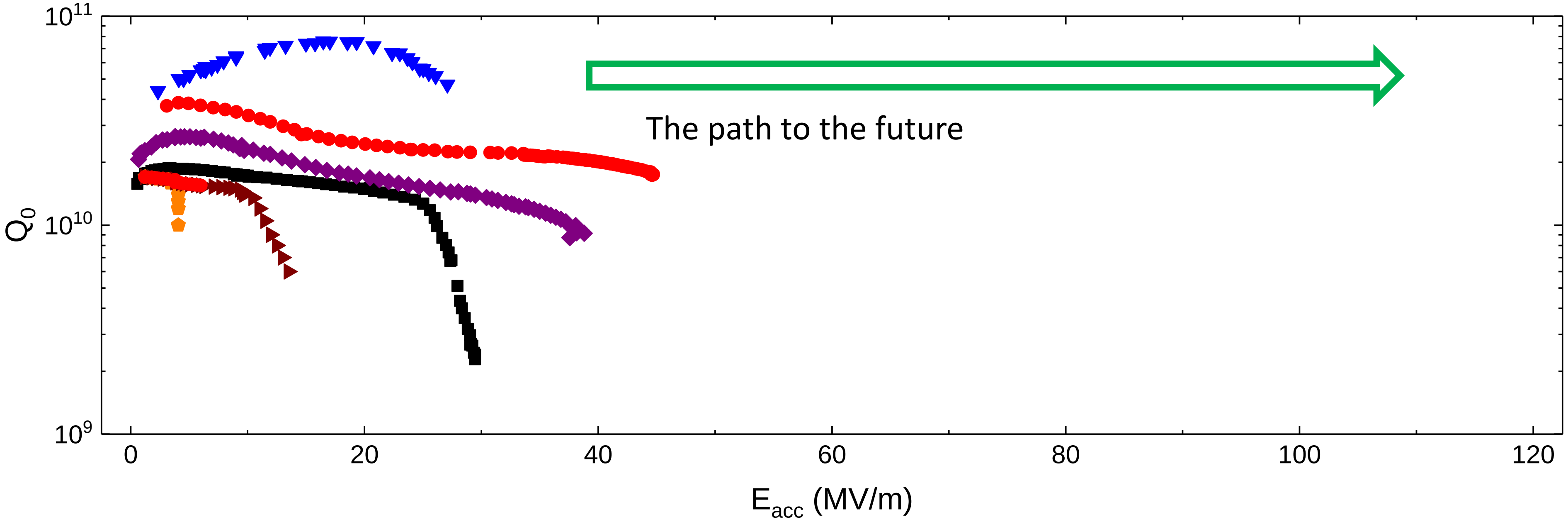
Recent progress and future trends in SRF technology

Pushing Nb performance

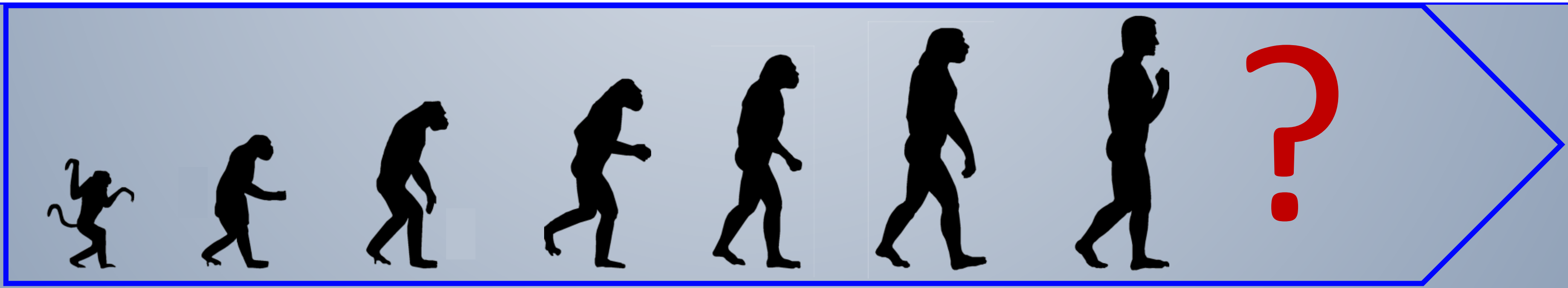
Special thanks to S. Belomestnykh, A. Grasselino (FNAL), C. Reece (JLAB), A. Romanenko (FNAL)

Photo:
Reidar Hahn

SRF “evolution”



