# High Performance $Nb_3Sn$ Cavities

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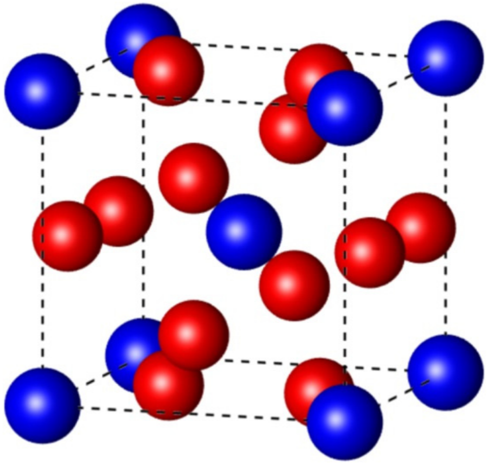
# Properties of $Nb_3Sn$

**Higher critical temperature**

→ Operation at 4.2 K

**Higher superheating field**

→ Double the limit of niobium



**Blue: tin**

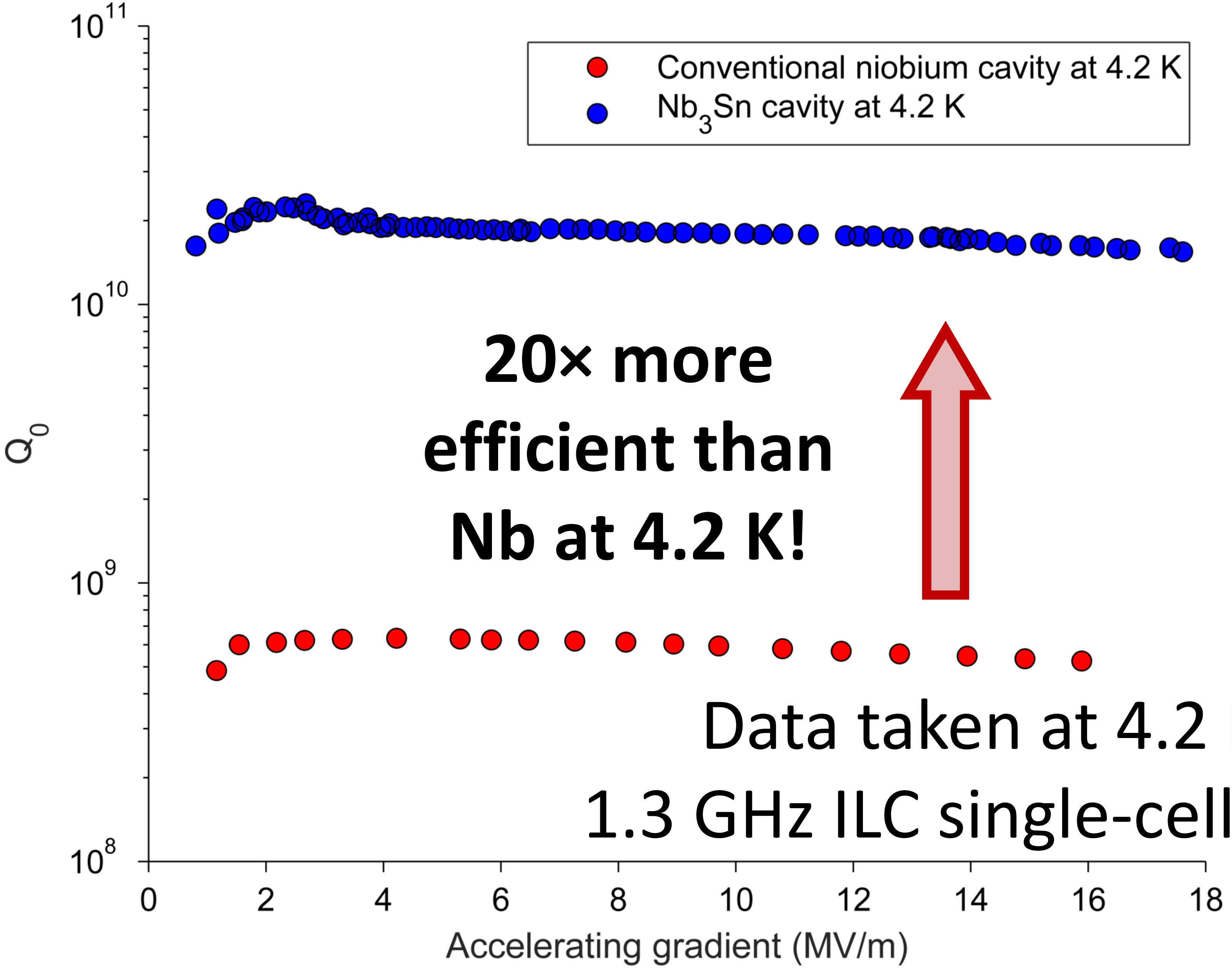
**Red: niobium**

| Parameter | Niobium | $Nb_3Sn$ |
|---|---|---|
| **Transition temperature** | **9.2 K** | **18 K** |
| **Superheating field** | **219 mT** | **425 mT** |
| Energy gap $\Delta/k_bT_c$ | 1.8 | 2.2 |
| $\lambda$ at $T = 0$ K | 50 nm | 111 nm |
| $\xi$ at $T = 0$ K | 22 nm | 4.2 nm |
| GL parameter $\kappa$ | 2.3 | 26 |

