1)-O/Nb(100) structure (NbO)
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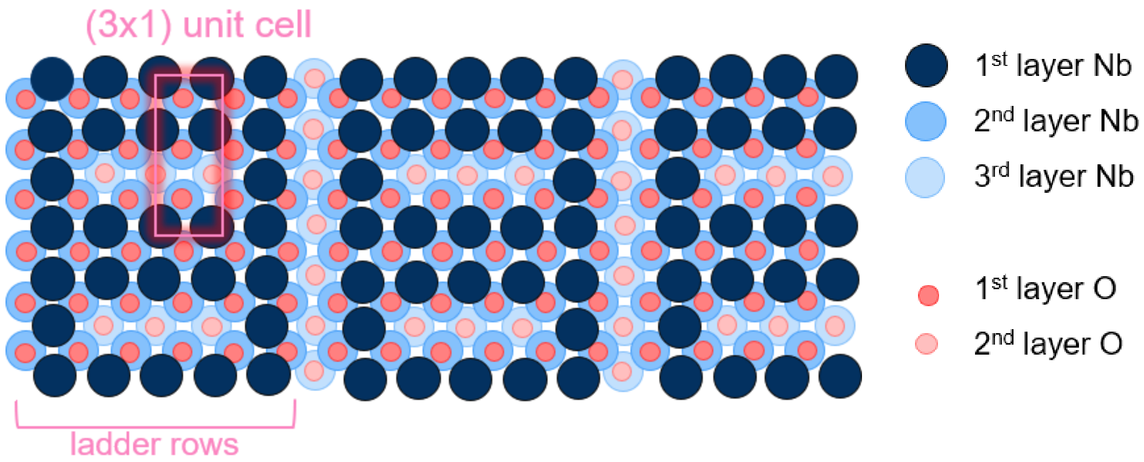
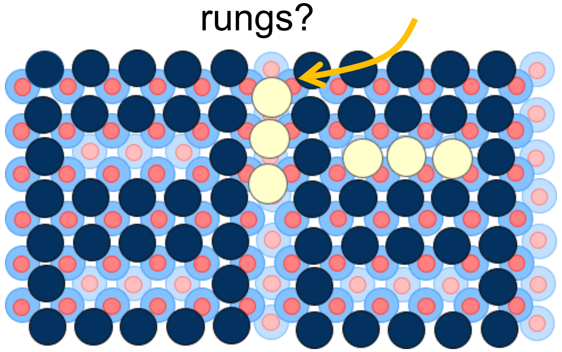
- in-situ PVD with STM

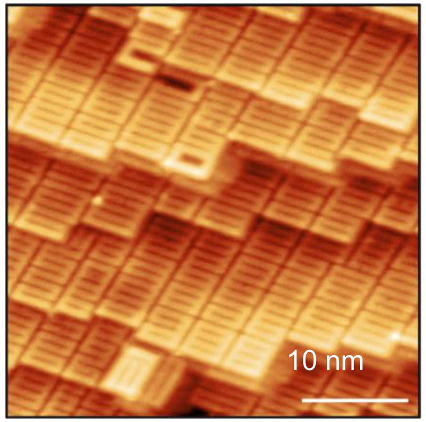


The nucleation stage determines the final film morphology and uniformity.

Preferential adsorption between ladder rows or rungs?