The path to the future

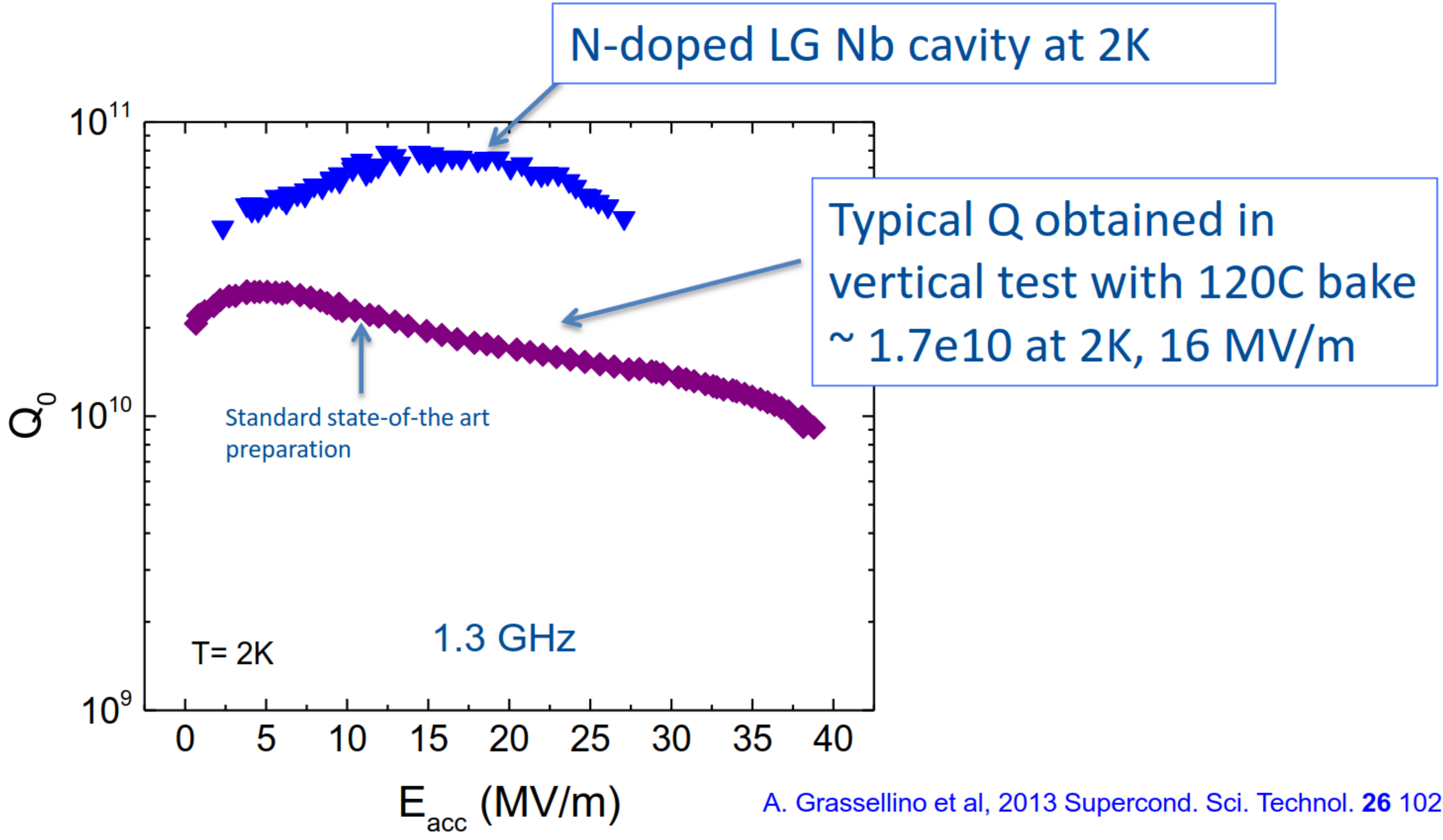


Courtesy: S. Belomestnykh/FNAL

Nitrogen doping


Photo:
Reidar Hahn

Nitrogen doping: a breakthrough for Q_0



N-doped LG Nb cavity at 2K

Typical Q obtained in vertical test with 120C bake ~ 1.7e10 at 2K, 16 MV/m

Standard state-of-the art preparation

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001


Photo:
Reidar Hahn

Nitrogen doping process - example

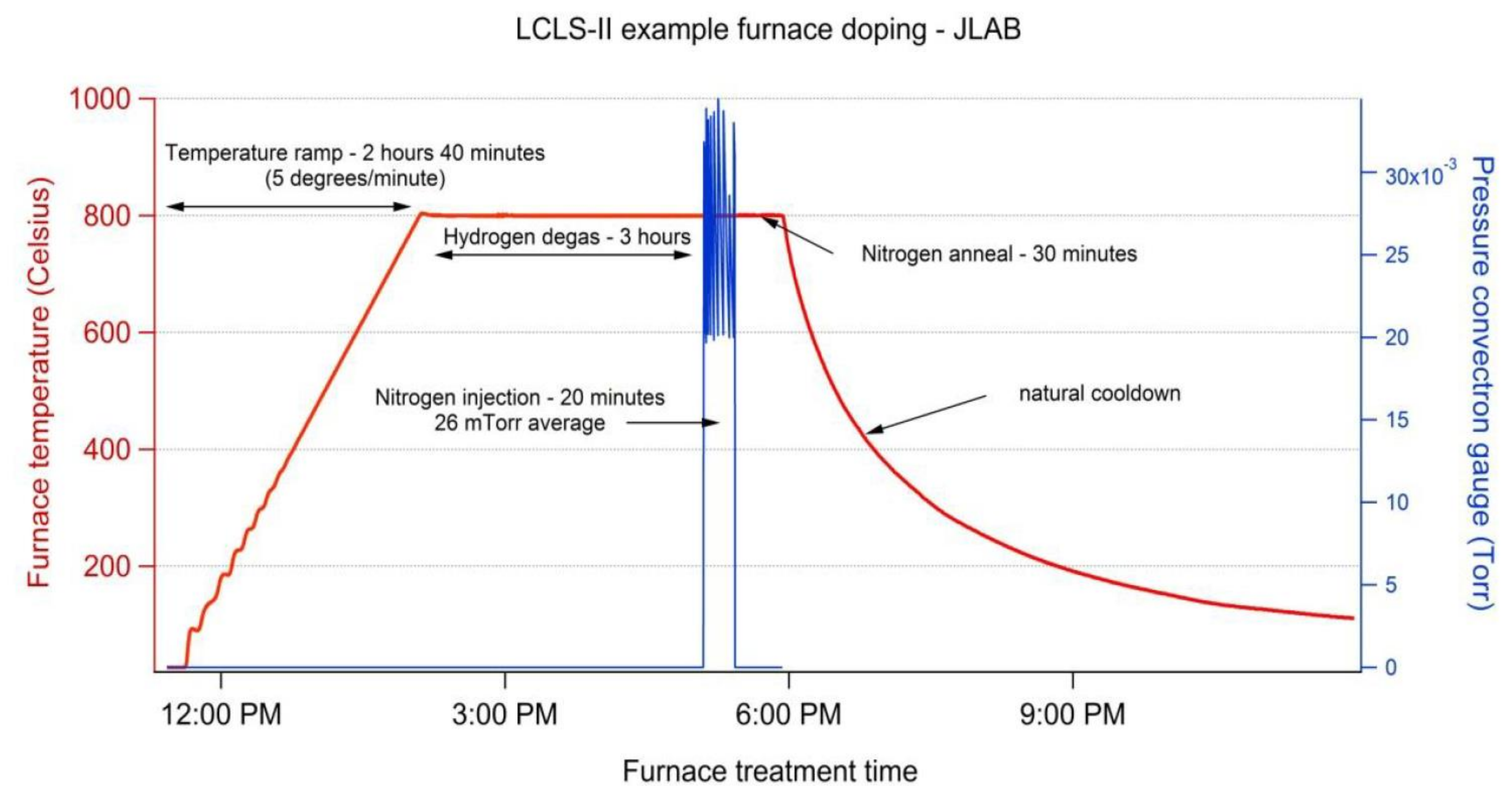
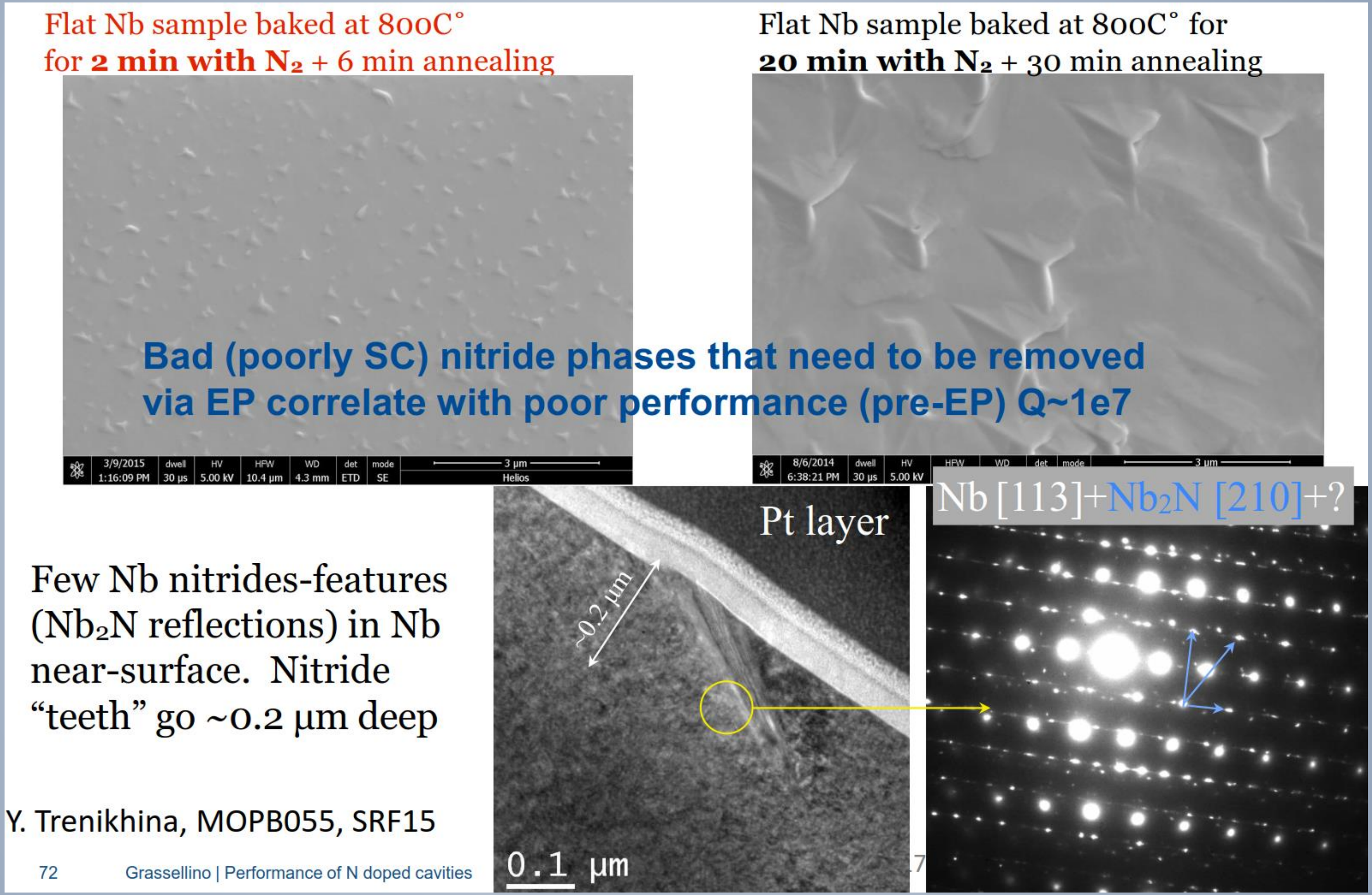