Lower losses

Higher gradients

# Comparison to niobium

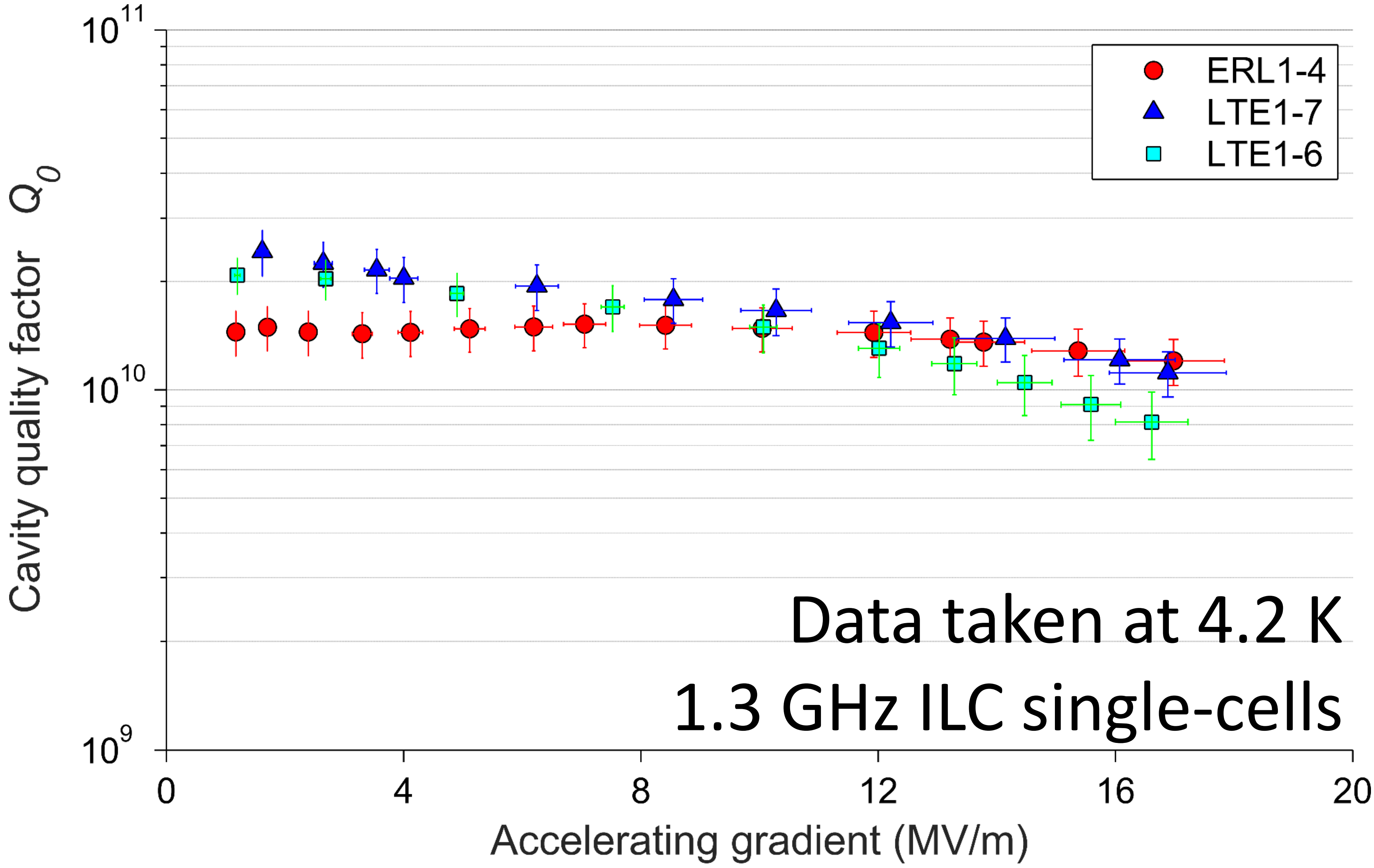


**20× more efficient than Nb at 4.2 K!**

Data taken at 4.2 K

1.3 GHz ILC single-cells

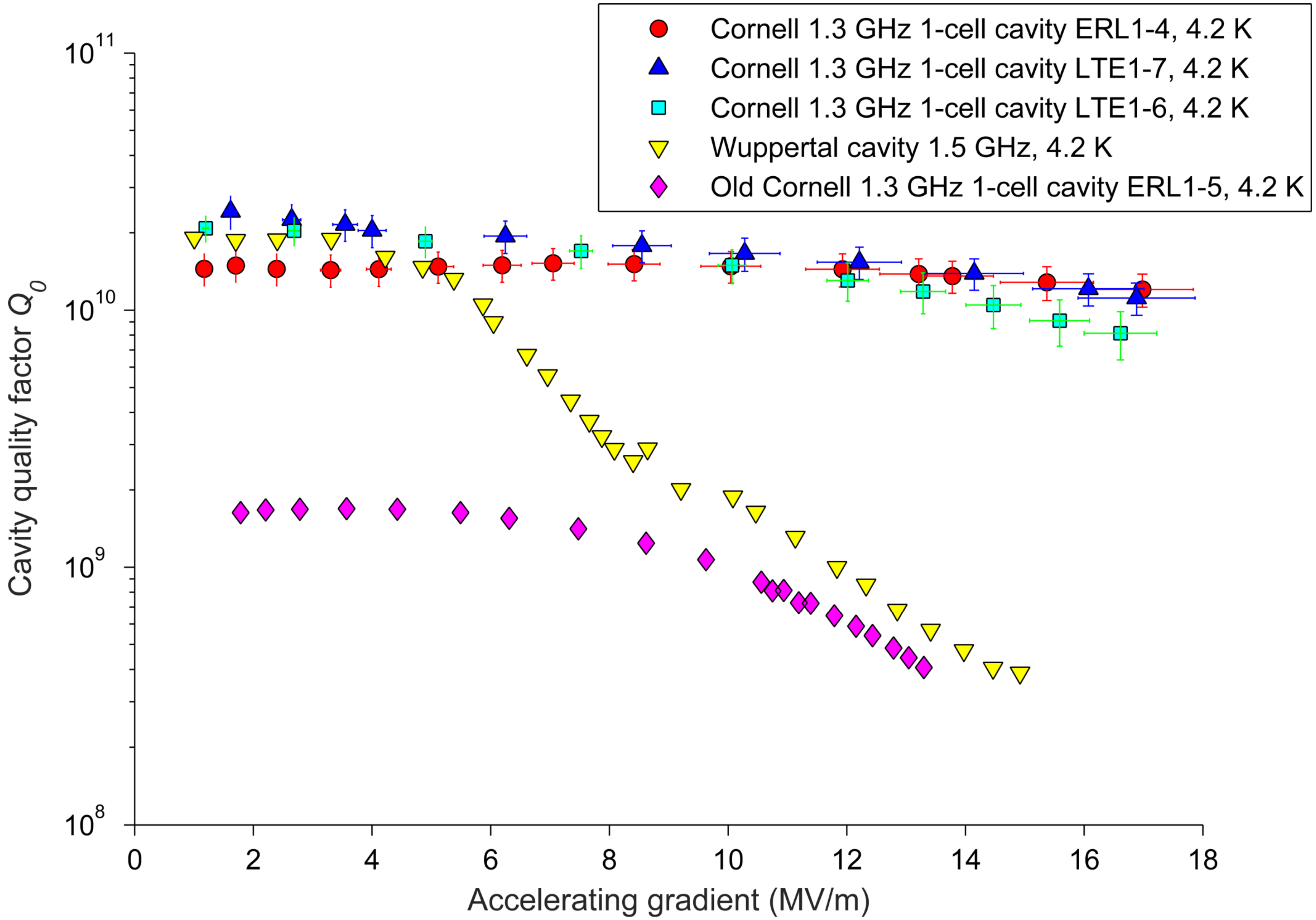
# Current performance



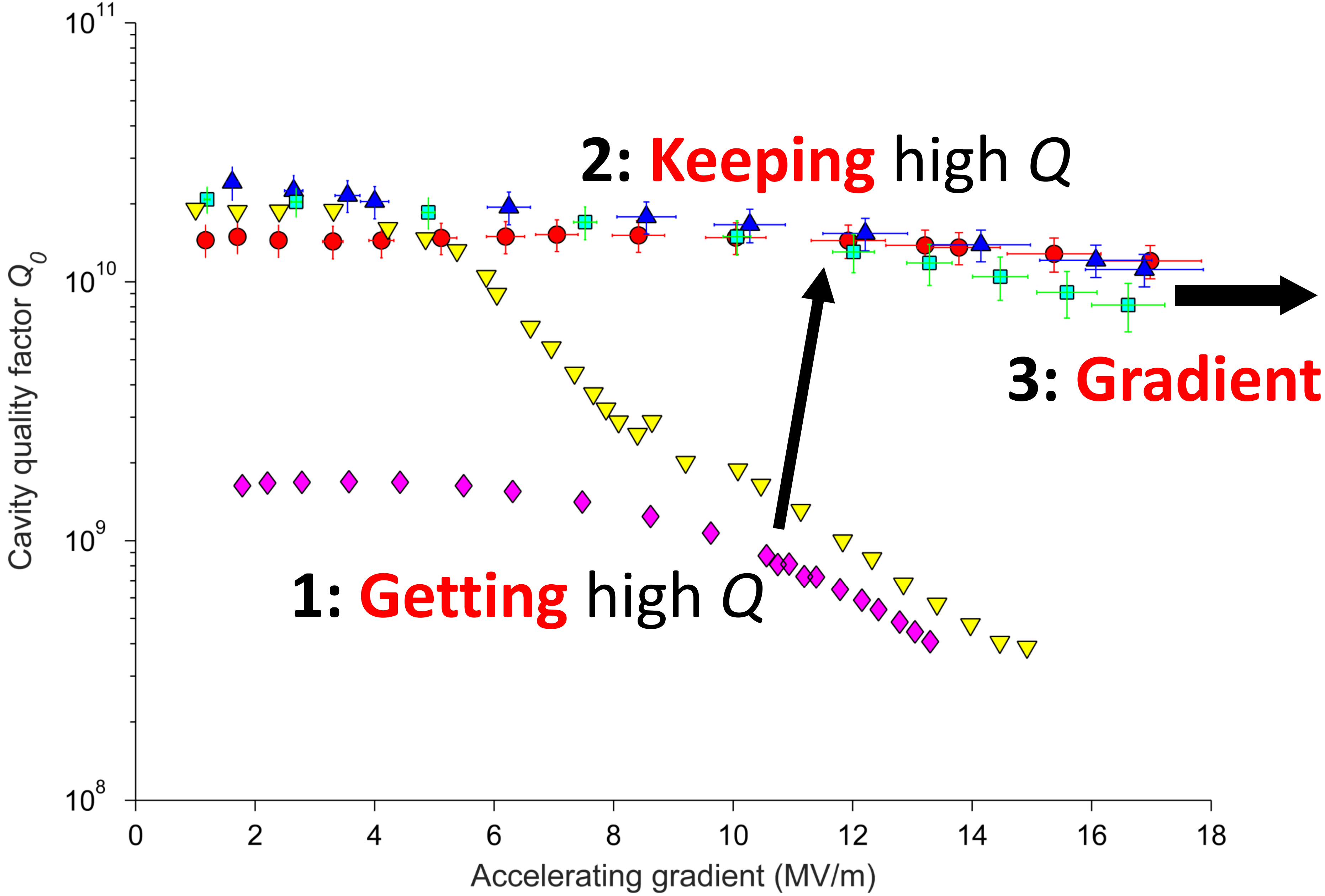
Data taken at 4.2 K

1.3 GHz ILC single-cells

# How far we've come



# Today’s talk

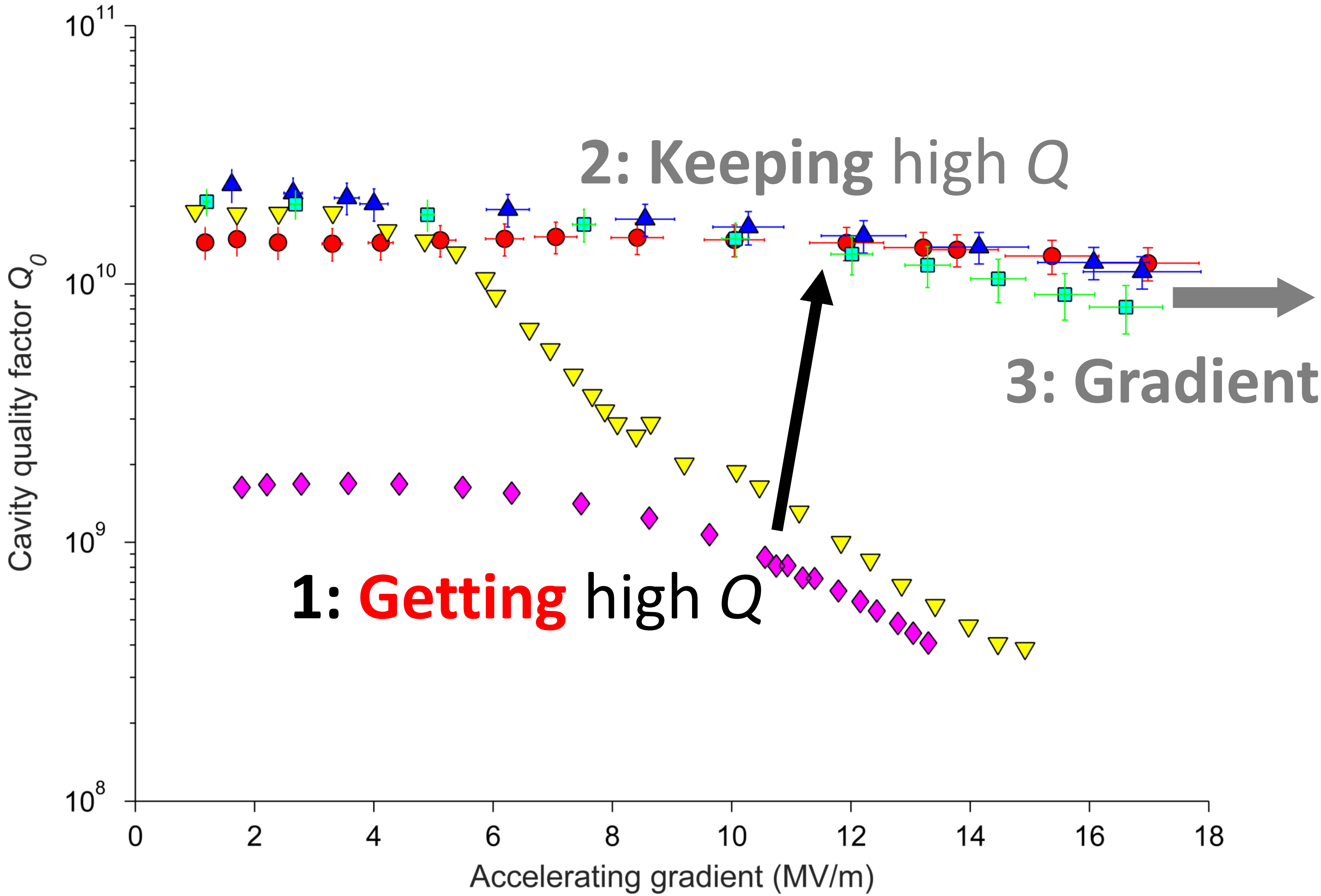


**2:** **Keeping** high *Q*

**3:** **Gradient**

**1:** **Getting** high *Q*

# Getting high *Q*



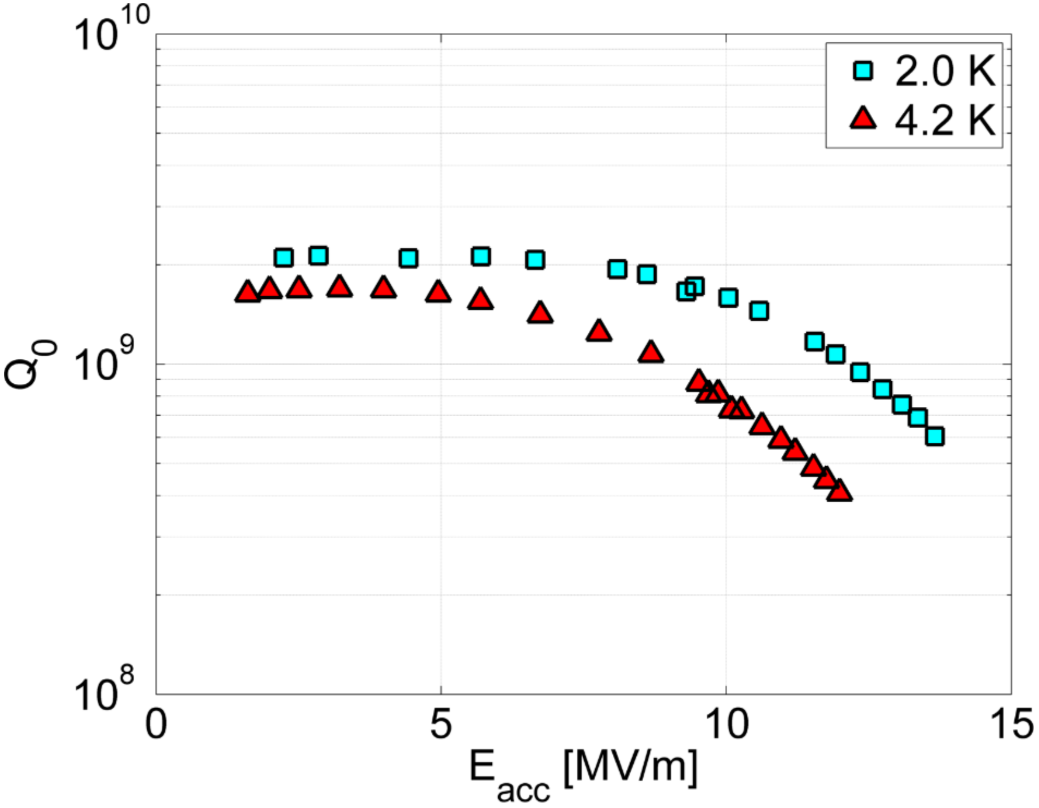
**2: Keeping** high *Q*

**3: Gradient**

**1: Getting** high *Q*

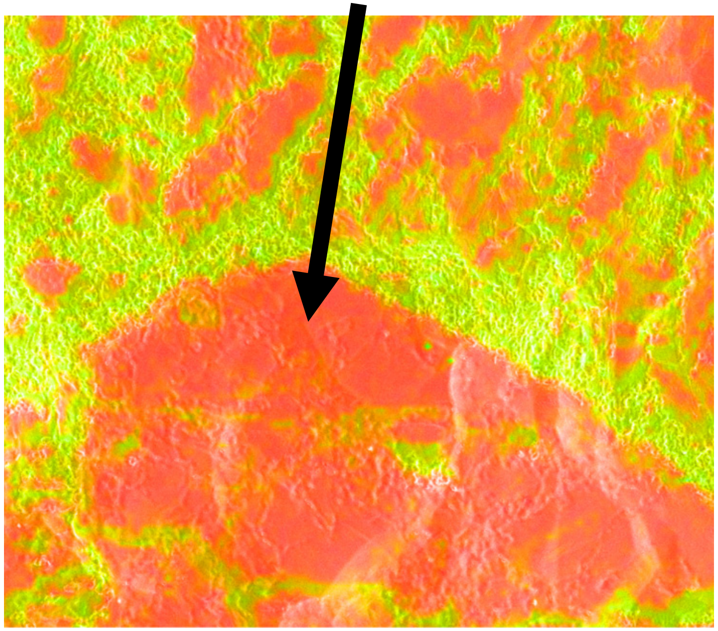
# Early cavity limitations

Early cavity showed **significant heating** on lower half-cell and **poor performance**



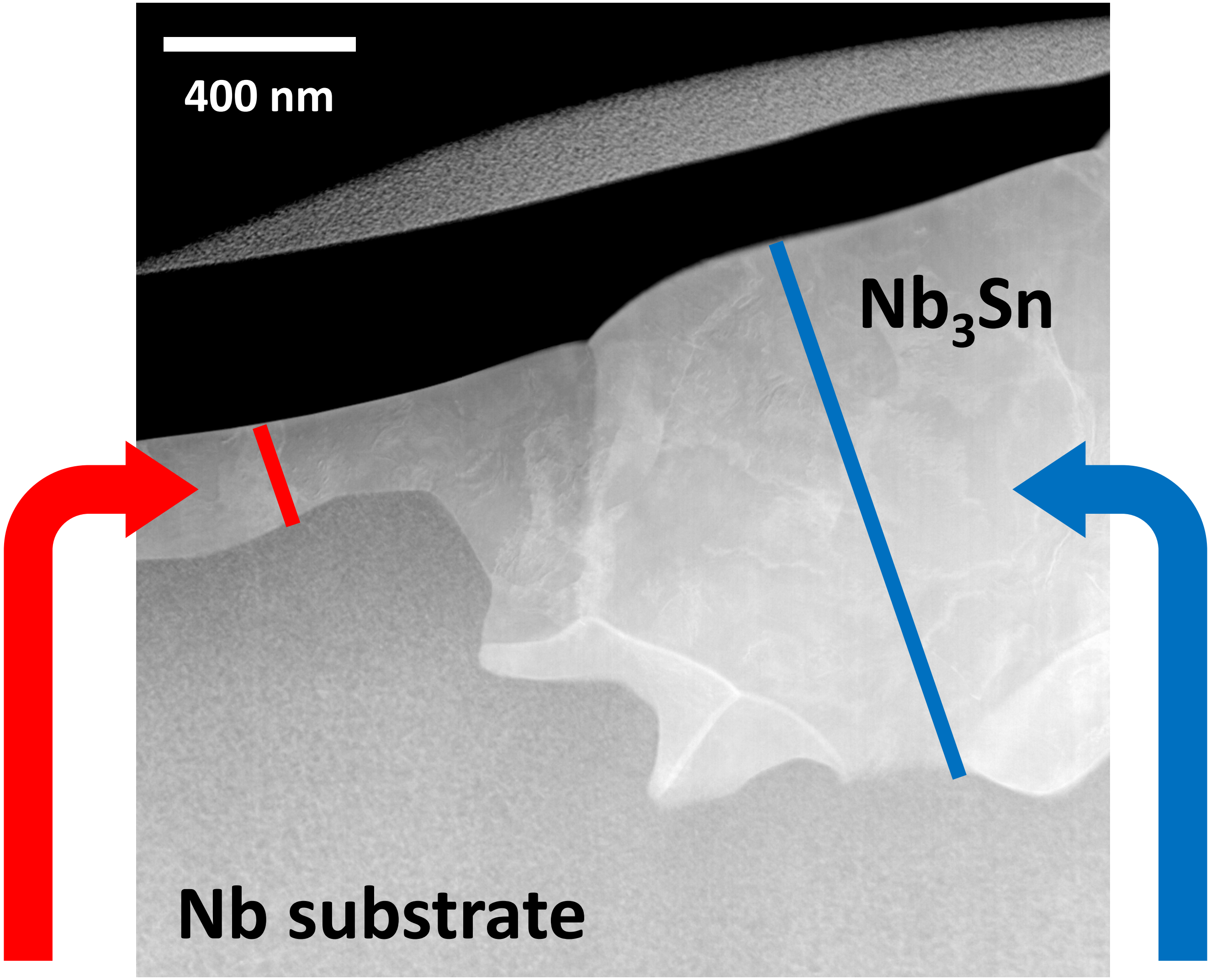
Cut-outs of the hot regions revealed large regions of **thin coating**

**Too thin!**



**100 µm**

# Thin film regions

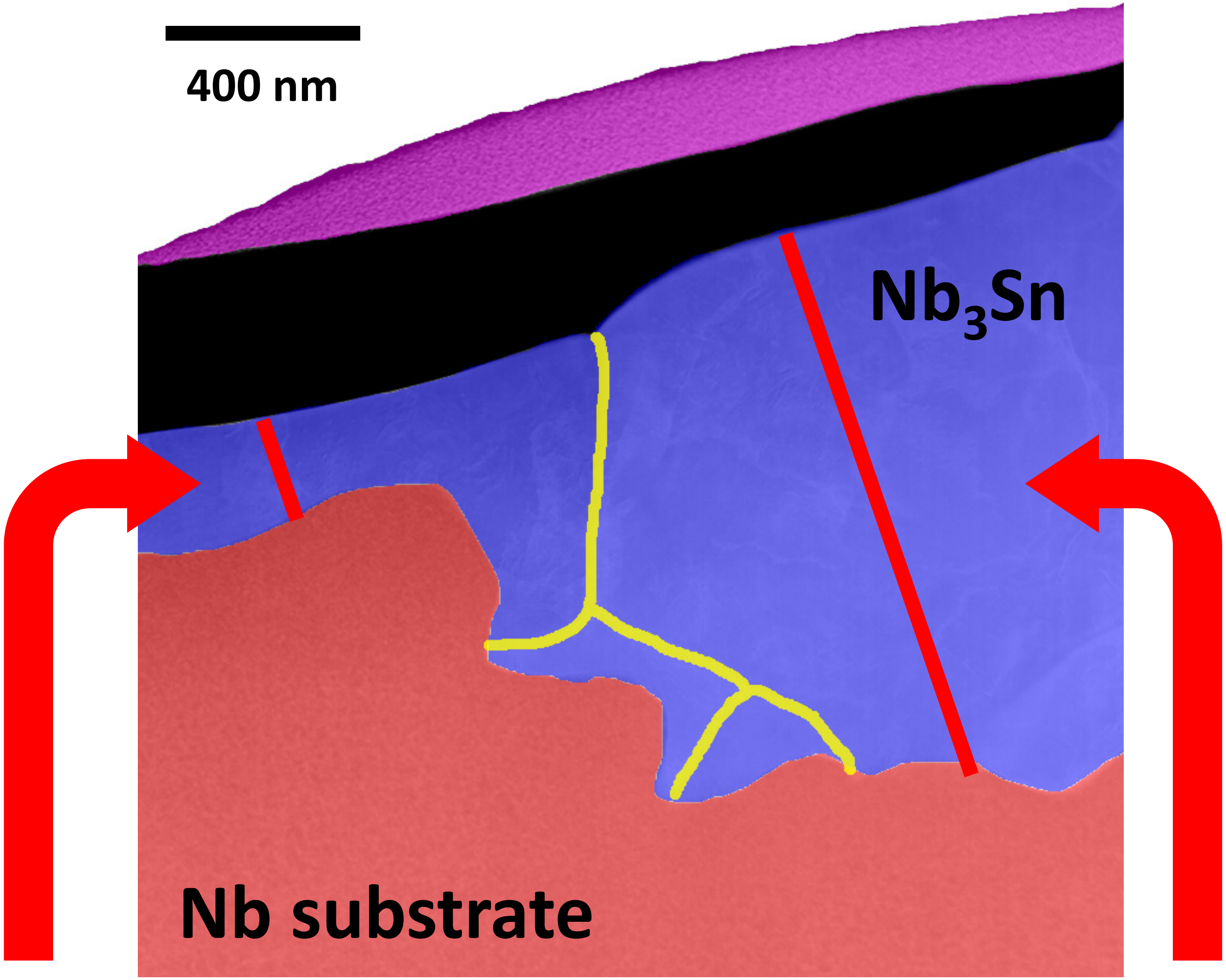


Too thin

Sufficiently thick

These **thin film regions** lead to **increased losses**

# Thin film regions



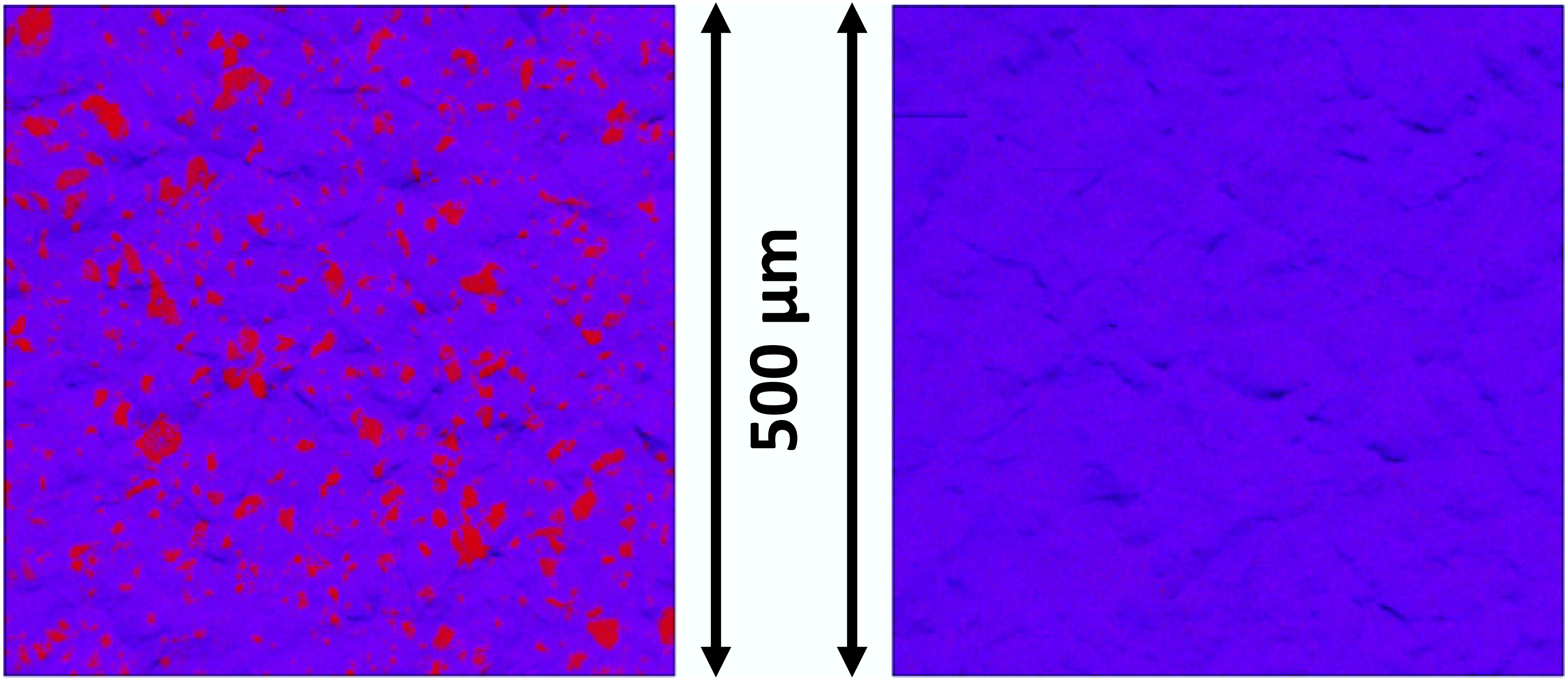
Too thin

Sufficiently thick

These **thin film regions** lead to **increased losses**

# Resolving thin film regions

Growing the **niobium oxide** prior to coating **suppresses the formation** of thin film regions