STM of (3 × 1)-O/Nb(100) structure



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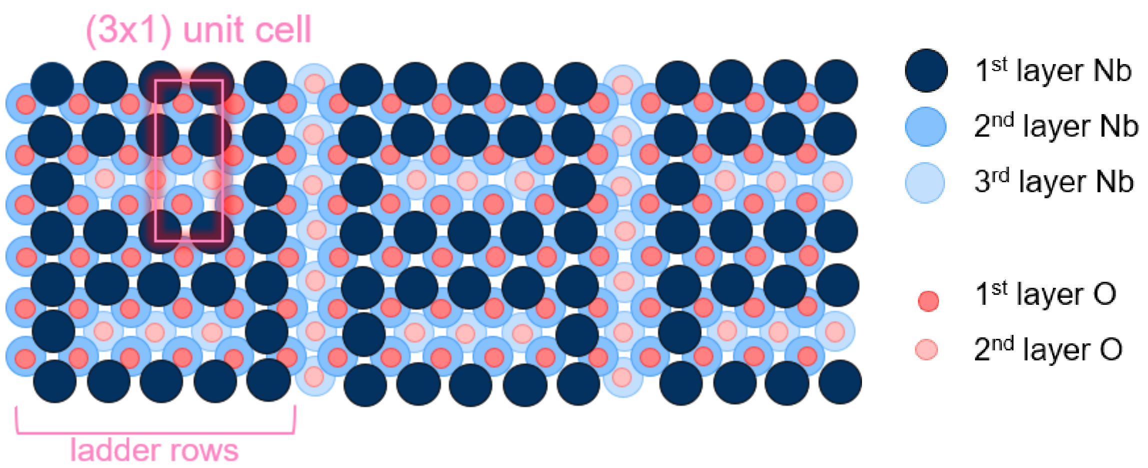
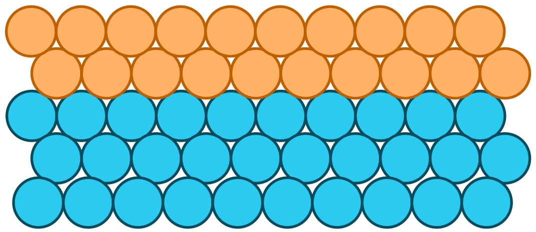
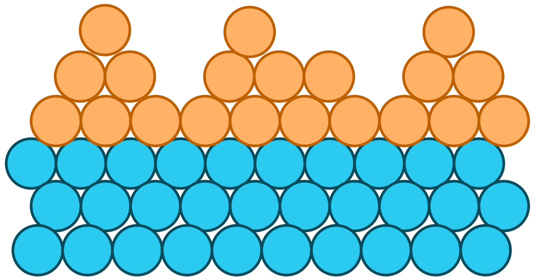


The model system enables systematic studies of nucleation by varying:
- **Deposition Rate**
- **Substrate Temperature**
- **Surface Preparation**

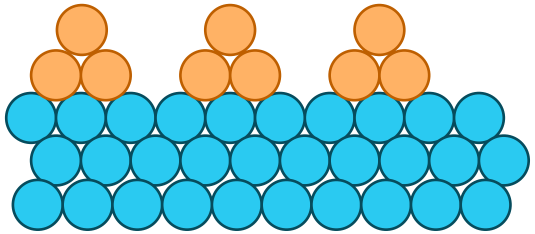
Growth mechanism



Frank-van der Merwe
(Layer-by-Layer)



Stranski-Krastanov
(Layer Plus Island Growth)

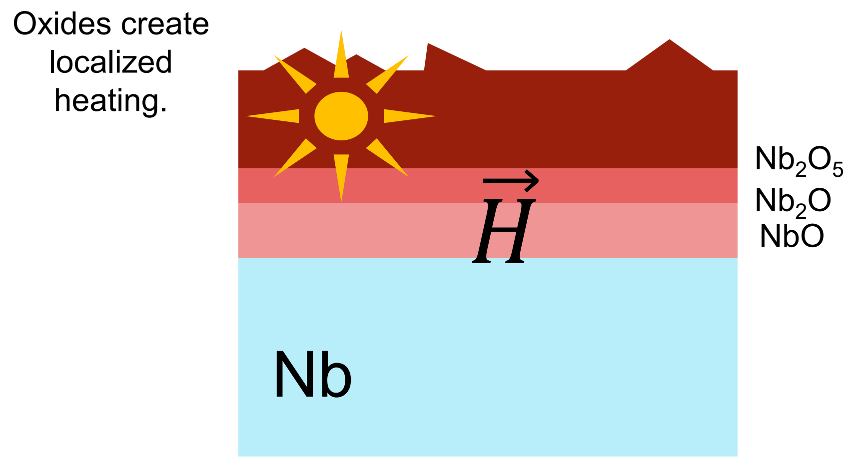


Volmer-Weber
(Island Growth)

Preventing Lossy Nb Oxide Formation

Nb forms deleterious oxides that limit accelerating performance.