Photo:
Reidar Hahn

Surface post N bake – nitrides (poor SC)


Flat Nb sample baked at 800C°
for **2 min with N_2** + 6 min annealing

Flat Nb sample baked at 800C° for
20 min with N_2 + 30 min annealing

Bad (poorly SC) nitride phases that need to be removed via EP correlate with poor performance (pre-EP) Q~1e7

Few Nb nitrides-features (Nb_2N reflections) in Nb near-surface. Nitride "teeth" go ~0.2 µm deep

Y. Trenikhina, MOPB055, SRF15

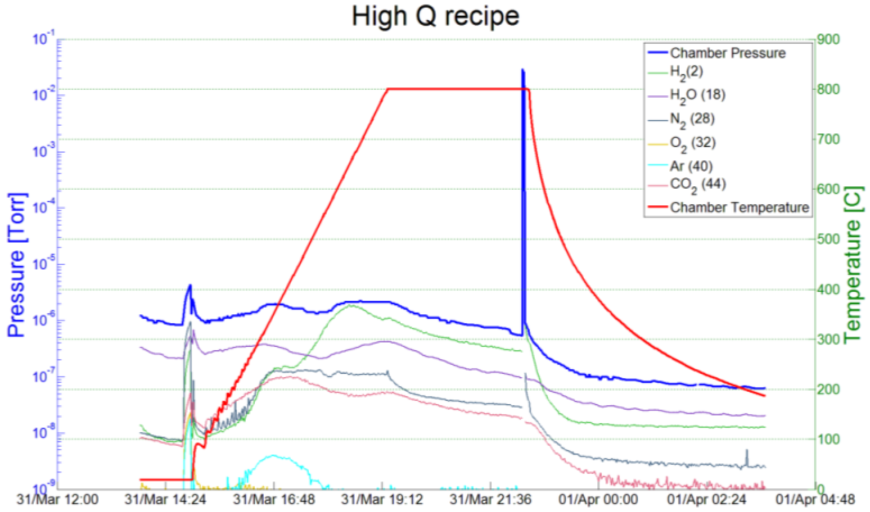
72 Grassellino | Performance of N doped cavities