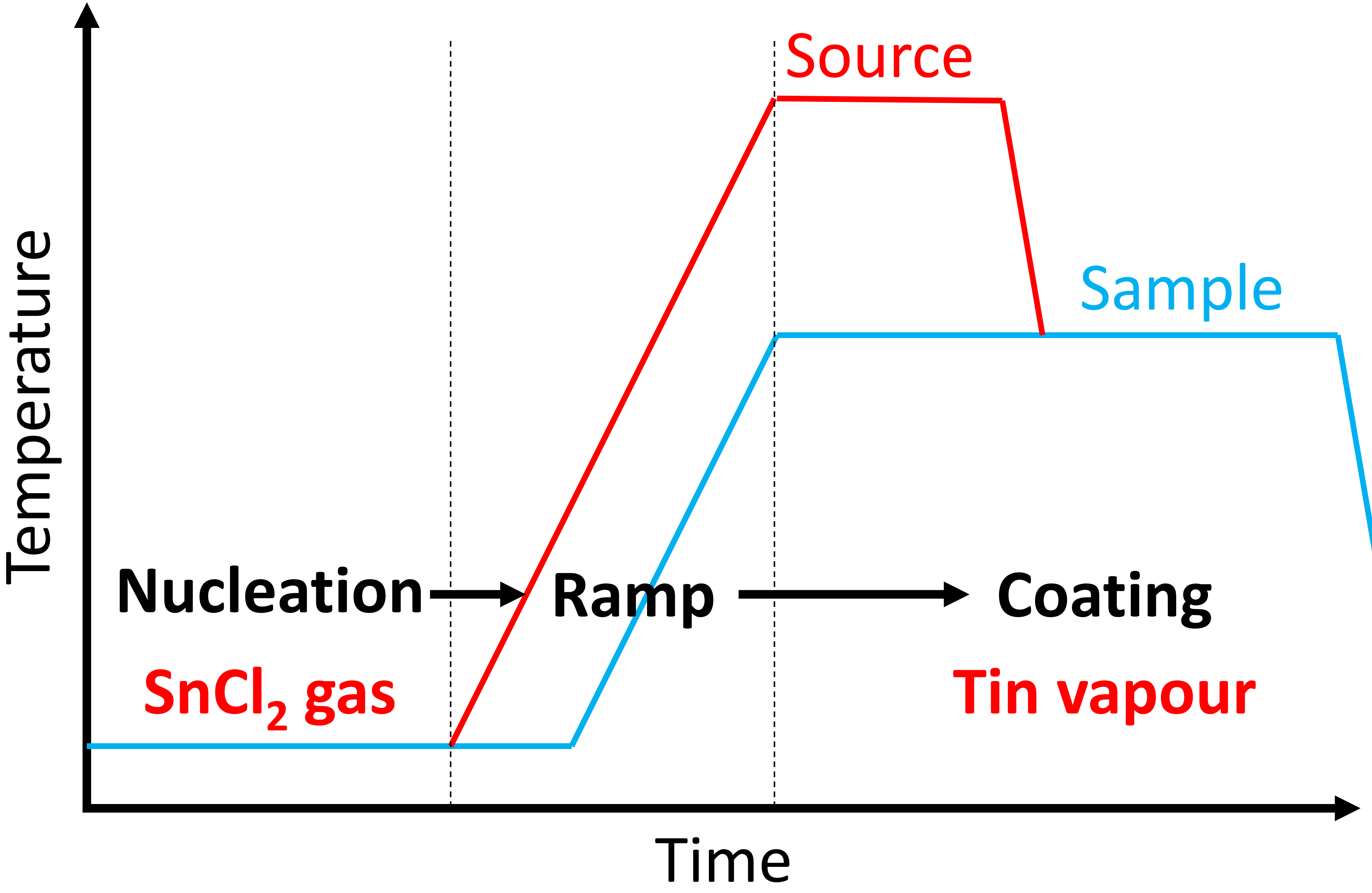
**Not pre-anodised**

**Pre-anodised substrate**

**Red**: too thin

**Blue**: sufficiently thick

# Stop-motion coating

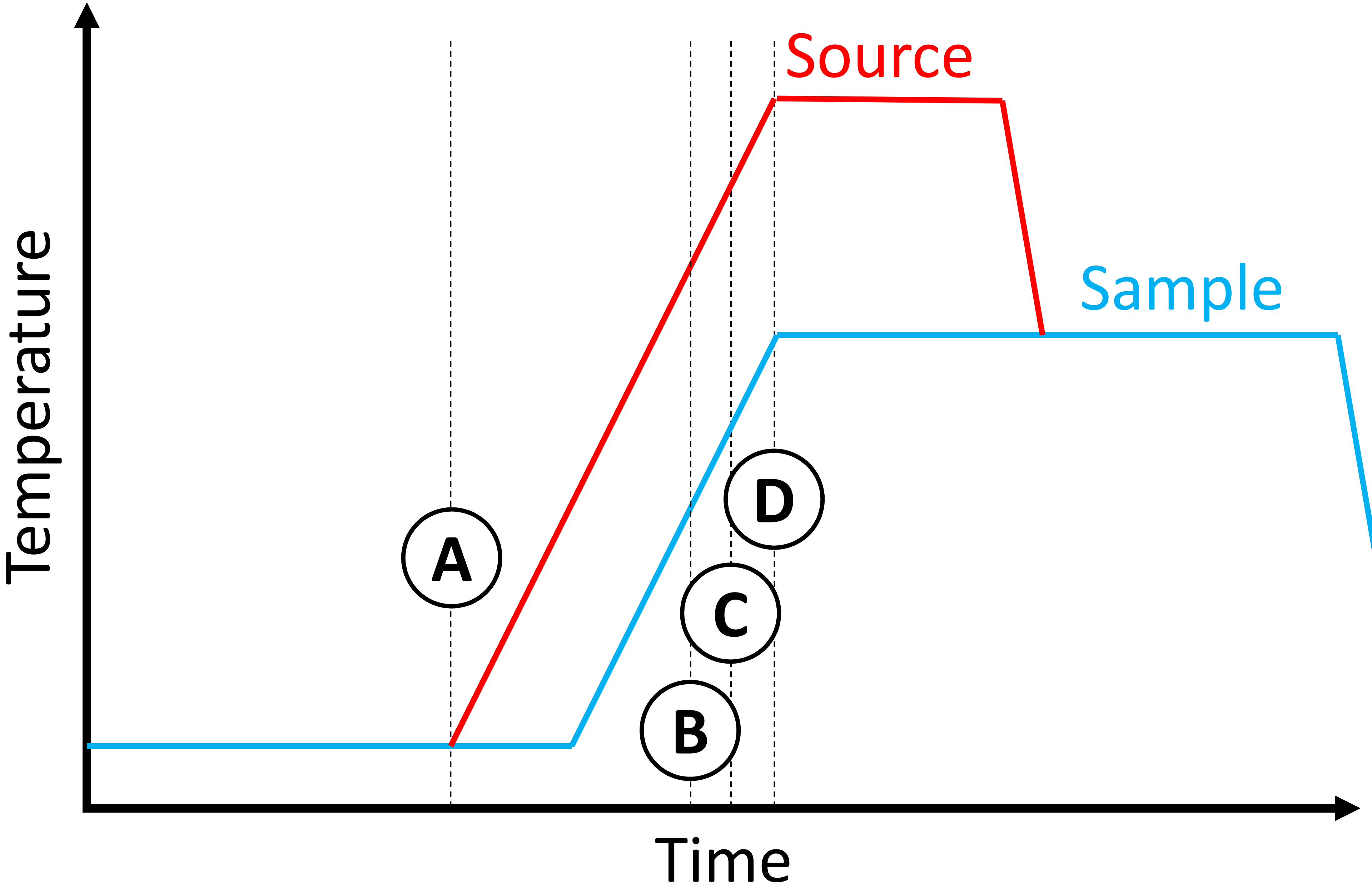


**Nucleation** → **Ramp** → **Coating**

$SnCl_2$ gas

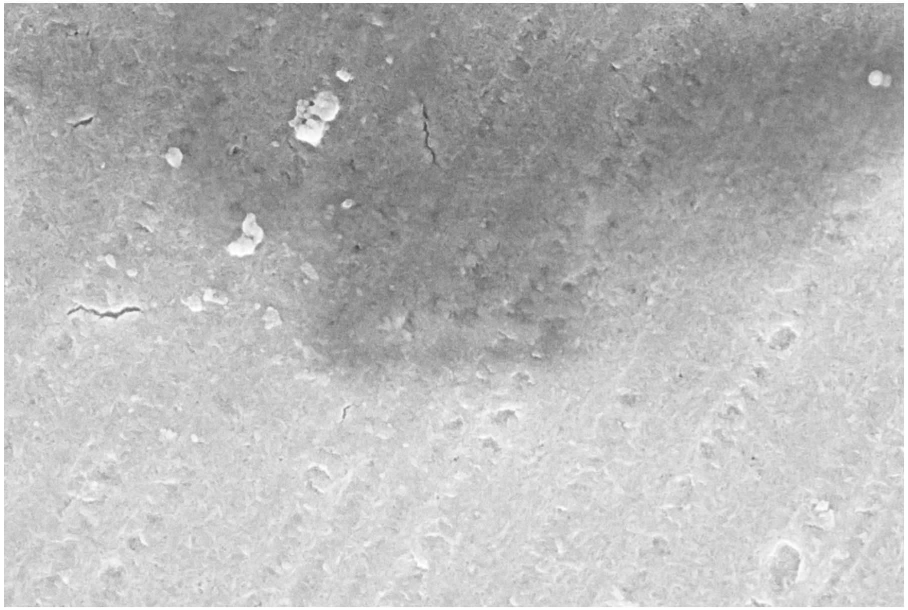
Tin vapour

# Stop-motion coating

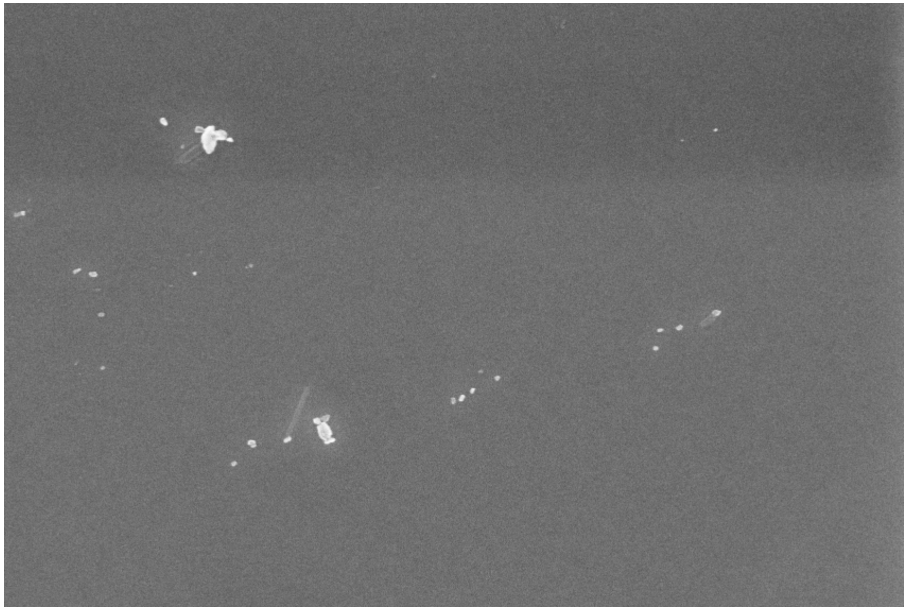


# Layer growth during ramp

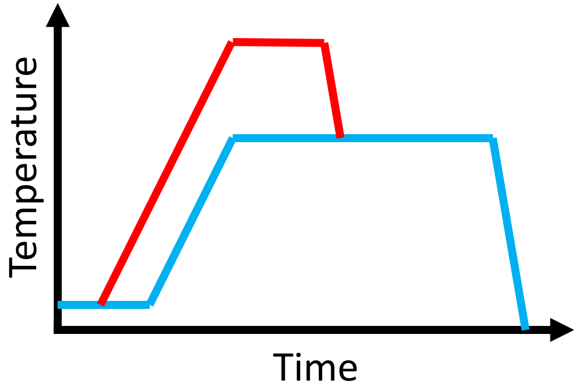
**Pre-anodised**



**Not anodised**



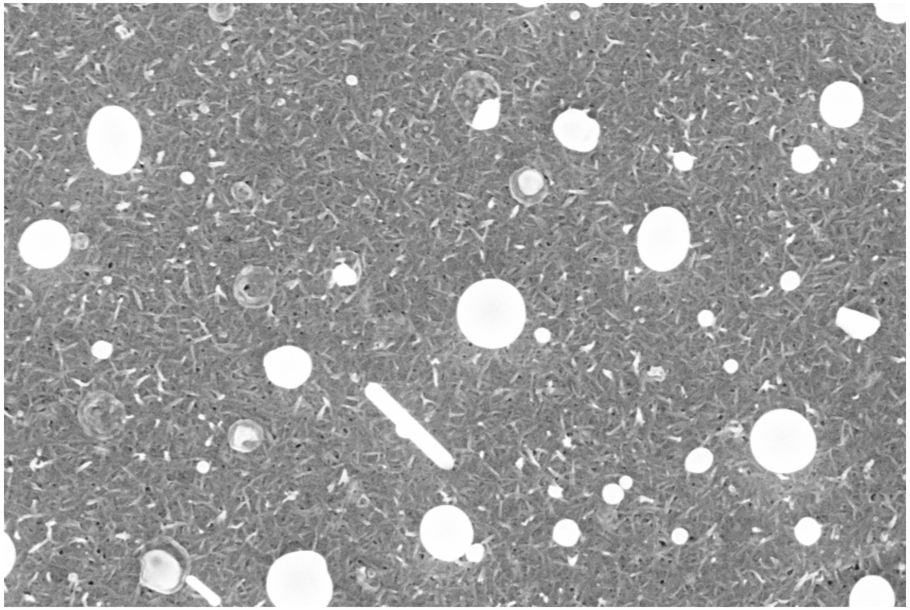
**2 µm**



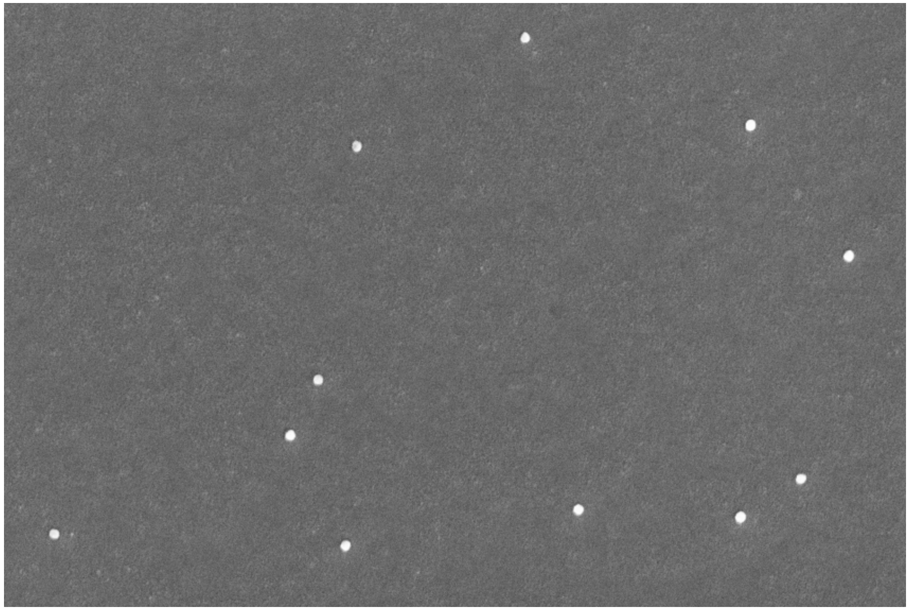
**Start**

# Layer growth during ramp

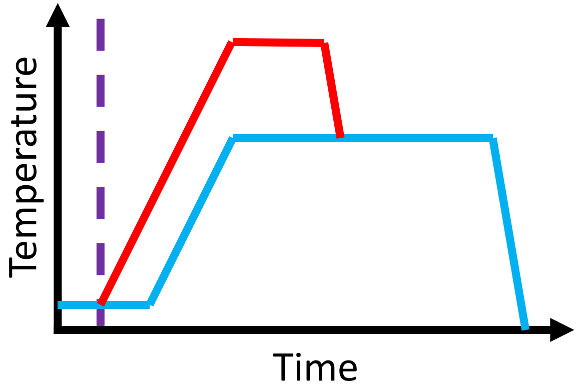
## Pre-anodised



## Not anodised



**2 µm**

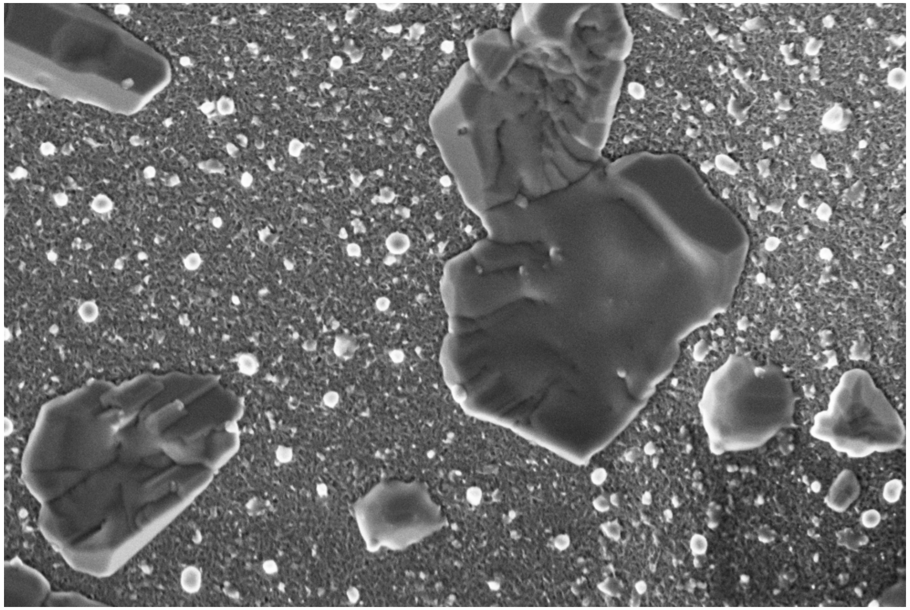


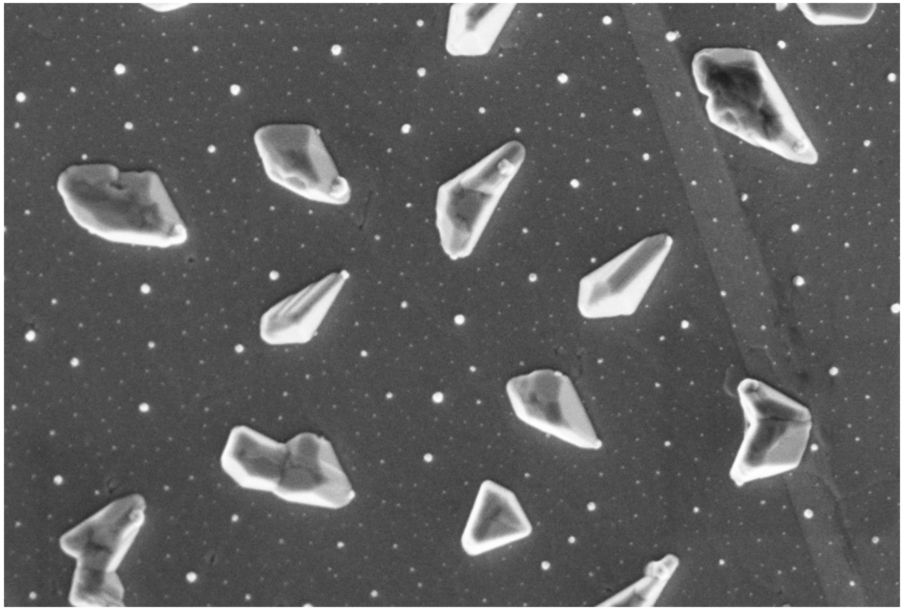