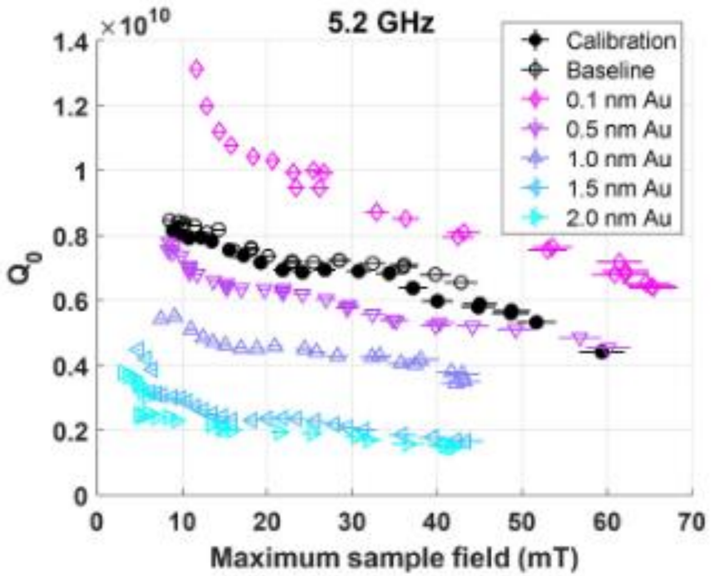
- Nb readily forms insulating oxides that increase RF losses and promote quench
- Native Nb_2O_5 Formation
  - –Amorphous
  - –Insulating, non-SC
  - –5-7 nm



Preventing Lossy Nb Oxide Formation With Inert Coating

Nb forms deleterious oxides that limit accelerating performance.

- Au capping layers have been shown to increase Q-factor
- Caveat! The effectiveness of Au depends on forming a continuous ultrathin film.



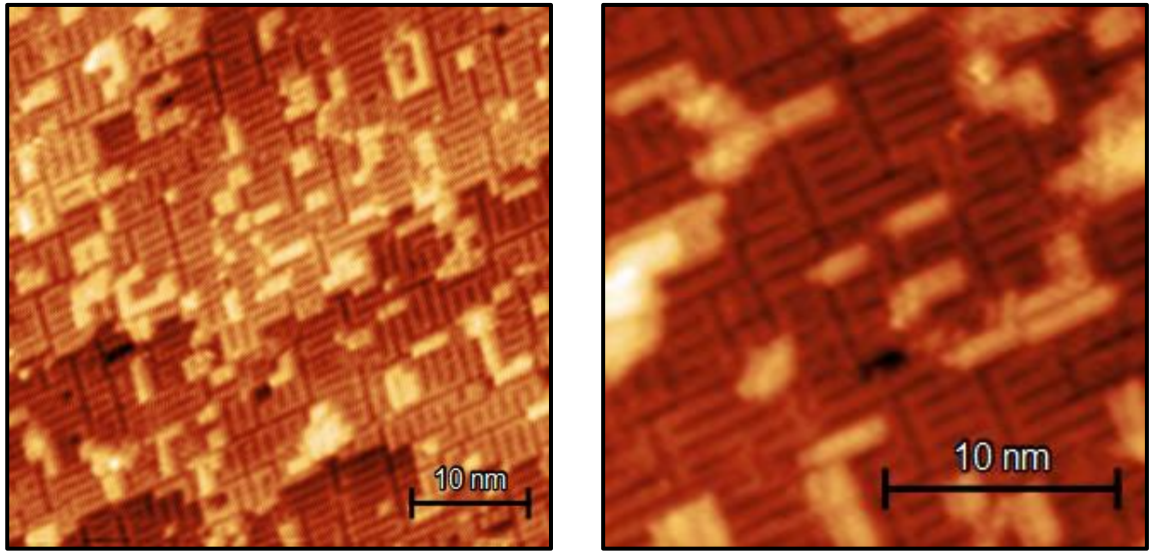
Oseroff, T.; Sun, Z.; Liepe, M. U. *Supercond. Sci. Technol.* **2023**, *36* (11), 115009.