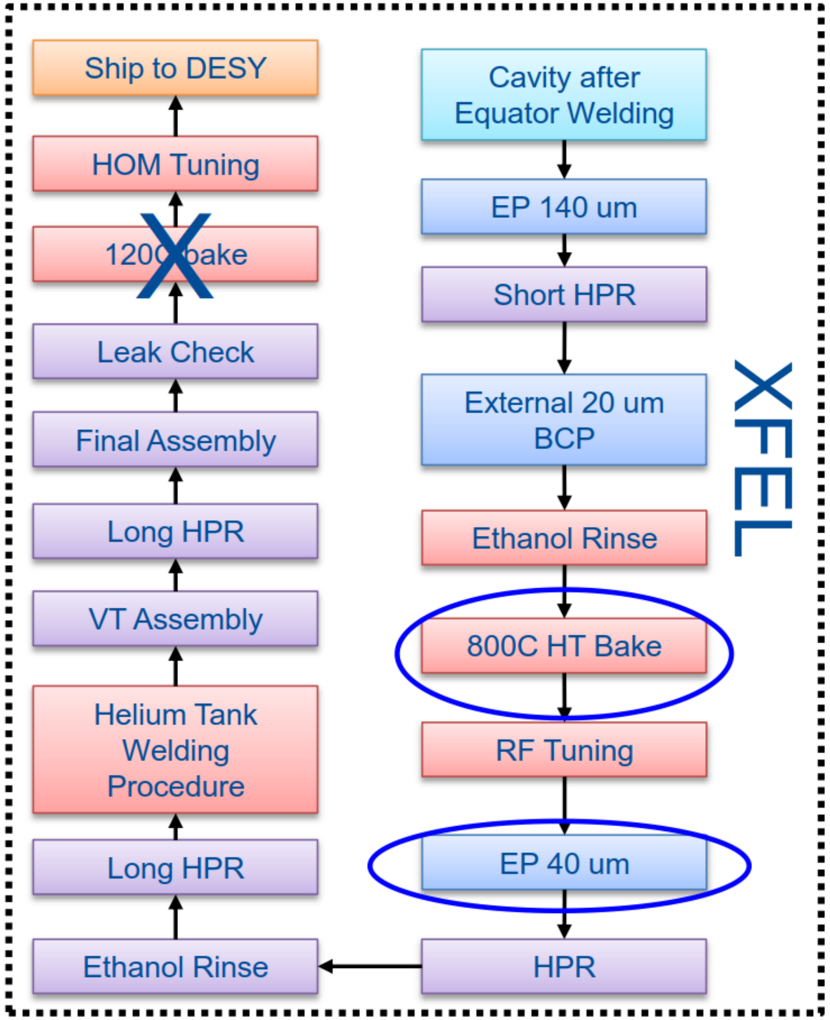
Photo:
Reidar Hahn

Doping treatment – small variation from standard

Example from a doping process developed for LCLS-2:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP



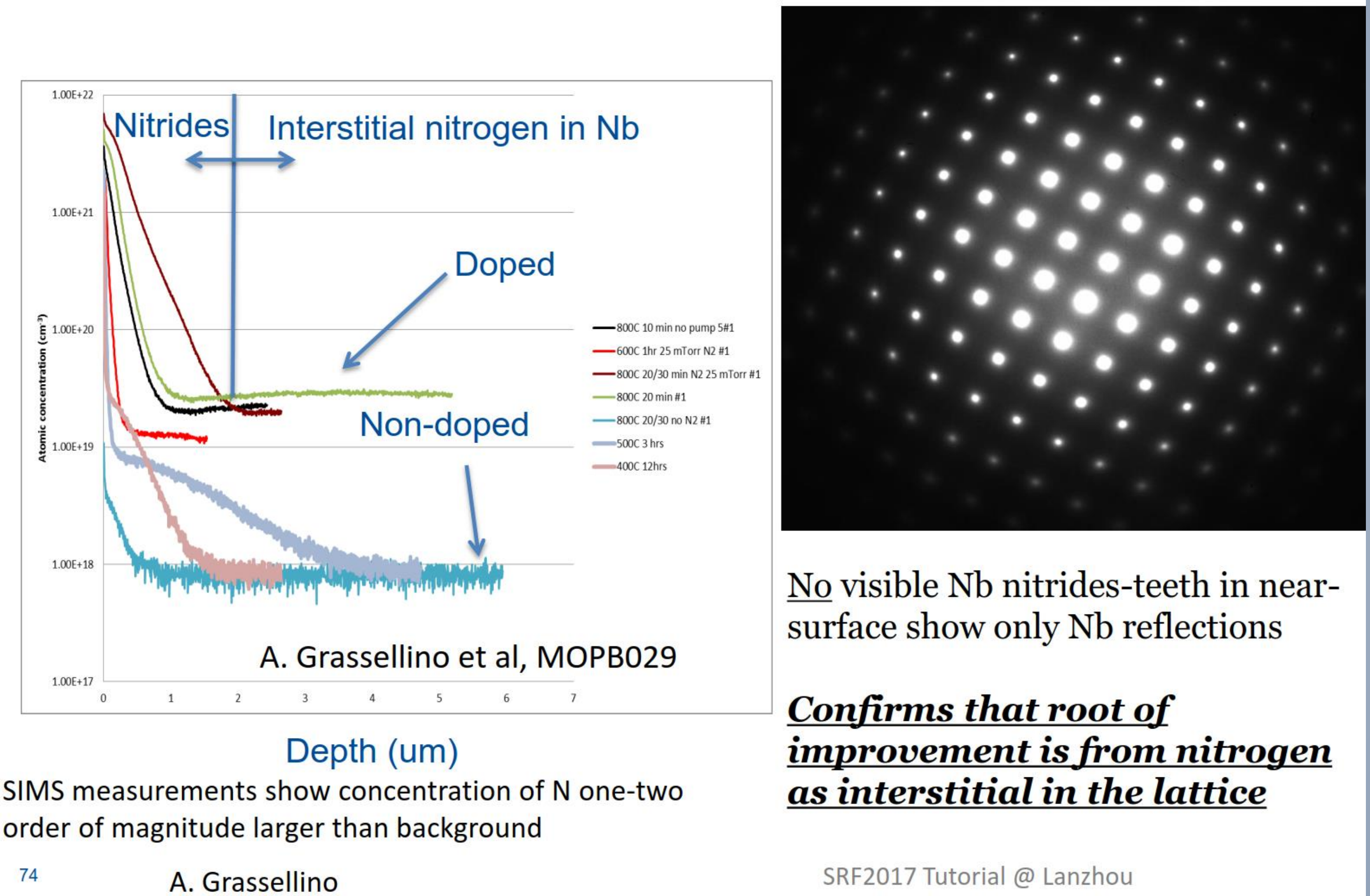


XFEL

- Cavity after Equator Welding
- EP 140 um
- Short HPR
- External 20 um BCP
- Ethanol Rinse
- 800C HT Bake
- RF Tuning
- EP 40 um
- HPR
- Ethanol Rinse
- Long HPR
- Helium Tank Welding Procedure
- VT Assembly
- Long HPR
- Final Assembly
- Leak Check
- ~~120C bake~~
- HOM Tuning
- Ship to DESY