**500°C**

# Layer growth during ramp

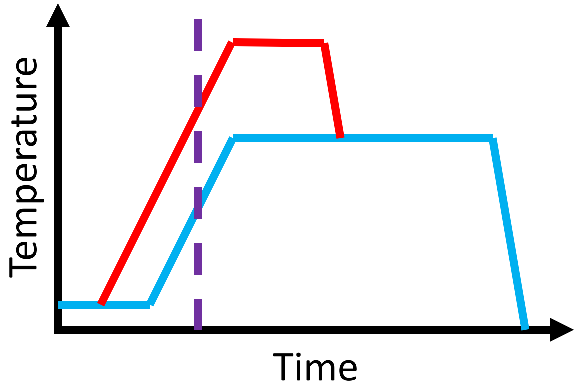
**Pre-anodised**

**Not anodised**





**2 µm**

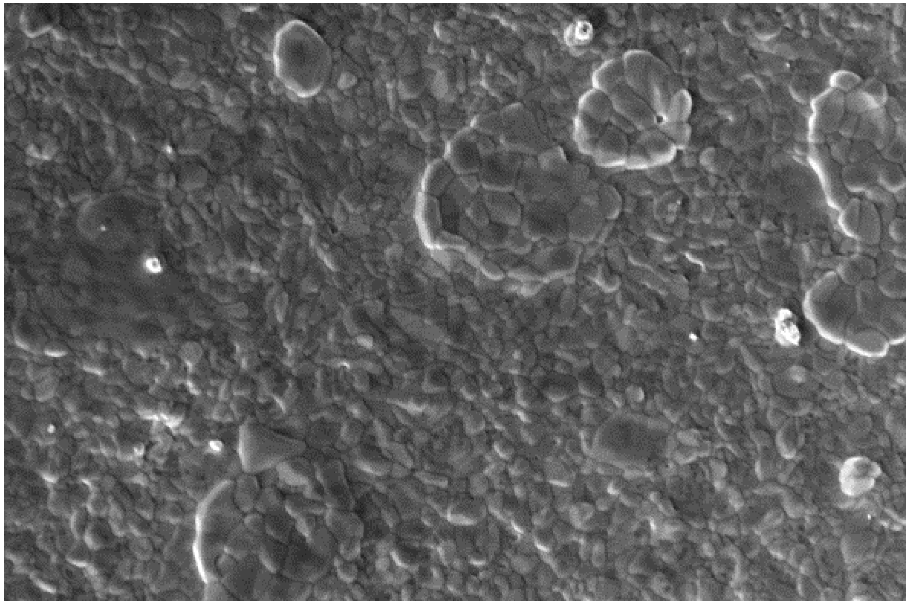


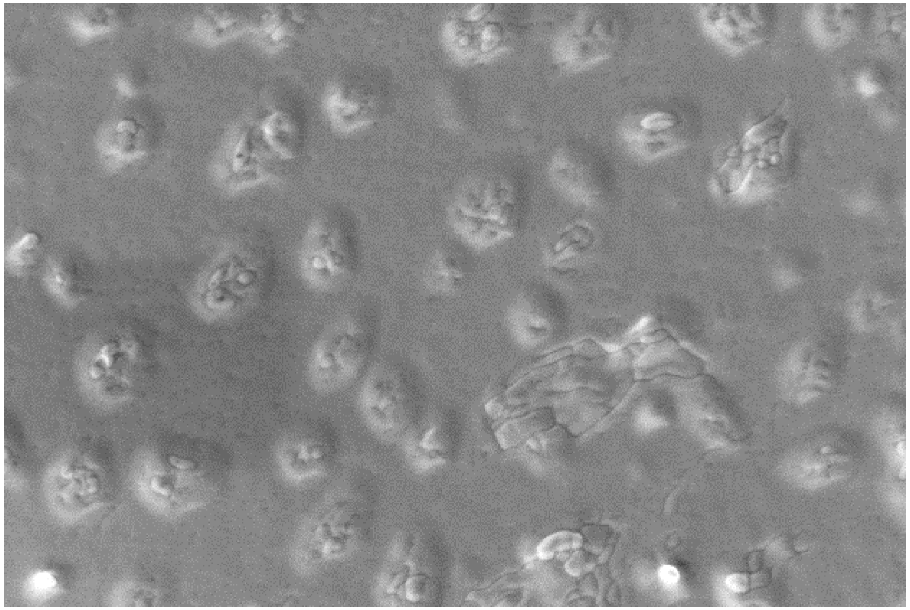
**800°C**

# Layer growth during ramp

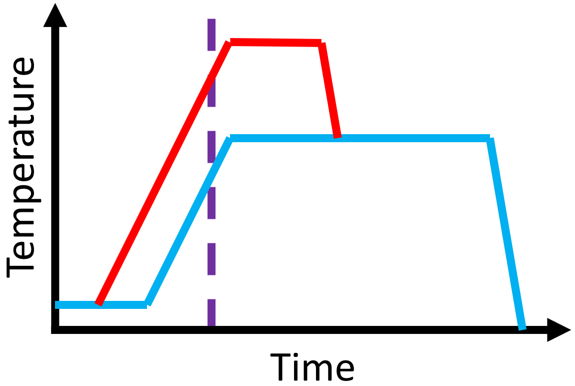
**Pre-anodised**

**Not anodised**





**2 µm**



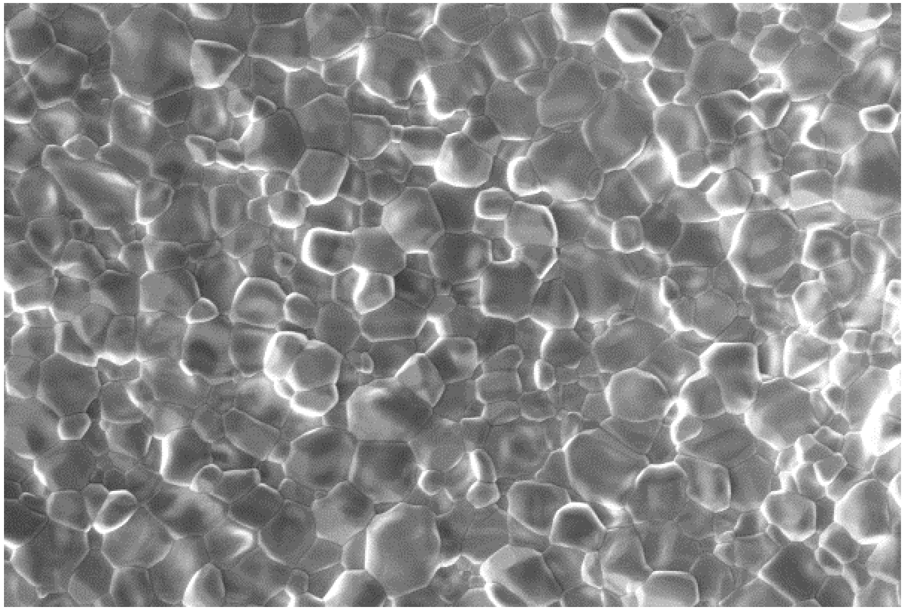
**950°C**

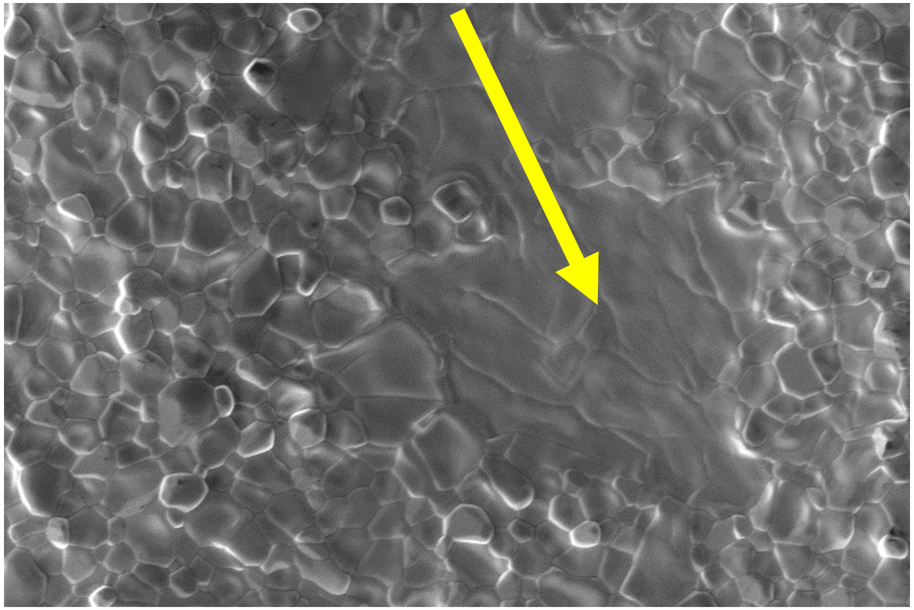
# Layer growth during ramp

**Pre-anodised**

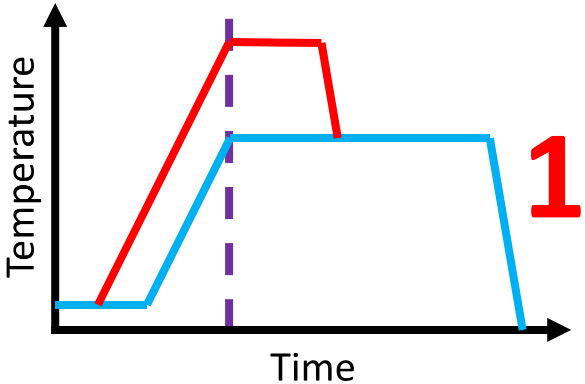
**Not anodised**

**Too thin!**



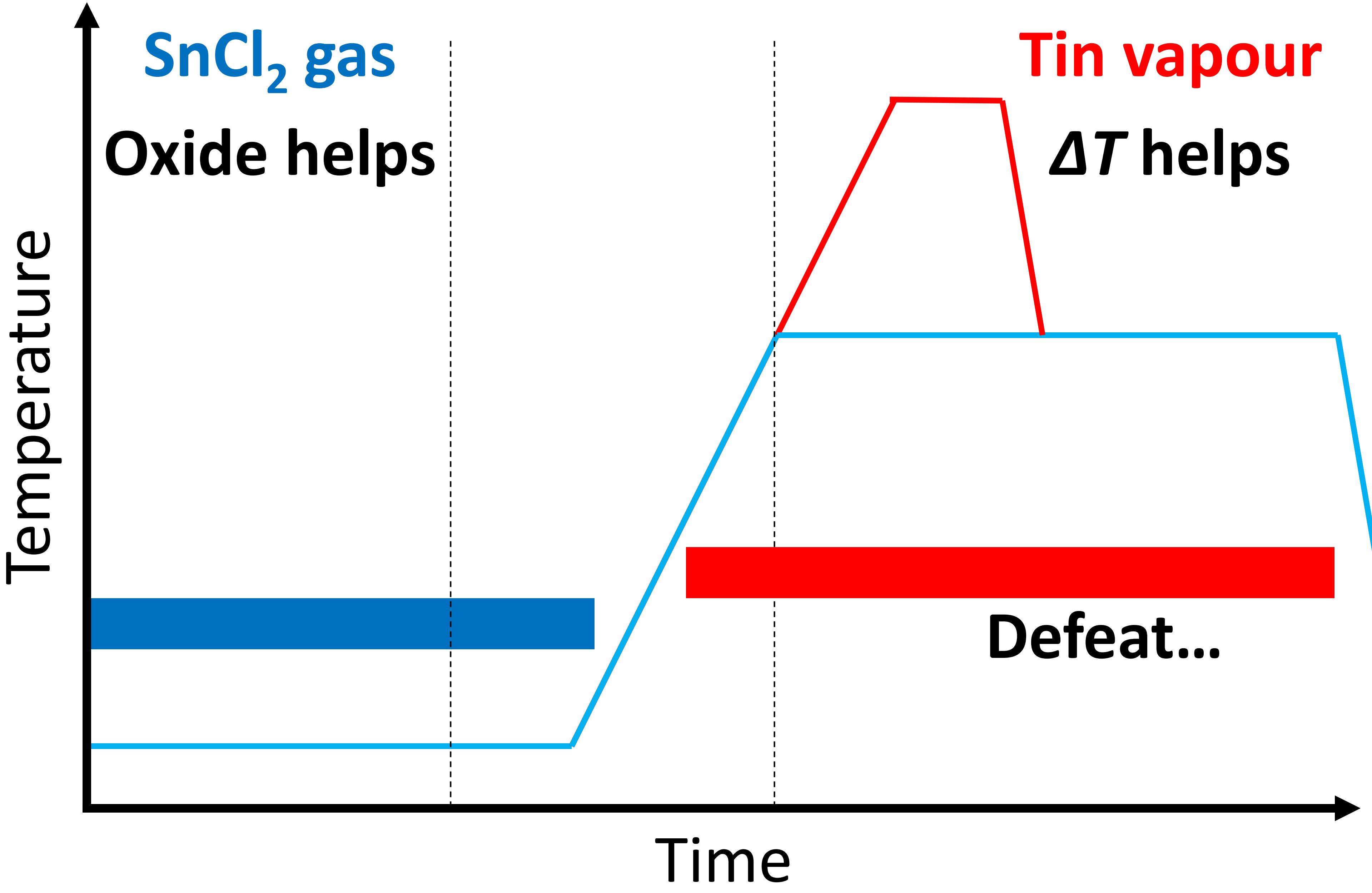


**2 µm** 🟥

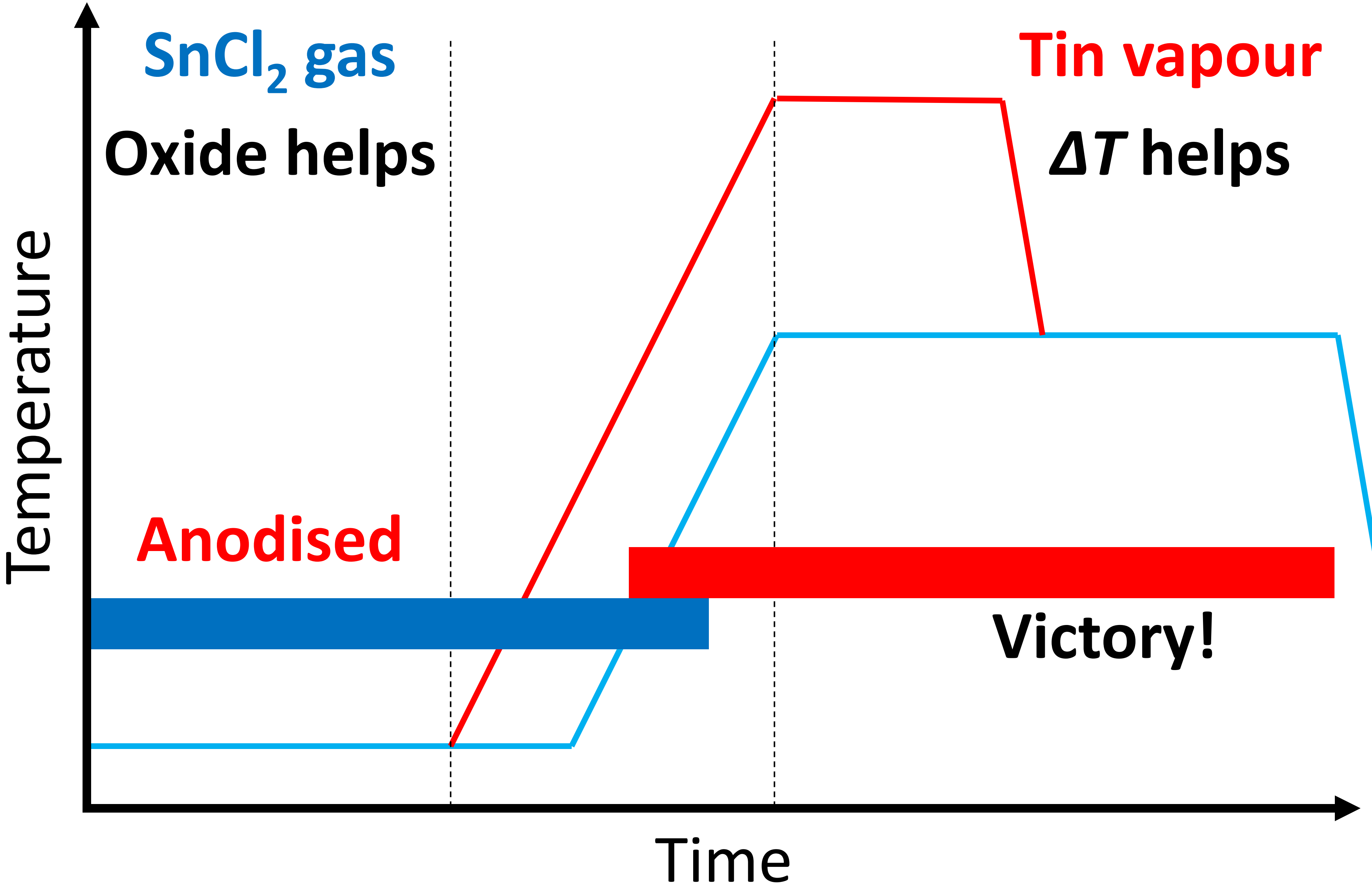


**1120°C**

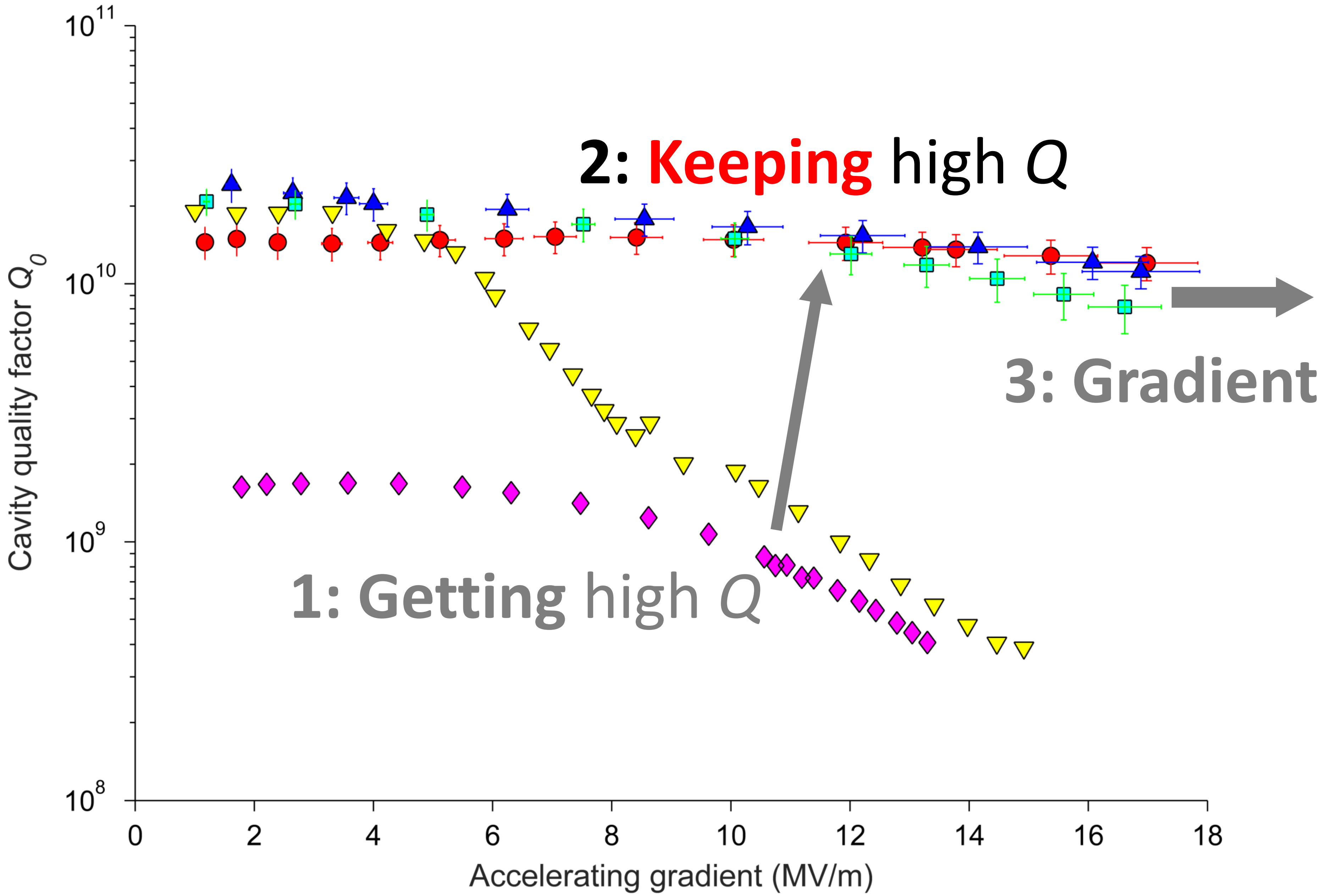
# Successful handover is critical



# Successful handover is critical



# Keeping high *Q*

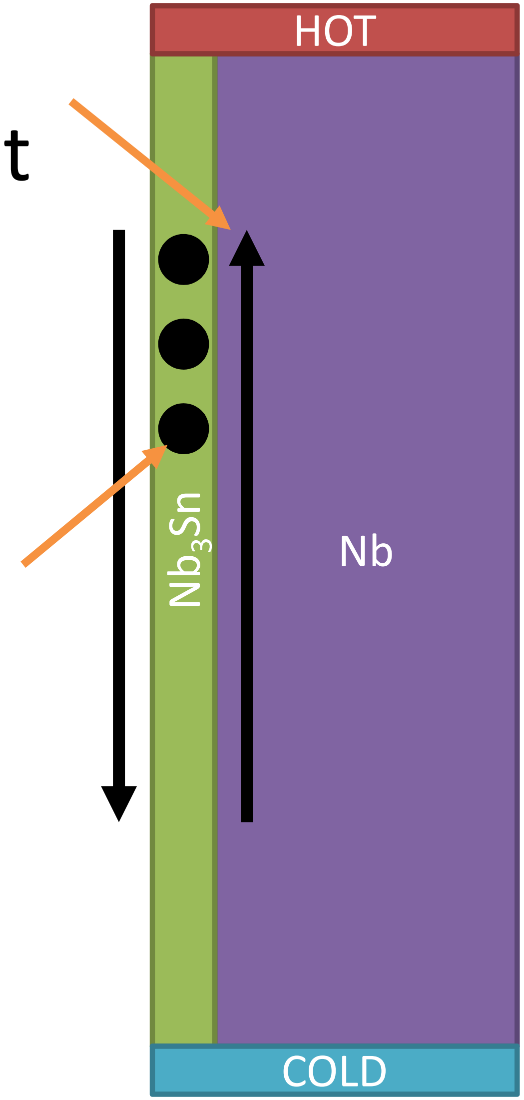