An atomic-scale, mechanistic investigation is needed to understand Au nucleation and growth.

Low Au Coverage Leads to Island Formation

- **0.25 ML Au deposition on (3 × 1)-O/Nb(100)**
- 10 minute anneals
  - 500°C – Au reorganizes to wire-like island aligned with the (3 × 1)-O/Nb(100) reconstruction

500°C



Au nucleates as islands rather than a continuous film.

Low Au Coverage Leads to island formation

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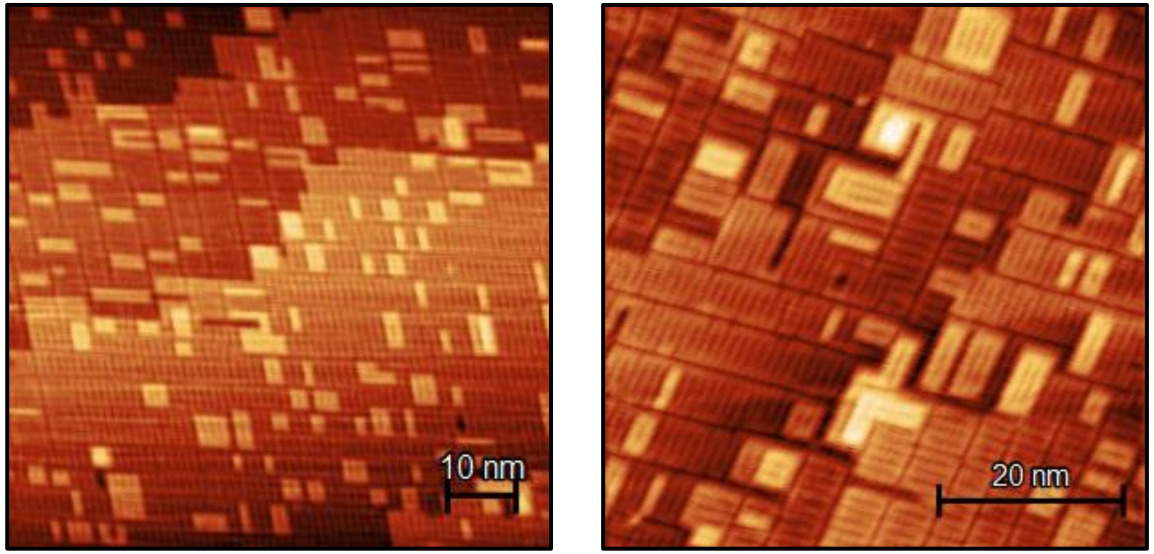
  - 800°C – Further organization