Photo:
Reidar Hahn

EP required to get rid of nitride layer



A. Grassellino et al, MOPB029

SIMS measurements show concentration of N one-two order of magnitude larger than background

No visible Nb nitrides-teeth in near-surface show only Nb reflections

Confirms that root of improvement is from nitrogen as interstitial in the lattice

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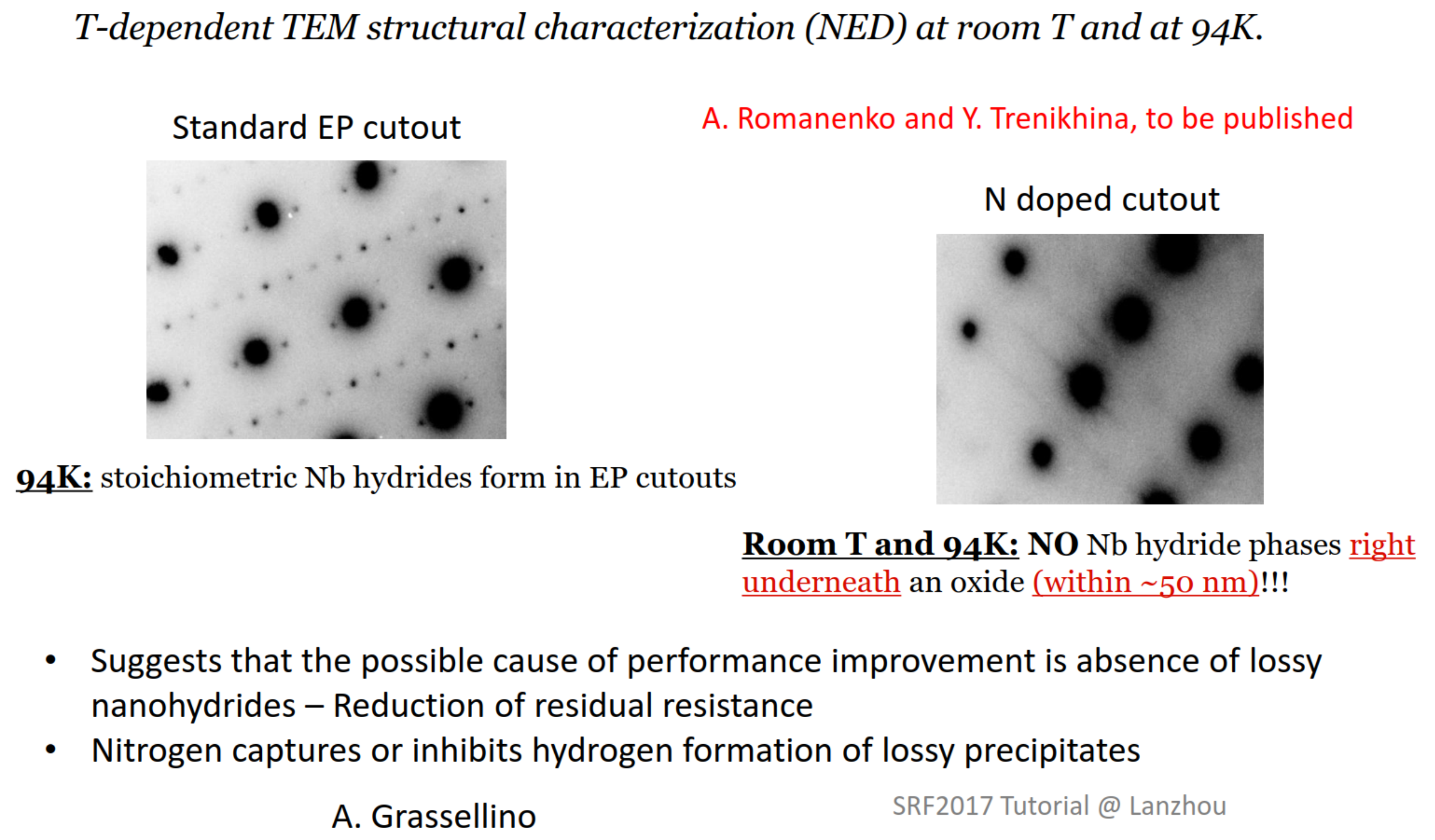
A. Grassellino

SRF2017 Tutorial @ Lanzhou

Photo:
Reidar Hahn

Why does interstitial nitrogen bring benefit? (1)

- Observed difference: absence of nanohydrides in doped cutouts



T-dependent TEM structural characterization (NED) at room T and at 94K.

Standard EP cutout

A. Romanenko and Y. Trenikhina, to be published

N doped cutout

94K: stoichiometric Nb hydrides form in EP cutouts

Room T and 94K: NO Nb hydride phases right underneath an oxide (within ~50 nm)!!!

- Suggests that the possible cause of performance improvement is absence of lossy nanohydrides – Reduction of residual resistance
- Nitrogen captures or inhibits hydrogen formation of lossy precipitates

A. Grassellino

SRF2017 Tutorial @ Lanzhou


Photo:
Reidar Hahn

Why does interstitial nitrogen bring benefit? (2)

- The decrease of $R_{BCS}(B_{RF})$ (negative Q-slope) is perhaps the strangest thing.
- Physically, one may understand that in the presence of flowing DC supercurrent, the Fermi surface becomes non-spherical,
  - The 3-D density of states for the quasiparticles changes
  - Quasiparticle scattering opportunities decrease
  - Less scattering lower dissipation
- With sufficiently low electron mean free path, quasiparticle scattering is local and much faster than an RF cycle.

This is still a lot of speculation, but extremely interesting!