**2: Keeping high *Q***

**3: Gradient**

**1: Getting high *Q***

# Thermal currents



Induced thermocurrent

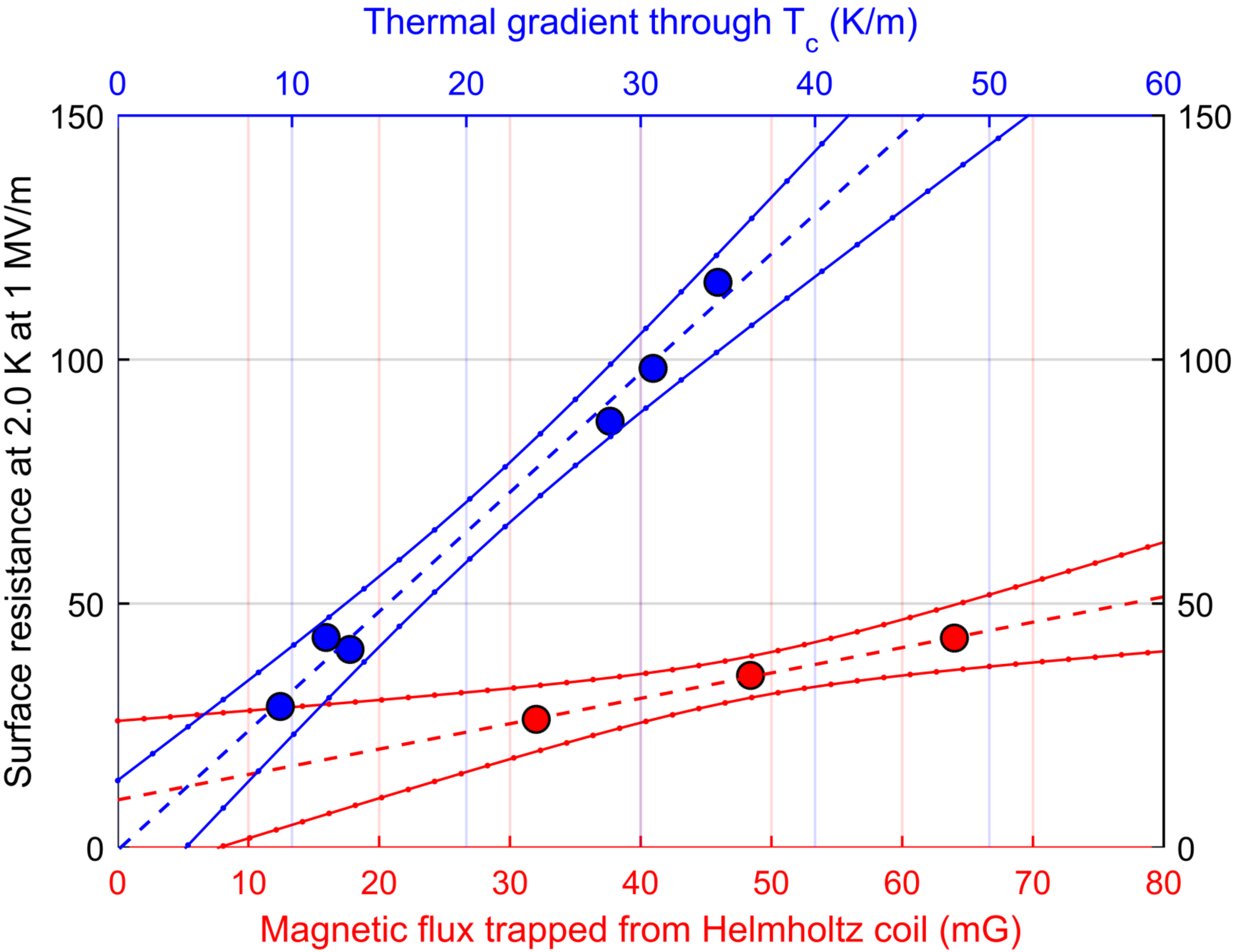
Generated $B$ field

$$V = -S\,\nabla T$$

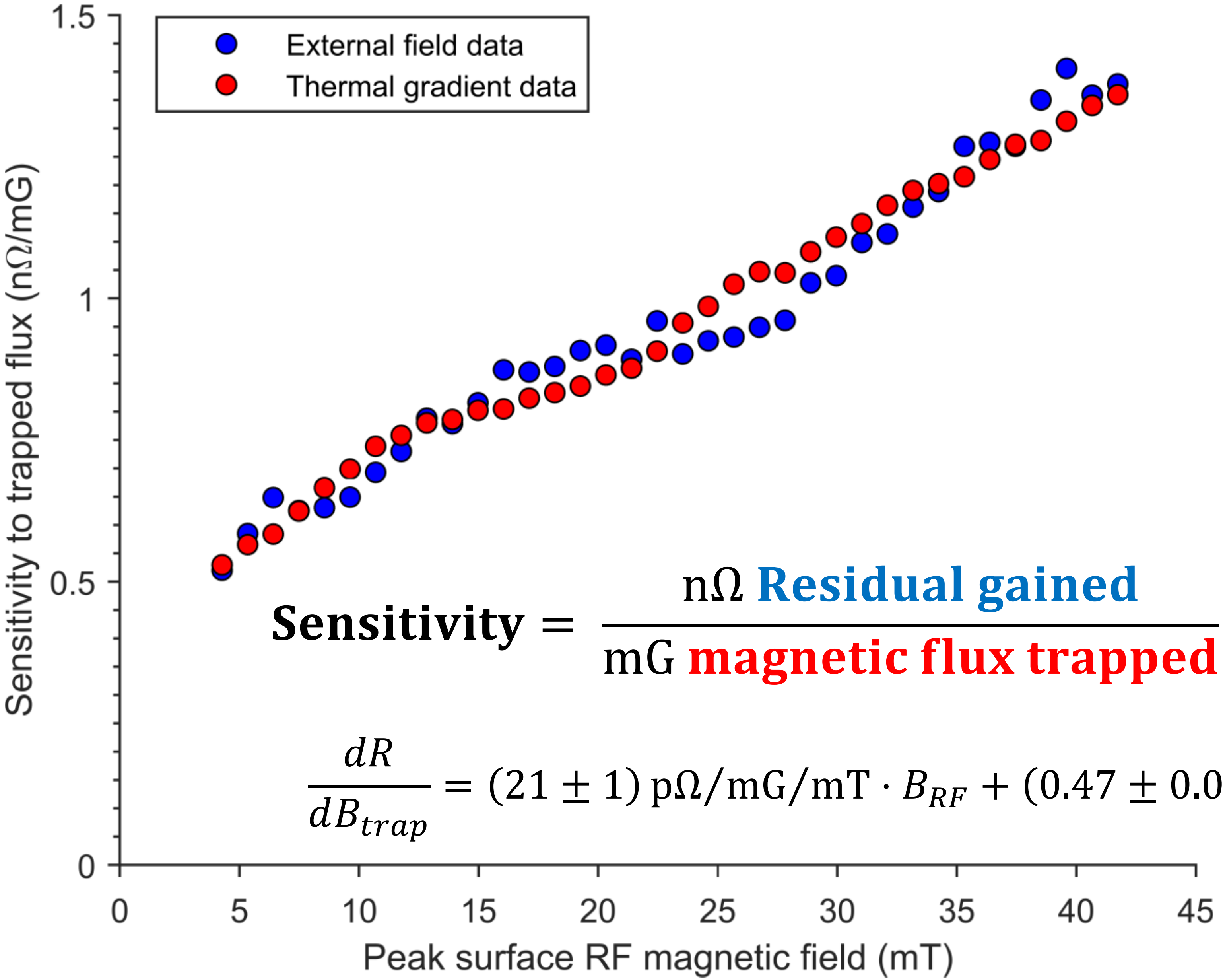
$S$ – Seebeck coefficient

Cooling in a **large thermal gradient** will generate a **large amount of trapped flux**!

# Losses from trapped flux



# Sensitivity with field



$$\textbf{Sensitivity} = \frac{\text{n}\Omega\ \textbf{Residual gained}}{\text{mG}\ \textbf{magnetic flux trapped}} = \frac{dR}{dB_{trap}}$$

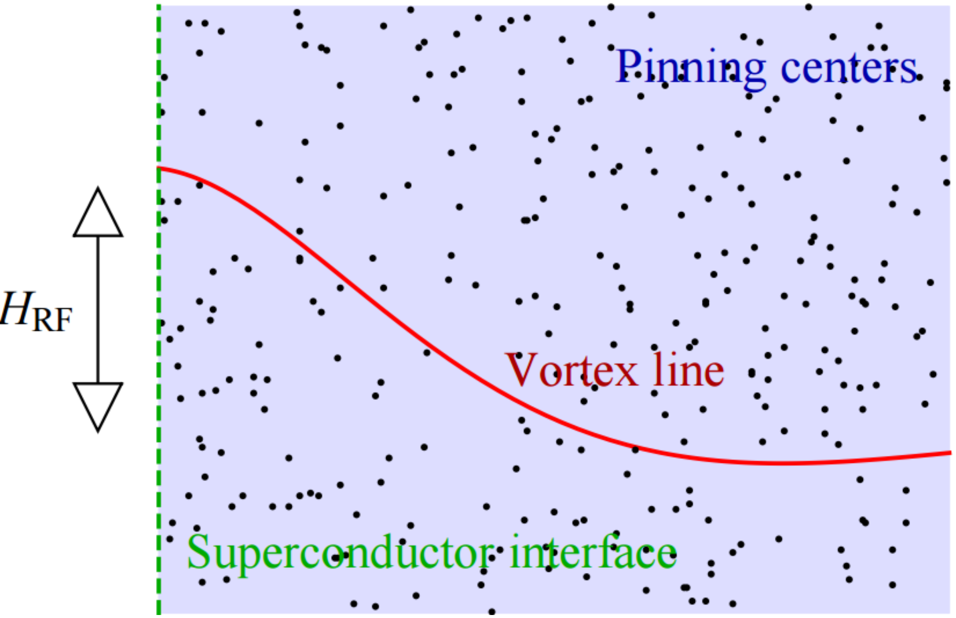
$$\frac{dR}{dB_{trap}} = (21 \pm 1)\ \text{p}\Omega/\text{mG}/\text{mT} \cdot B_{RF} + (0.47 \pm 0.02)\ \text{n}\Omega\ /\ \text{mG}$$