800°C

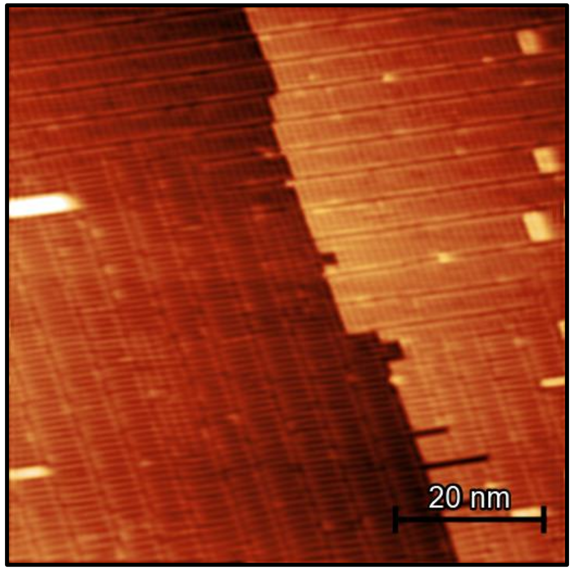


Annealing enhances ordering but does not produce complete wetting.

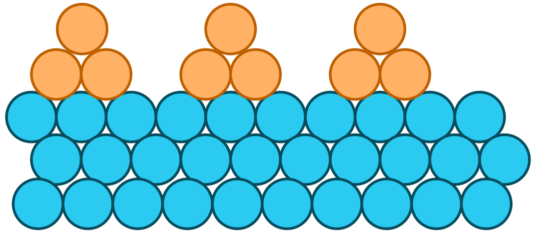
Low Au Coverage Leads to Island Formation

- **0.25 ML Au deposition on (3 × 1)-O/Nb(100)**
- 10 minute anneals
  - 500°C – Au reorganizes to wire-like island aligned with the (3 × 1)-O/Nb(100) reconstruction
  - 800°C – Further organization
  - 900°C – Au desorption

900°C



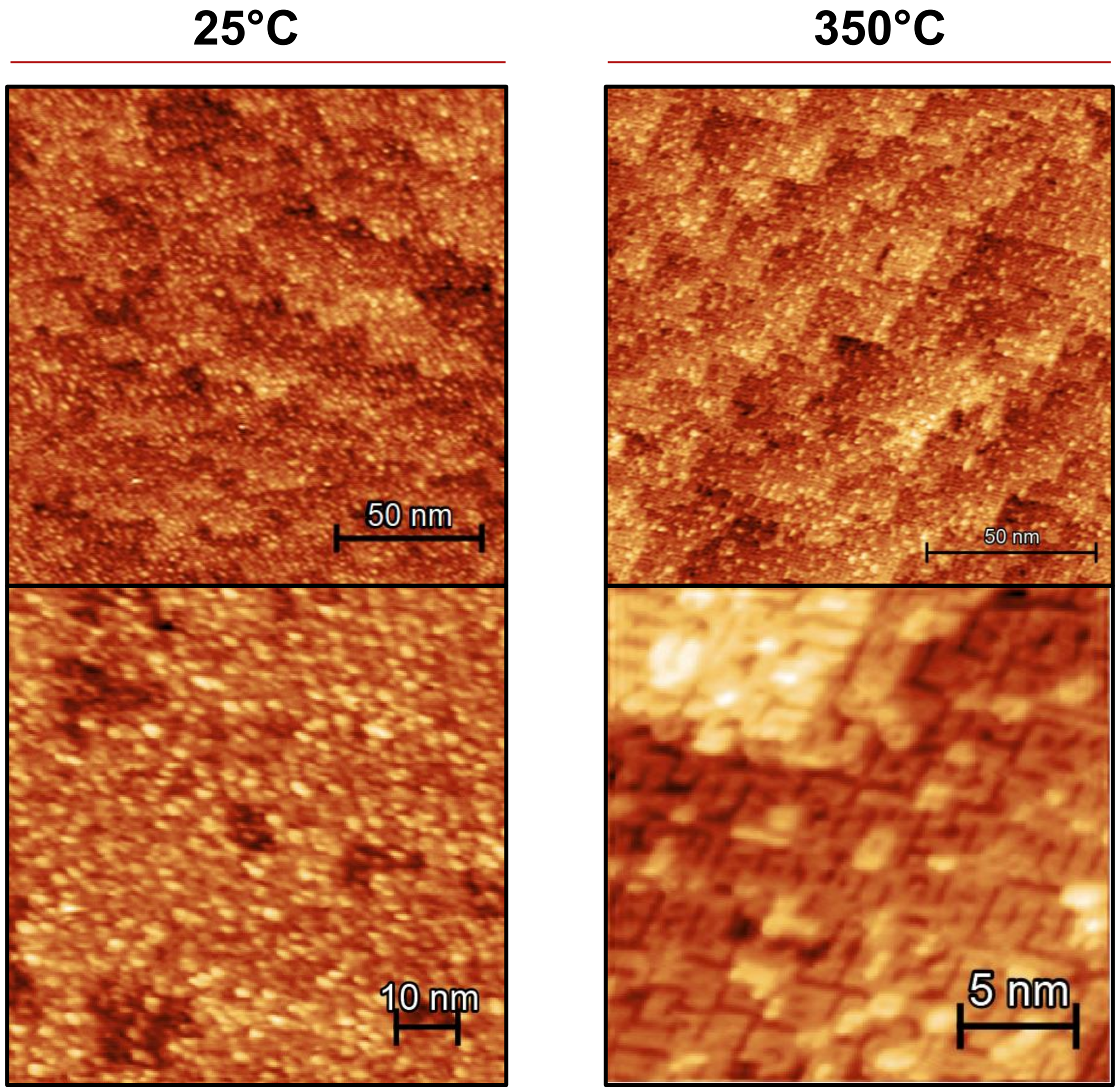
Au–Au interactions are stronger than Au–NbO interactions, favoring 3D island formation.