Thin films Nb on Cu

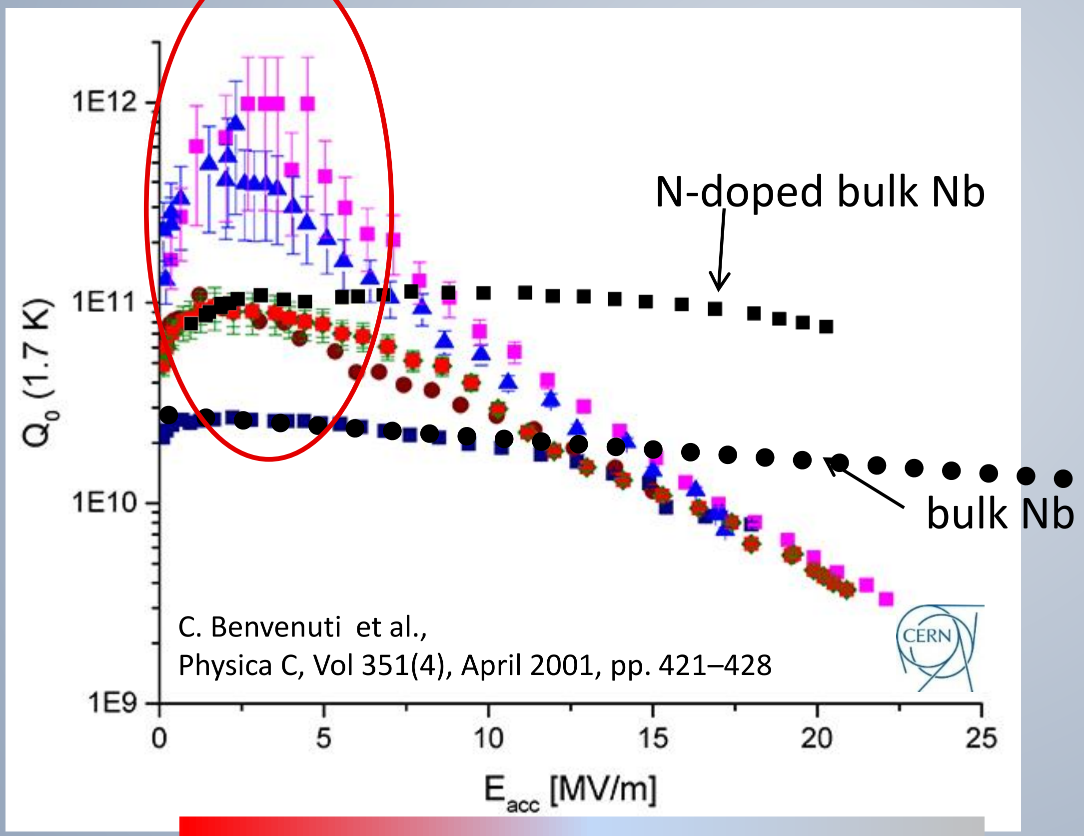
Special thanks: S. Aull (CERN), A.-M. Valente Feliciano (JLAB), G. Rosaz (CERN)


Photo: Reidar Hahn

Thin films – state of the art

- Thickness of interest for SRF applications = RF penetration depth, i.e. the very top 40 nm of the Nb surface.

1.5 GHz Nb/Cu cavities, sputtered w/ Kr @ 1.7 K (Q_0=295/R_s)



N-doped bulk Nb

bulk Nb

C. Benvenuti et al.,
Physica C, Vol 351(4), April 2001, pp. 421–428

High Q at low field BUT strong Q-slope

Photo:
Reidar Hahn

Nb on Cu QWR cavities for HIE-ISOLDE

- Nb on Cu technology was used for LEP and is used in LHC.
- CERN has successfully built around 20 quarter-wave resonators with Nb/Cu technology for HIE-ISOLDE.
- The quality of the Cu substrate is of crucial importance, but with a good substrate, excellent thermal and mechanical stability is obtained.

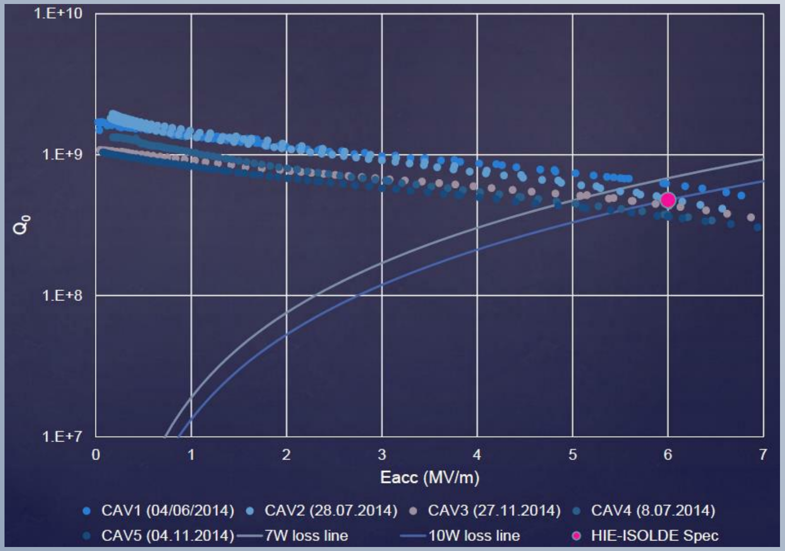
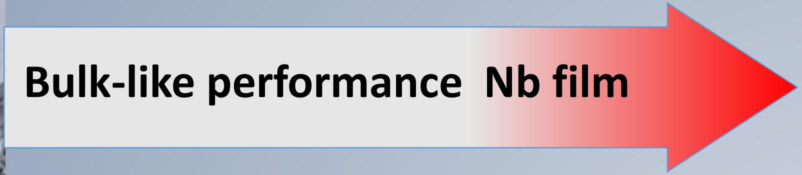



Photo: Reidar Hahn

Next generation Nb films



Bulk-like performance Nb film

- ❑ Minimize Rres, maximize Q
- ❑ Potential major system simplifications
- ❑ Highest level of quality assurance and reliable performance.
- ❑ Use of substrates with higher thermal conductivity (Cu, Al)

Identify and correct the cause(s) of anomalous Q-slope

(not limited to Nb films alone, higher T_c films & multi layers also affected, especially with such issues as the entry of Josephson vortices driven by the RF field.)

focused on the entire problem and all possible causes in order to understand, identify, and eliminate the causes.

What are the differences between bulk and thin-film Nb in reference to the RF surface?