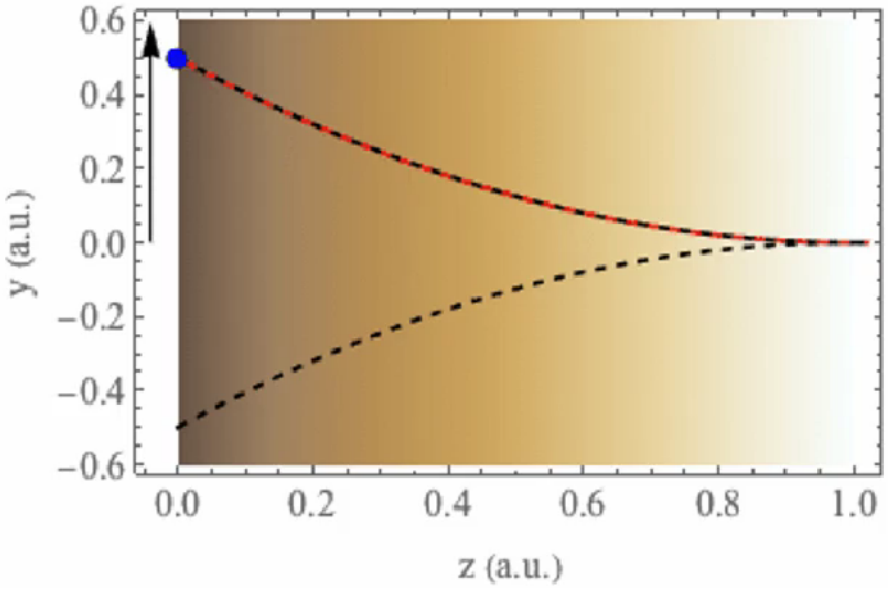
# Weak collective pinning scenario

## ***Collective weak pinning scenario***

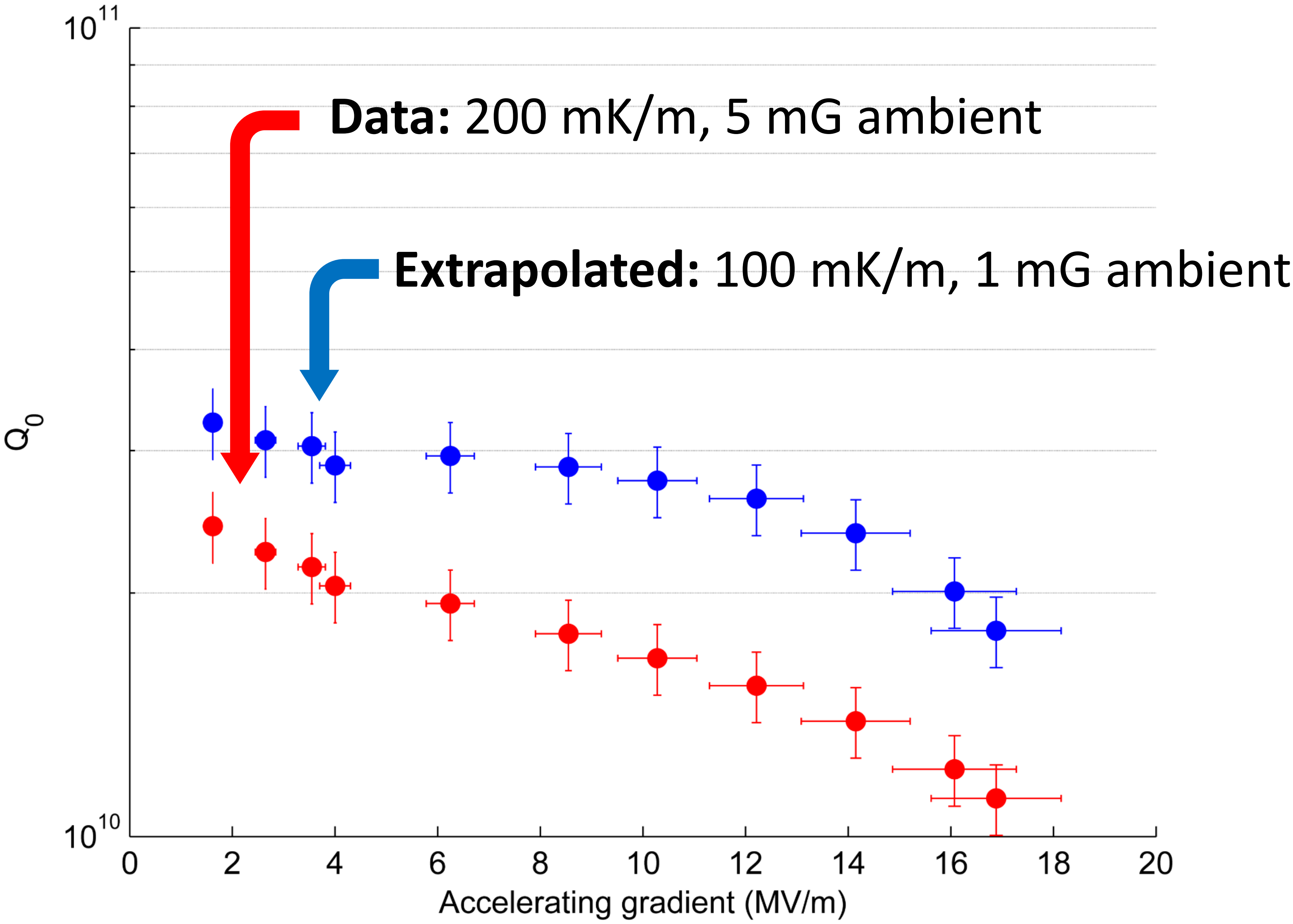
Model by **Danilo Liarte** and **James Sethna**

$$\frac{\boldsymbol{R_0}}{\boldsymbol{B_{trapped}}} = \frac{16\pi}{3}\frac{f\lambda^2}{|F_{pin}|}\boldsymbol{B_{RF}}$$