Annealing Promotes to Island Formation

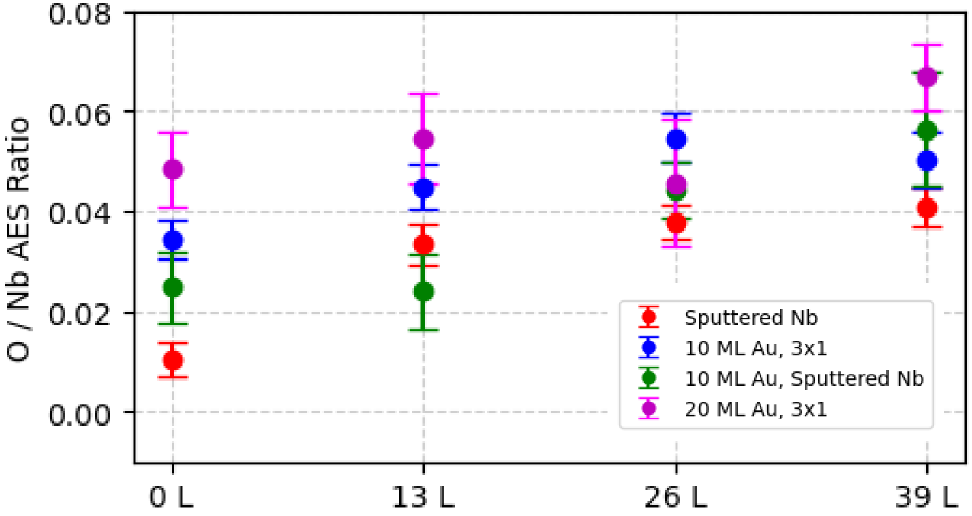
- **1 ML Au deposition on (3 × 1)-O/Nb(100)**
- Post-Deposition (25°C) – Flat but disordered Au coverage
    - 350°C – Au island formation

Although Au initially wets the surface, annealing drives dewetting Au islands, exposing NbO to oxidation.