Higher density of grain boundaries

Different spectrum of grain boundary energies than for bulk Nb surfaces

Thermal diffusivity of the RF surface (from the thermal properties of the film itself in addition to the thermal impedance of the Nb/ substrate interface).

Surface chemistry

Presence of defects (dislocations, porosities, inclusions)

Surface morphology

Magnetic field losses- several sources: field enhancing surface features , external stray fields captured in form of vortices or arising from thermoelectric currents as Nb transitions from normal to superconducting state.

Crystallographic structure (orientation, grain size)

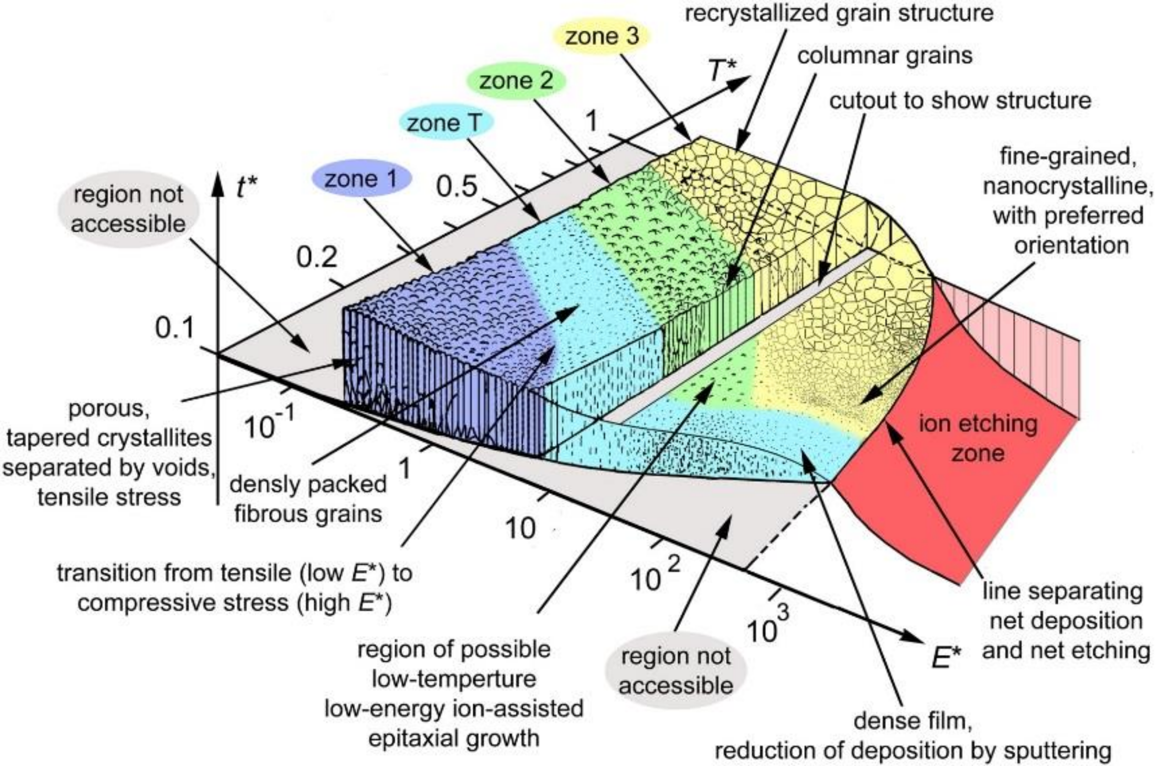
Photo:
Reidar Hahn

Energetic condensation

- To improve surface morphology and thin film adhesion, Nb ions get accelerated towards the surface by an additional energy – this allows to control the film-growth process.
  - ☐ residual gases desorbed from the substrate surface
  - ☐ chemical bonds may be broken and defects created thus affecting nucleation processes & film adhesion
  - ☐ enhanced mobility of surface atoms
  - ☐ stopping of arriving ions under the surface

⇒ Changes & control in

- ☐ Film density
- ☐ morphology
- ☐ microstructure
- ☐ stress
- ☐ low-temperature epitaxy

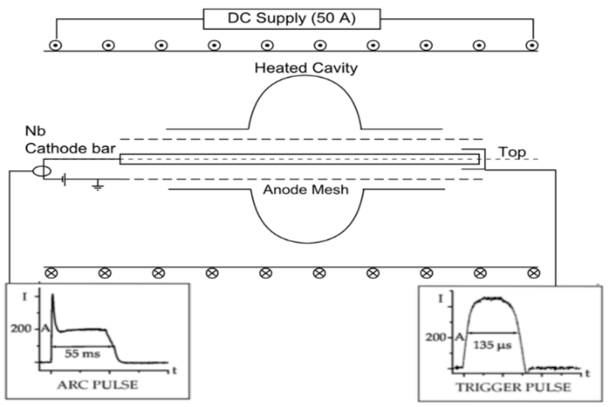


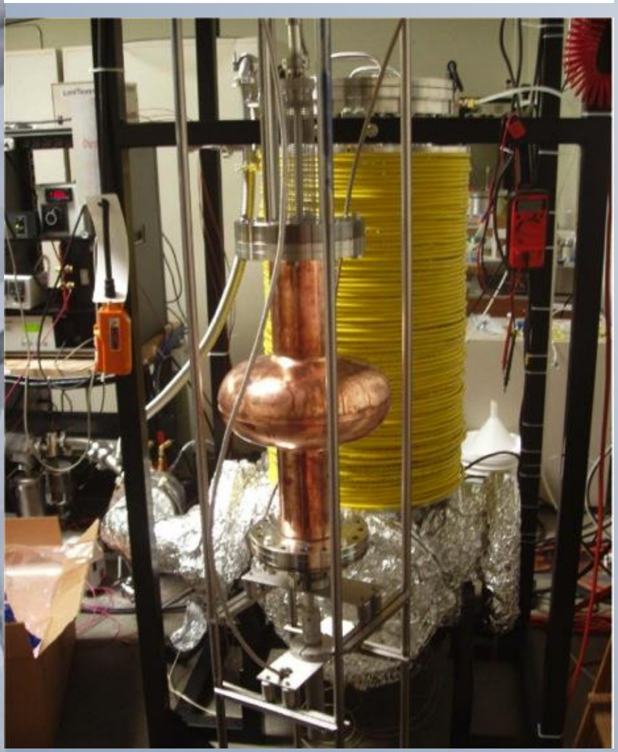
A variety energetic condensation technologies