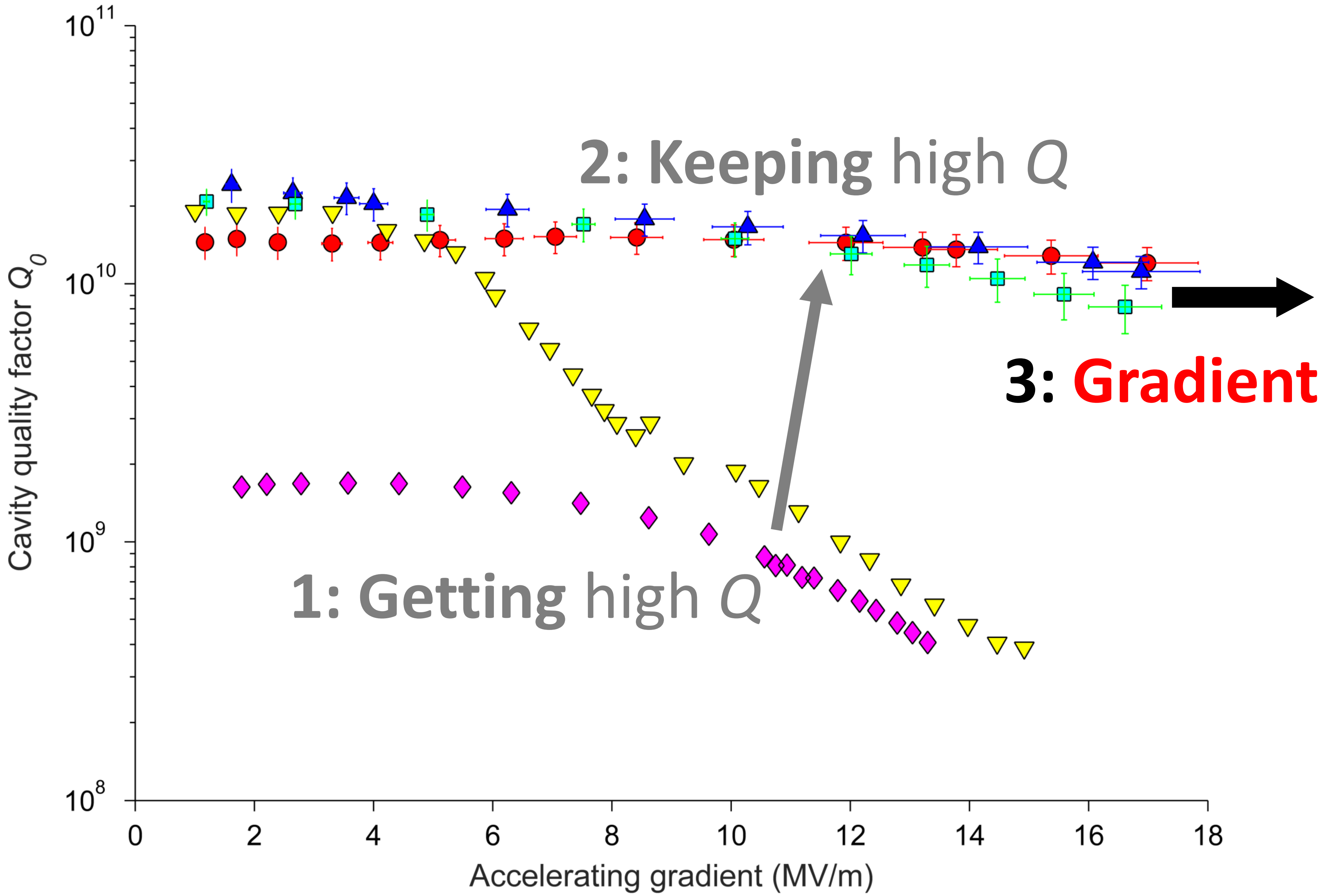
# Extrapolated performance



**Data:** 200 mK/m, 5 mG ambient

**Extrapolated:** 100 mK/m, 1 mG ambient

# Limitation on gradient

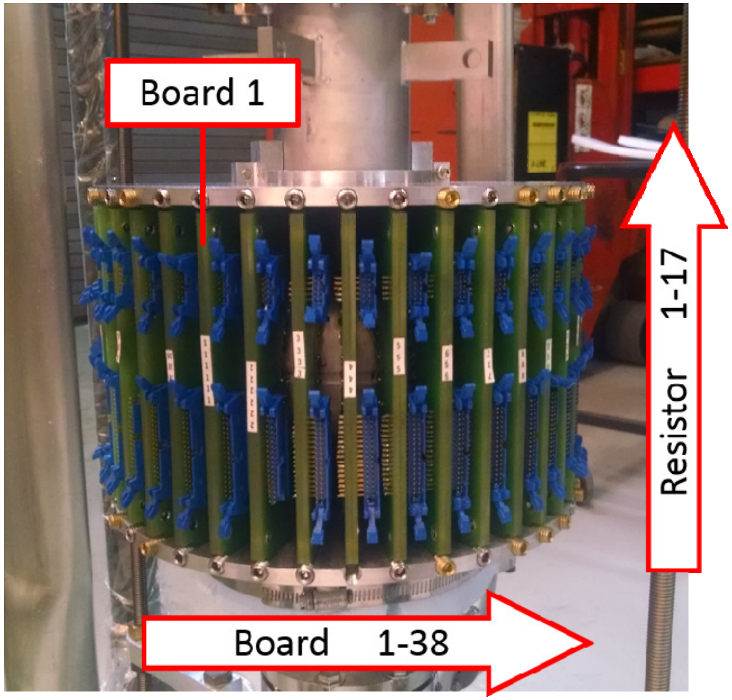


**2: Keeping** high *Q*

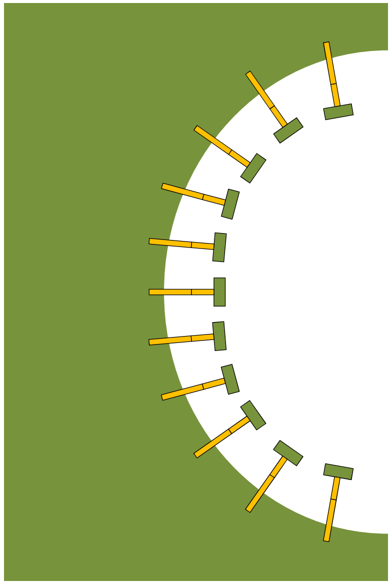
**1: Getting** high *Q*

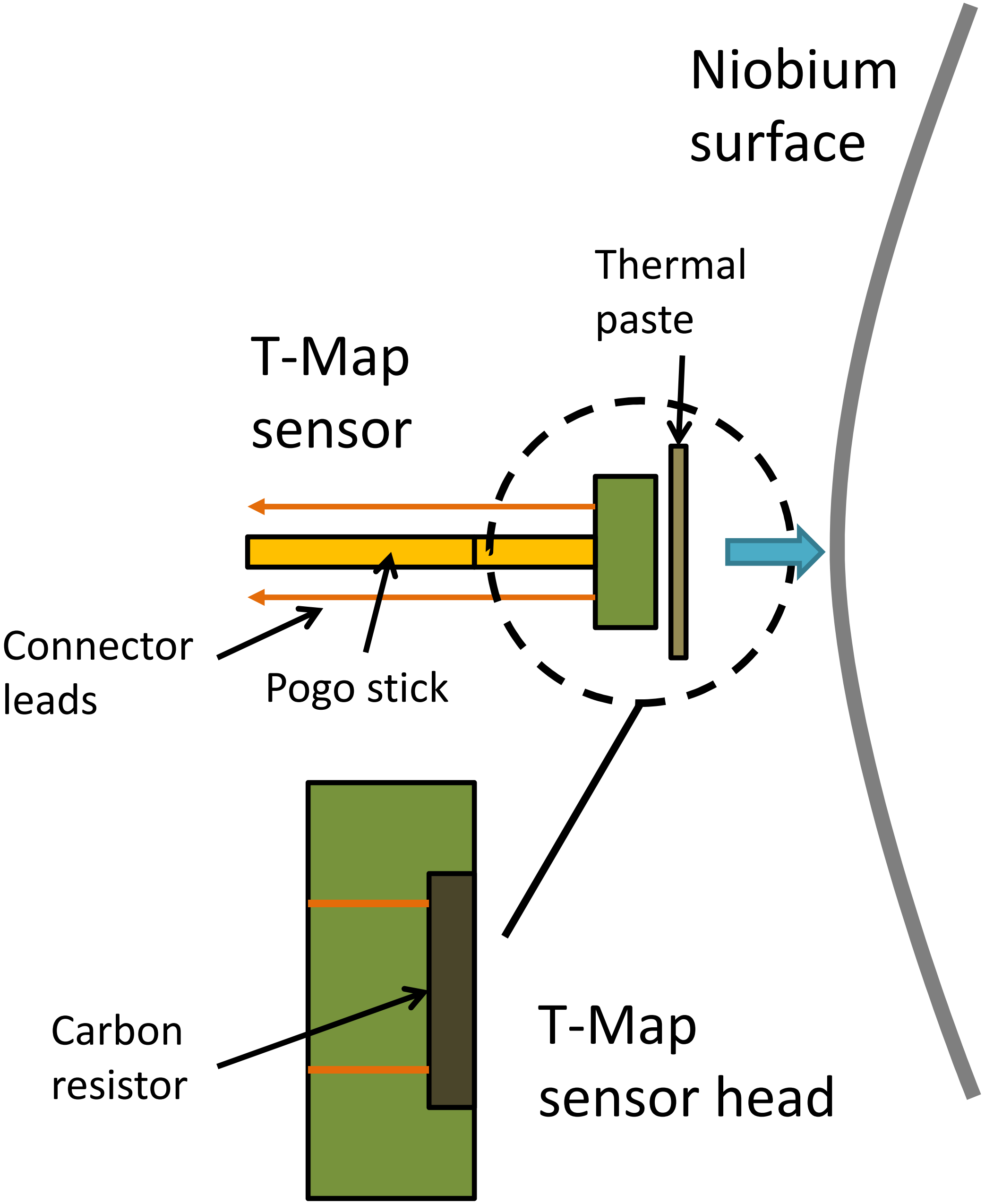
**3: Gradient**

# T-Map experiment



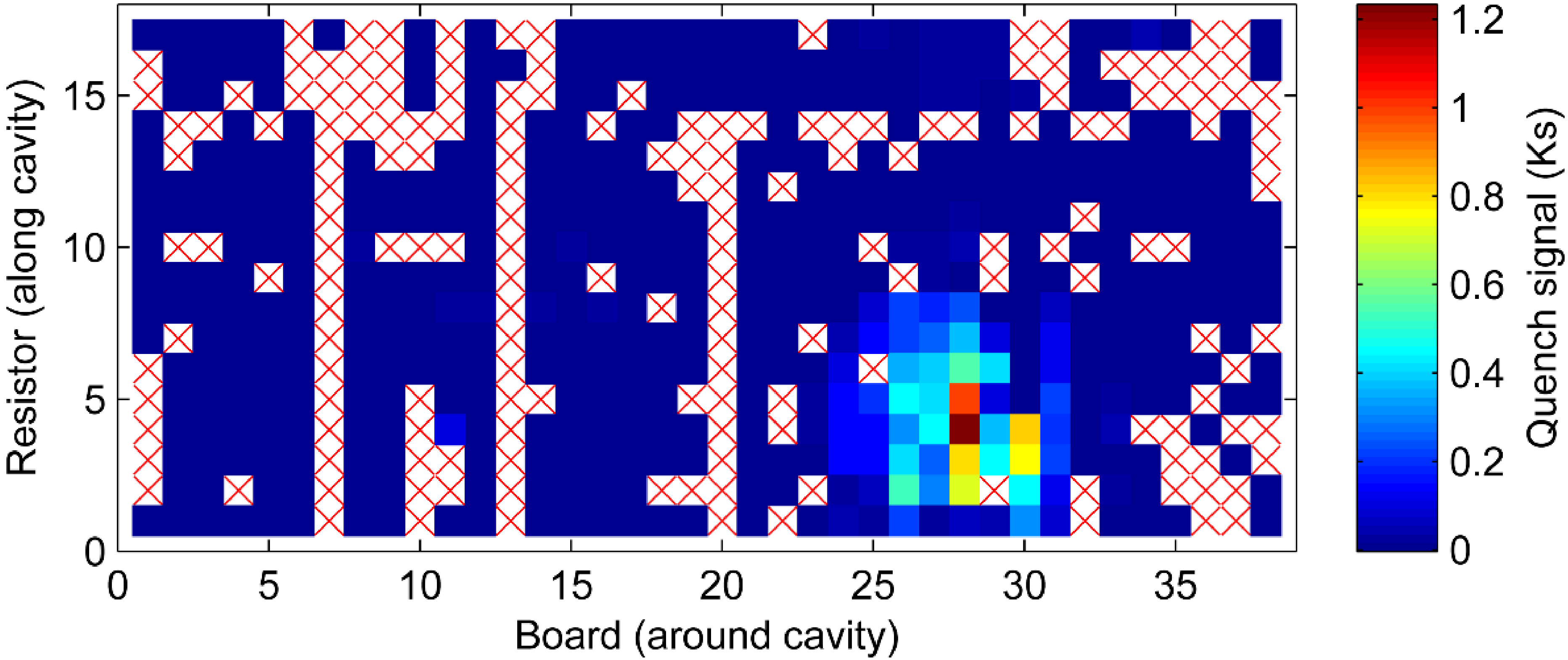
T-Map board





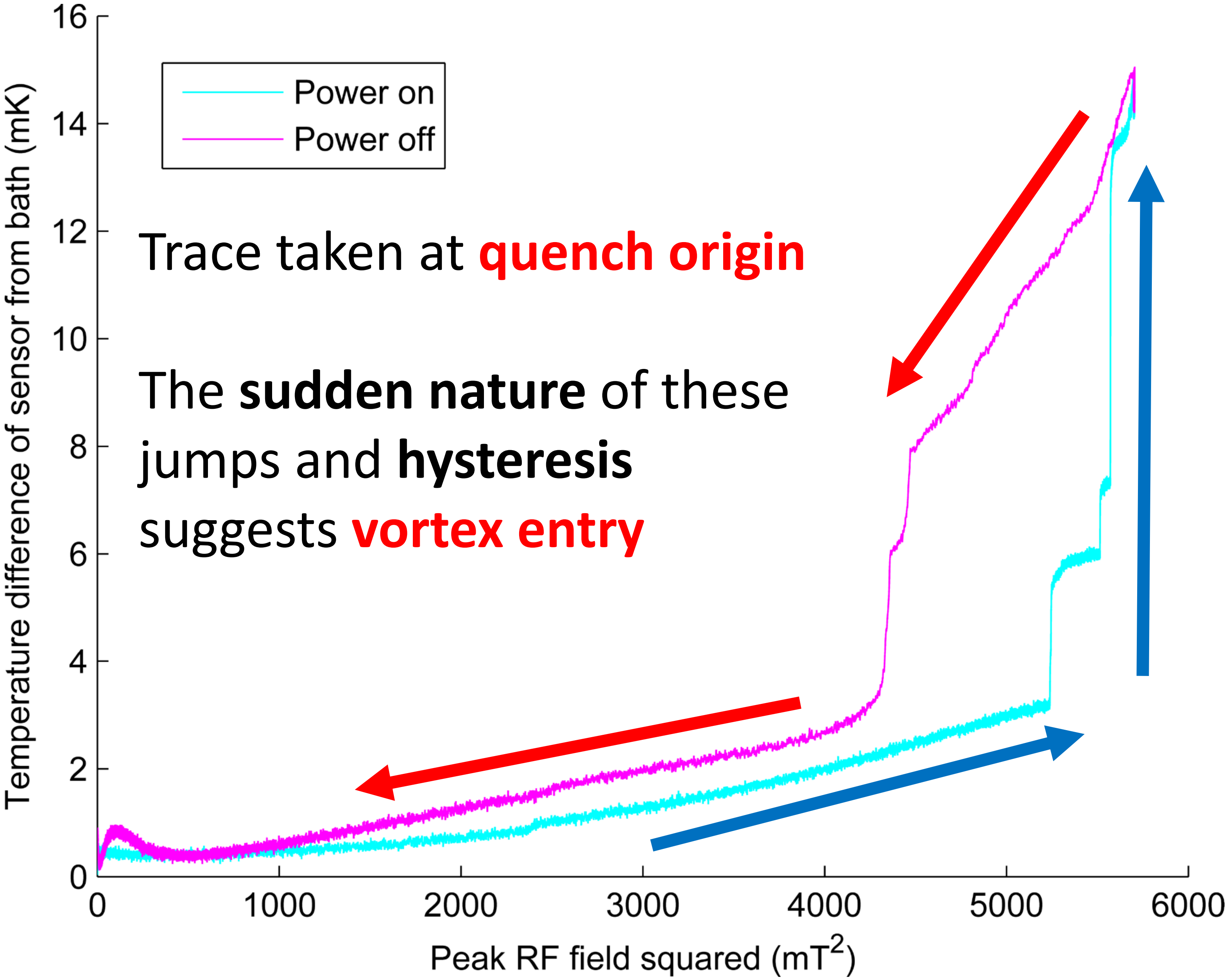
# Localised quench

Nb$_3$Sn cavities are limited by a quench at a defect



But what kind of defect, and why?

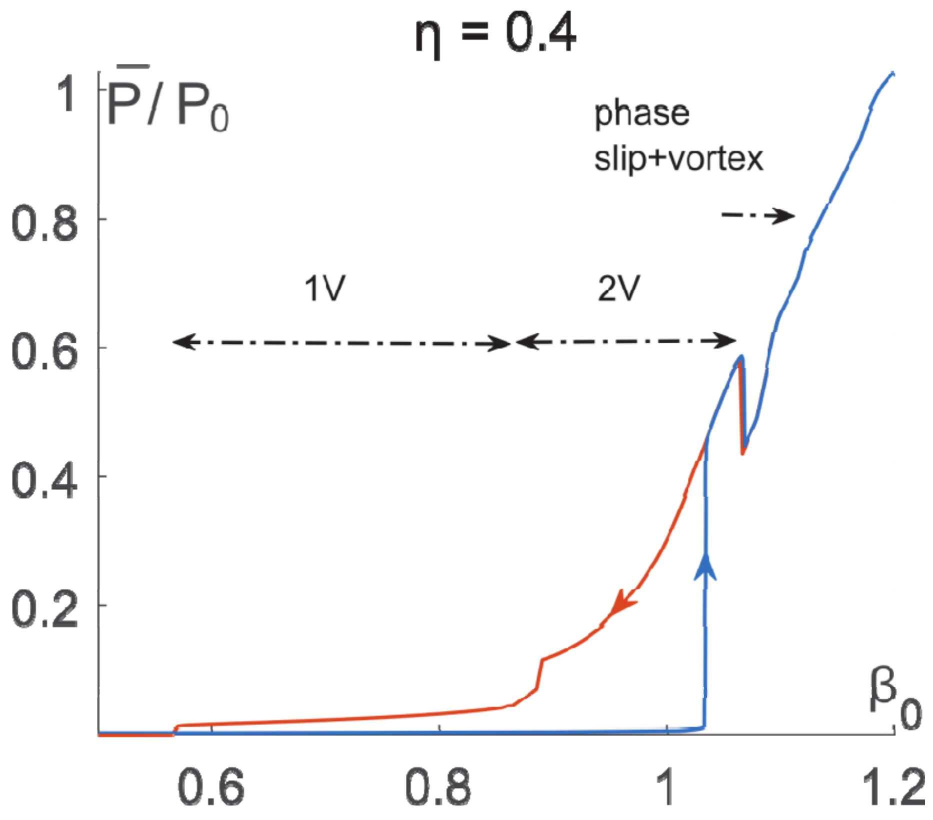
# Near quench behaviour



Trace taken at **quench origin**

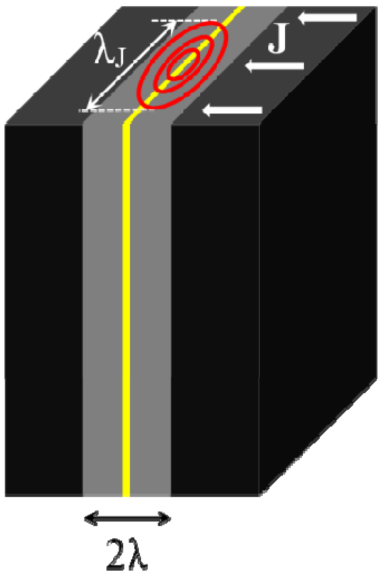
The **sudden nature** of these jumps and **hysteresis** suggests **vortex entry**

# Grain boundary vortex penetration



**Power dissipated in grain boundary**

**Increasing current across grain boundary (RF field)**



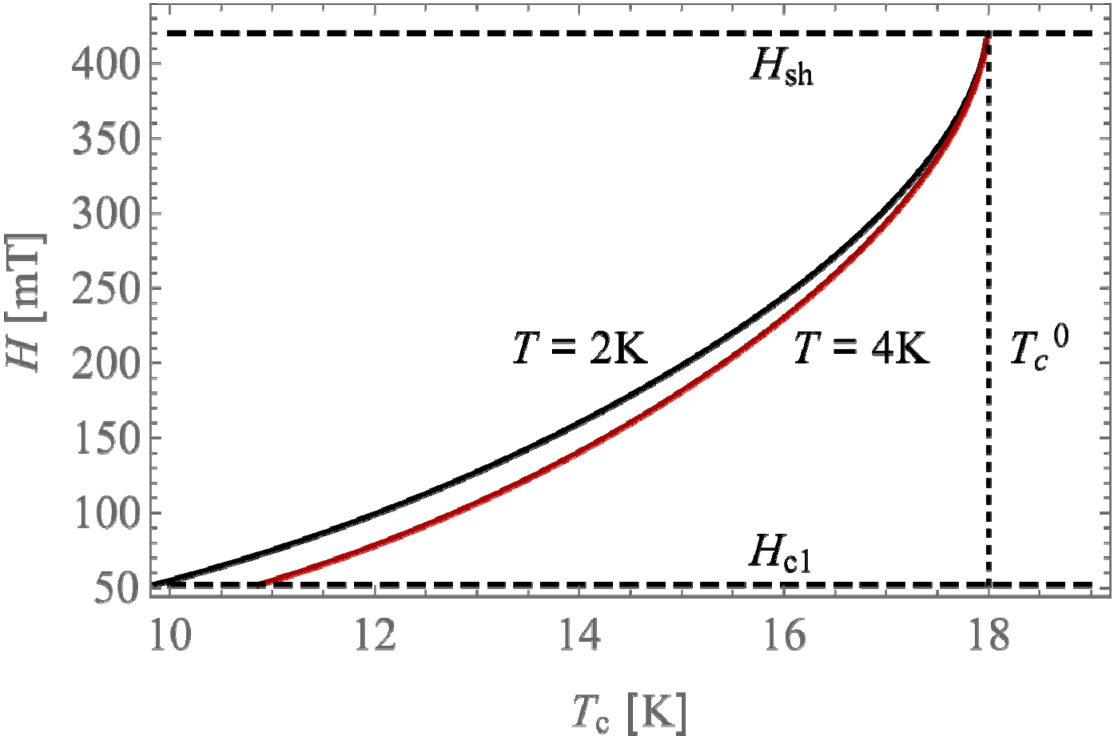
Modelling grain boundaries as Josephson junctions

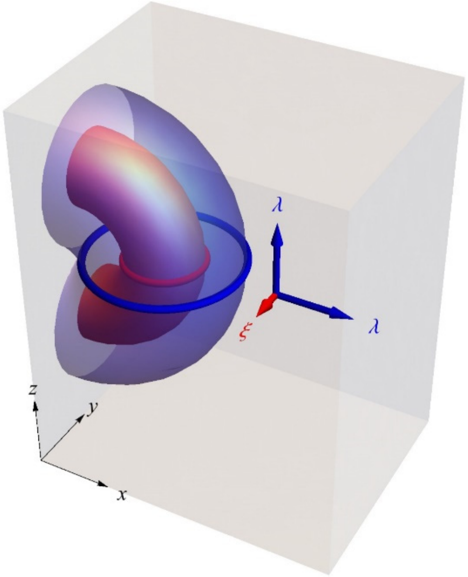
**Ahmad Sheikhzada** and **Alex Gurevich**
Physical Review B **95**, 214507 (2017)
*arXiv:1702.02843*

Upcoming talk!

# $T_c$ suppression and vortex entry

A tin depletion of only **3%** reduces field of vortex entry by **75%**



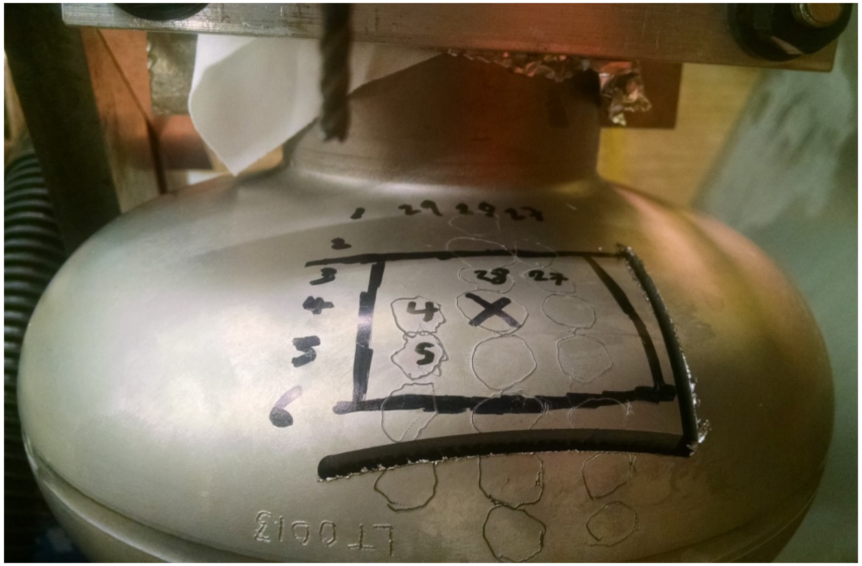


Flux entry could occur at tin-depleted surface defects

**Danilo Liarte** and **James Sethna**

Upcoming talk!

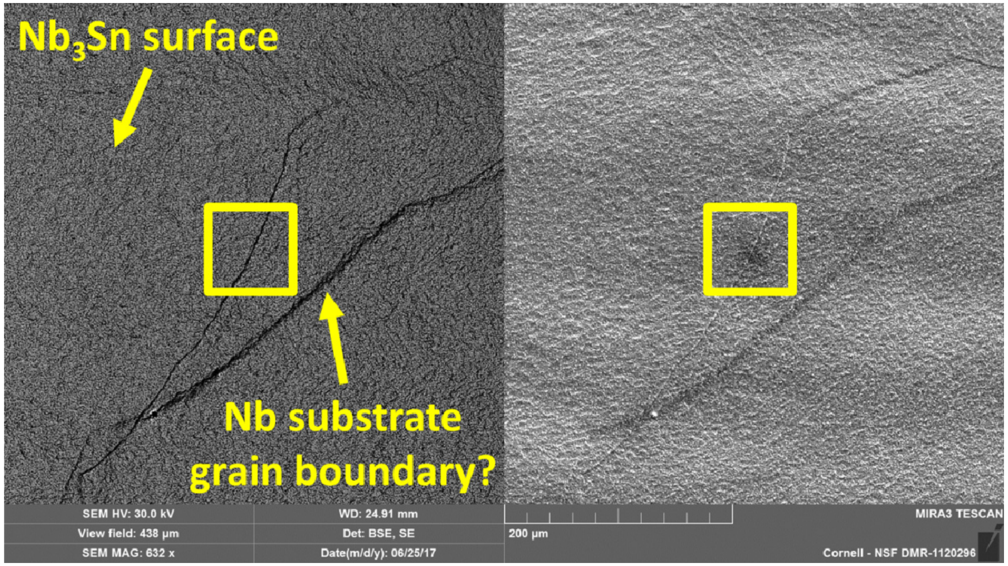
# Cut-out of the quench spot



Surface analysis of the quench origin **has begun**

**Stay tuned**

**Backscatter image** **Secondary image**



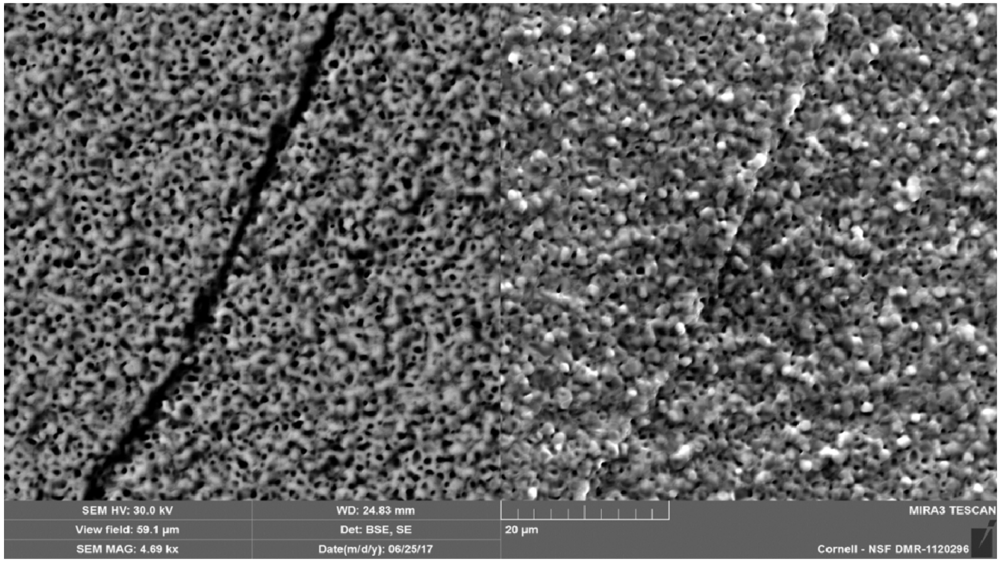
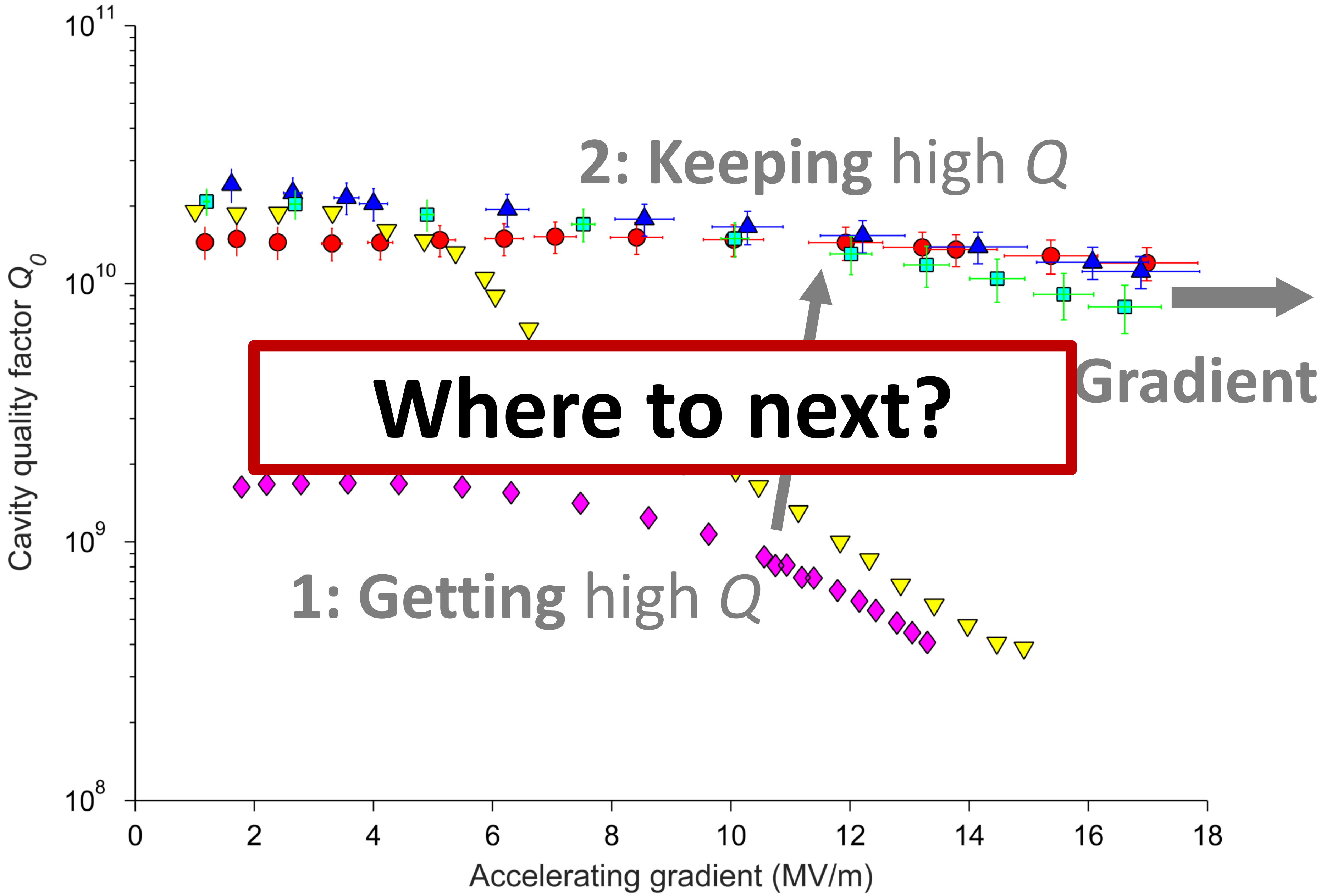