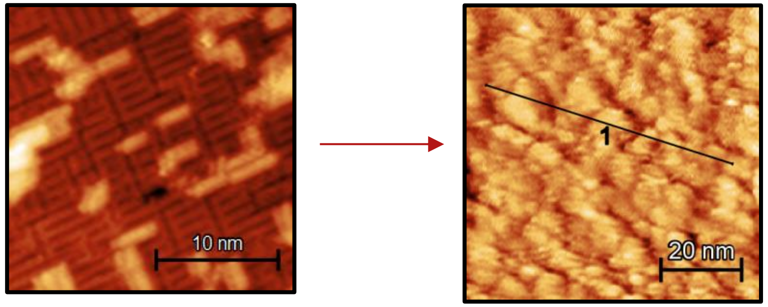
Early Island Nucleation Dictates the Final Porous Morphology Leading to Oxidation

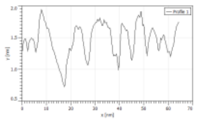
- Au depositions 1-20 ML on
  - (3 × 1)-O/Nb(100)
  - Sputtered Nb
- Tested anneals from 360°C - 1100 °C
- Nb_2O_5 forms after every ATM exposure

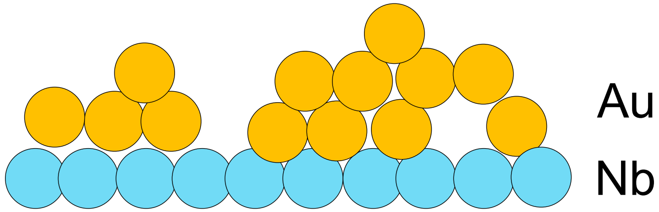


STM of 0.25 ML Au on (3 × 1)-O/Nb(100) + 500°C

STM of 10 ML Au on (3 × 1)-O/Nb(100) + 800°C Flash







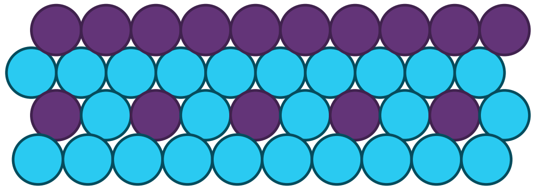
Island formation → porous Au layers

Early-stage island nucleation persists during growth, producing porous Au films even at high coverage.

Zr as a Sacrificial Oxygen Getter

Implementation of Zr - Beneficial reactivity

- Zr interdiffusion forms high TC superconducting Nb/Zr alloy (17.7 K)
- Preferential oxidation in Zr/Nb multilayer systems

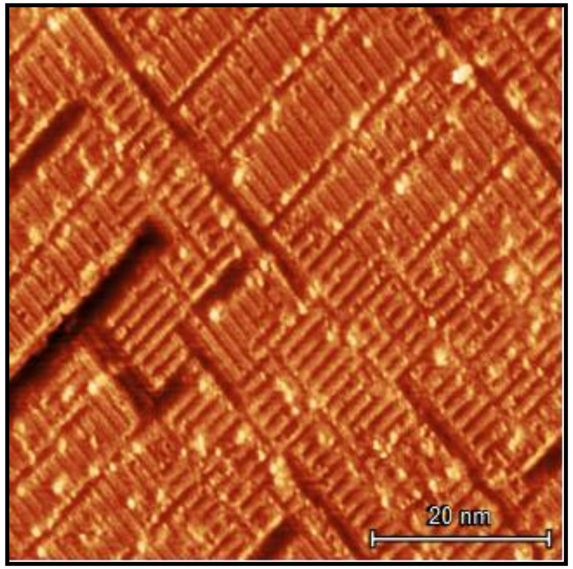


Volmer-Weber Growth of Zr on (3x1)-O/Nb(100)

Initial Zr deposition follows a Volmer–Weber growth mode, producing non-uniform islands rather than atomically flat films.

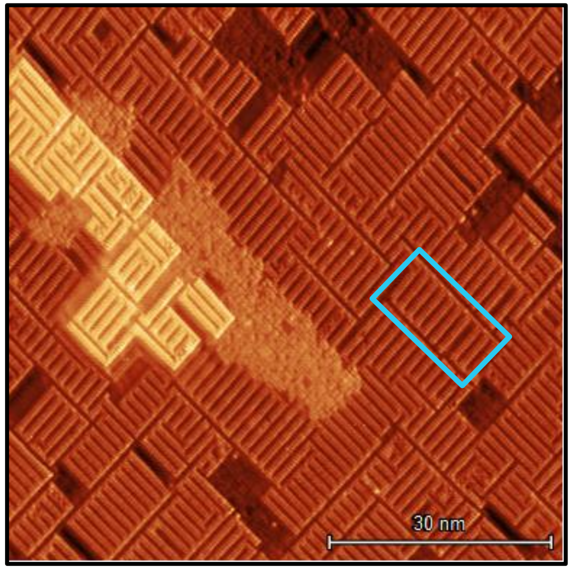
The reconstruction changes from (3×1) to cubic following Zr deposition, suggesting oxygen transfer from NbO to Zr.

Post Deposition at 25 ° C



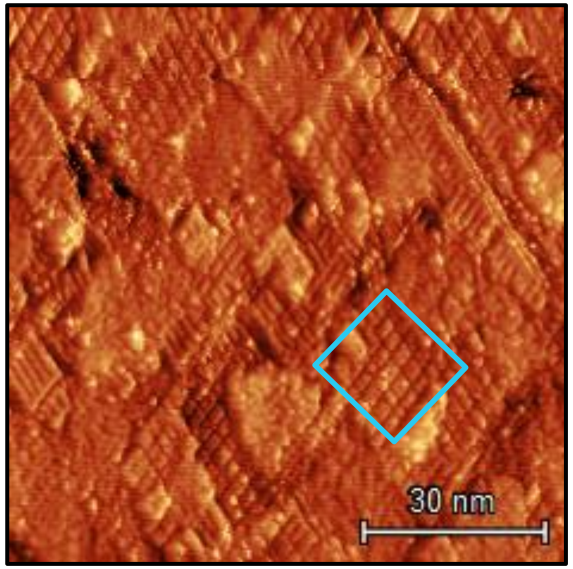
0.15 ML

800 °C



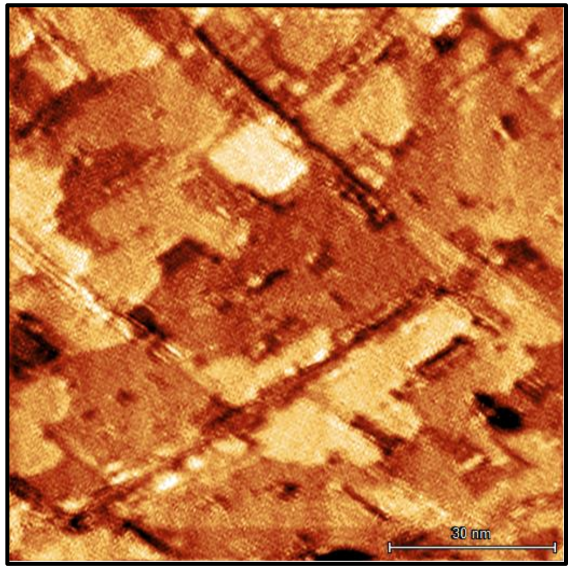
0.15 ML

650 °C



0.70 ML

650 °C



0.95 ML

STM Reveals Atomic-Scale Growth of Candidate SRF coatings

- **Au nucleates via Volmer–Weber island growth, producing porous films after annealing.**
- Porous Au coatings expose Nb to oxidation, limiting their effectiveness as protective layers.
- Zr growth also follows Volmer-Weber growth, but **Zr exhibits reactive growth behavior consistent with oxygen scavenging.**

Understanding nucleation and growth provides a pathway toward designing uniform, next-generation SRF material.

Thank you for listening!

Acknowledgements

- CBB
- Sibener Group

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