**Image taken near quench origin**

# The next step



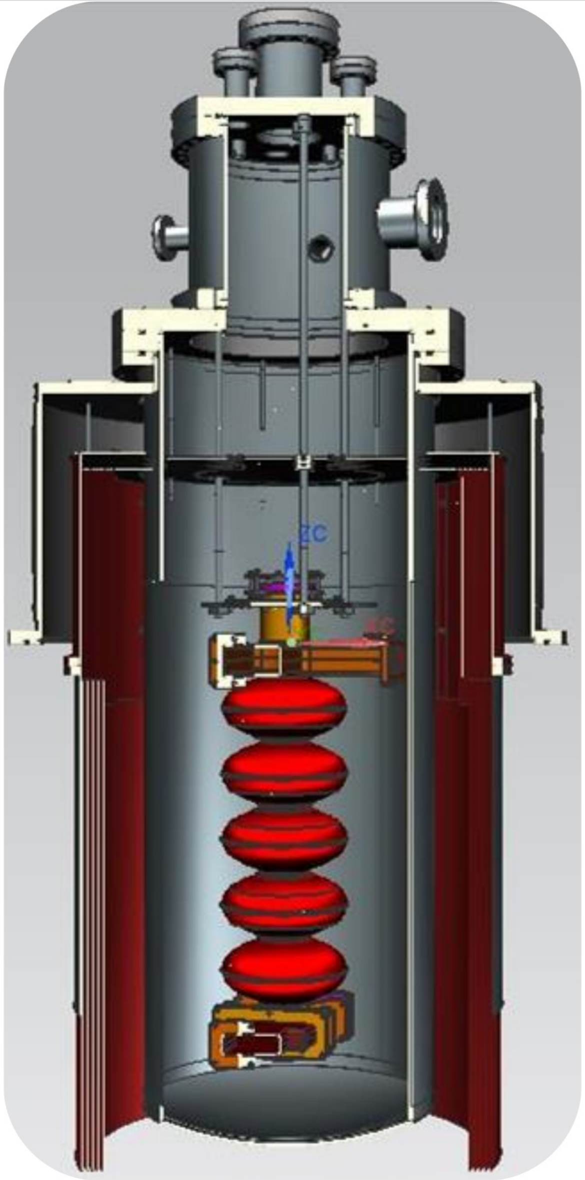
**2: Keeping** high *Q*

Gradient

**Where to next?**

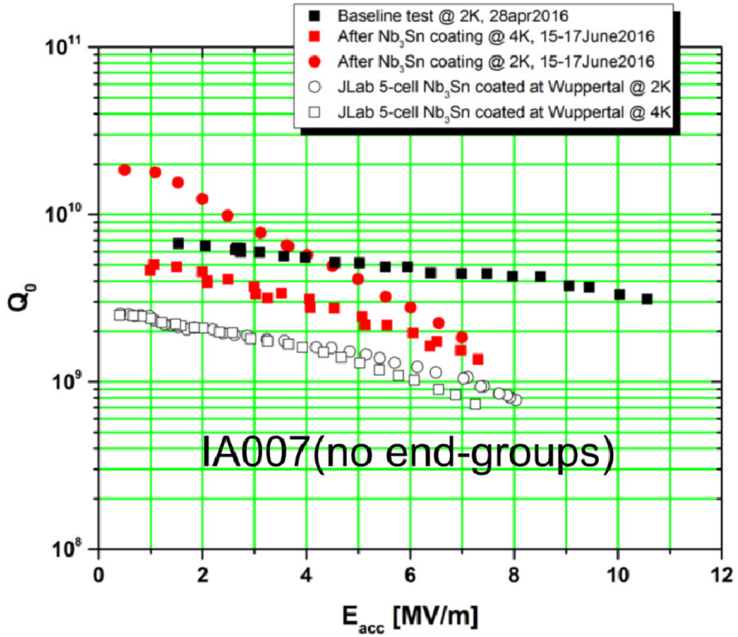
**1: Getting** high *Q*

# JLab $Nb_3Sn$ coating system upgrade



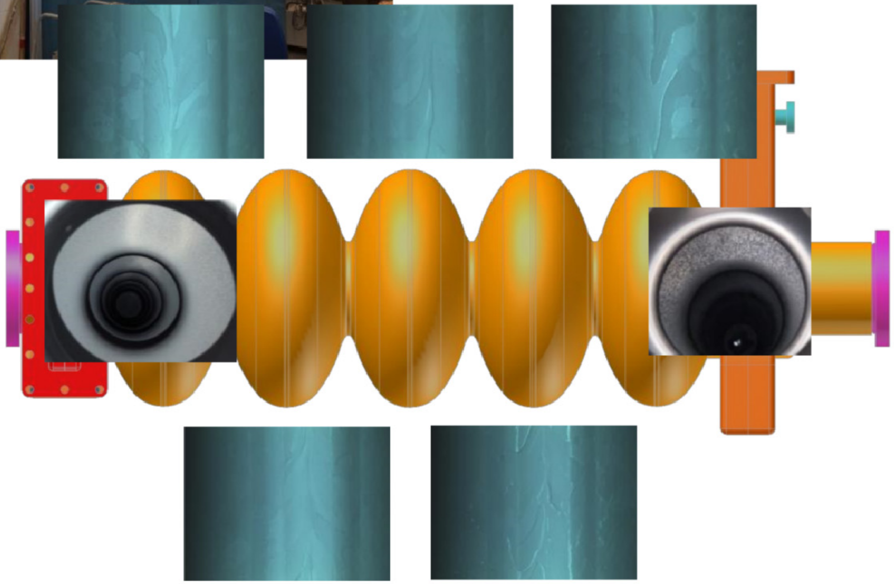
Slides courtesy of Grigory Eremeev

# JLab $Nb_3Sn$ 5-cell progress

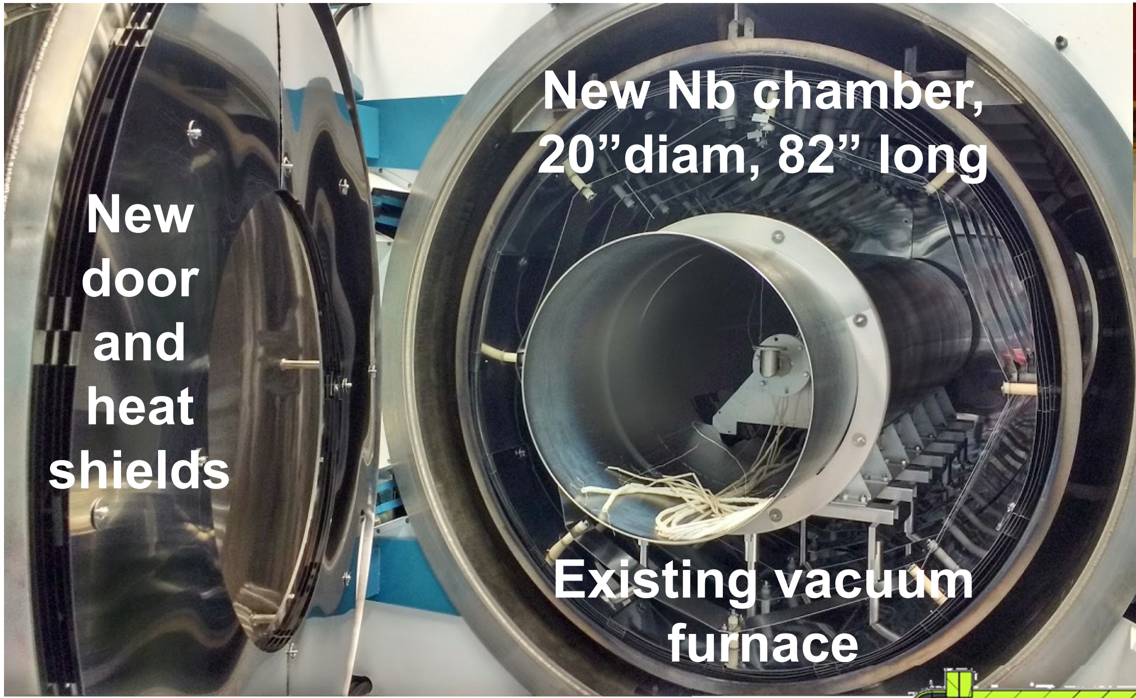


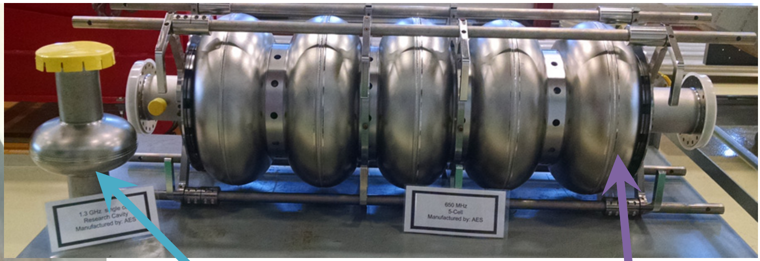
**$Nb_3Sn$ coating is present, but is not uniform. Progress is being made to improve the uniformity of CEBAF 5-cell cavity coatings.**

**Reasonable low-field $Q_0$, but a strong Q-slope, similar to the one measured in 5-cell cavity coated at Wuppertal University. Features in the substrate are suspected to be the cause.**



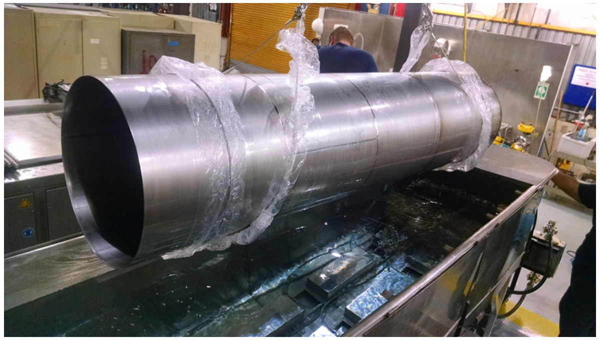
# Fermilab $Nb_3Sn$ Coating Chamber

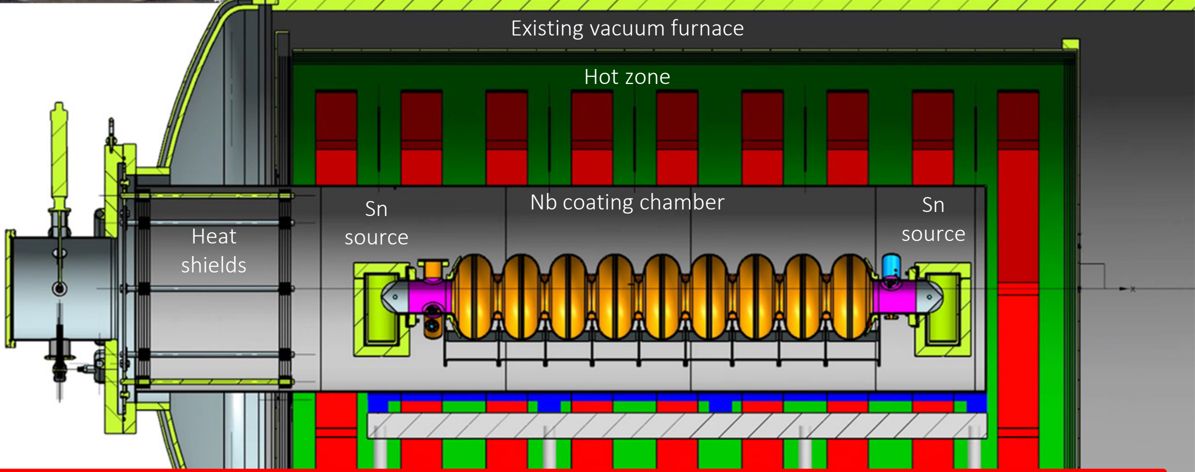




1.3 GHz 1-cell (current state of $Nb_3Sn$ R&D)

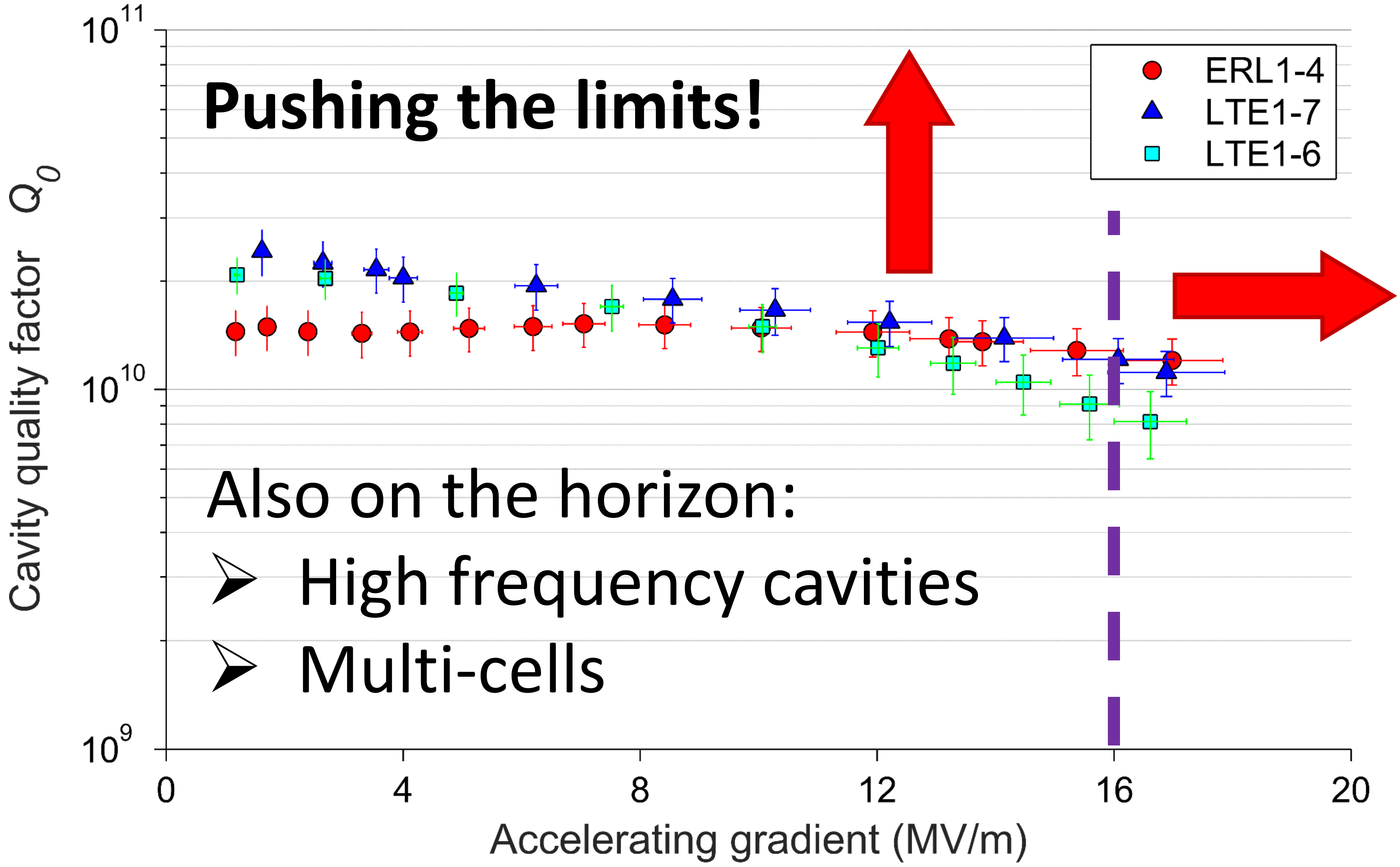
650 MHz 5-cell (future)





Slide courtesy of Sam Posen

# Next at Cornell



**Pushing the limits!**

Also on the horizon:

- High frequency cavities
- Multi-cells

# The future?

LCLS IV.2K

The world’s first $Nb_3Sn$ light source?

# Conclusions

- A **successful hand-over** from nucleation to coating is necessary to ensure **layer uniformity**

- Achieving high Q at **high gradients** requires the suppression of a **weak collective pinning effect**

- Temperature scans of **quench origin** suggest limitation is due to **flux entry** at a defect

- Coating of **multi-cell cavities** is **underway**

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