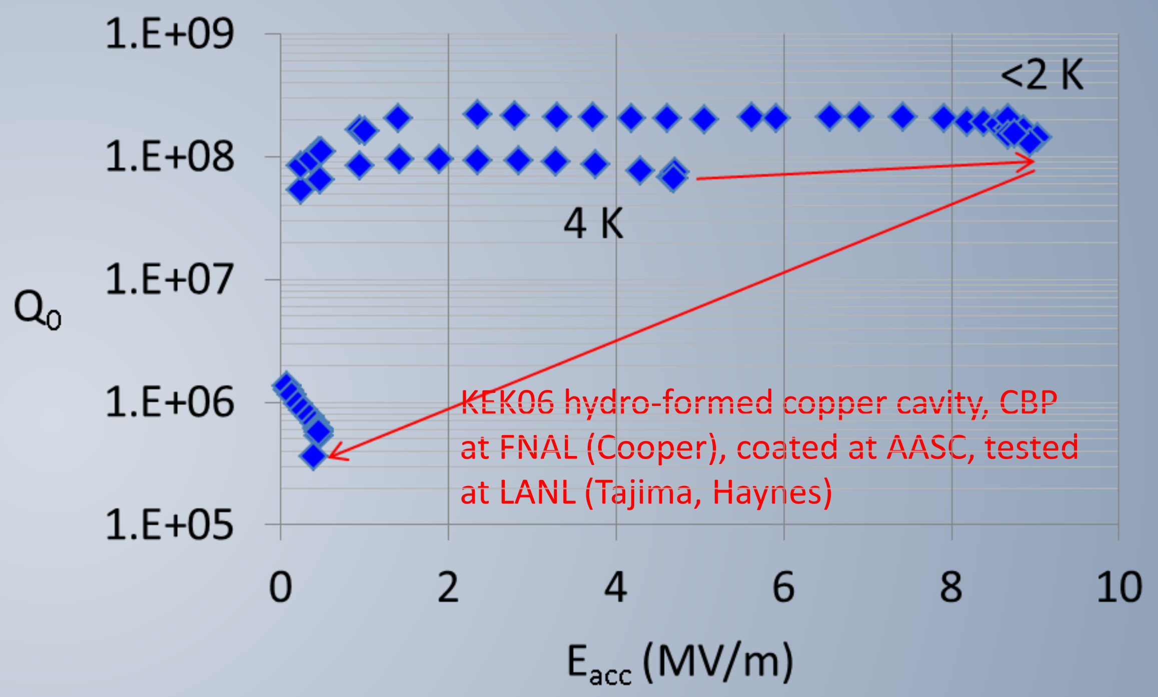
- ☐ Vacuum Arc Plasma & Coaxial Energetic Deposition (CED)
- ☐ Electron cyclotron Resonance (ECR)
- ☐ High Impulse Power Magnetron sputtering (HiPIMS)

Photo:
Reidar Hahn

Coaxial Energetic Deposition (CED)







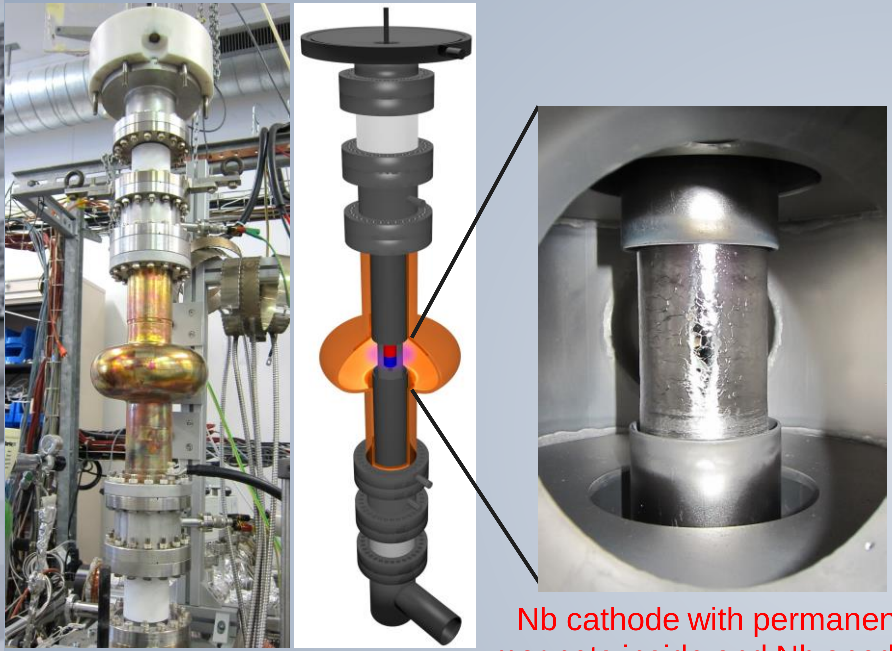
KEK06 hydro-formed copper cavity, CBP at FNAL (Cooper), coated at AASC, tested at LANL (Tajima, Haynes)

The difference between 4K and 2K is smaller than expected: BCS resistance should be about 40x less if all the surfaces are Nb.

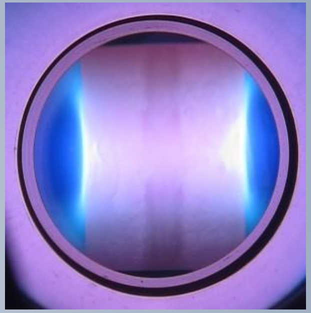
Photo: Reidar Hahn

High Power Impulse Magnetron Sputtering – HiPIMS

1.3 GHz cavity coating setup at CERN

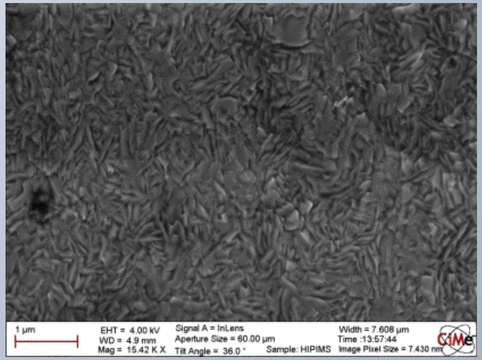


Nb cathode with permanent magnets inside and Nb anodes

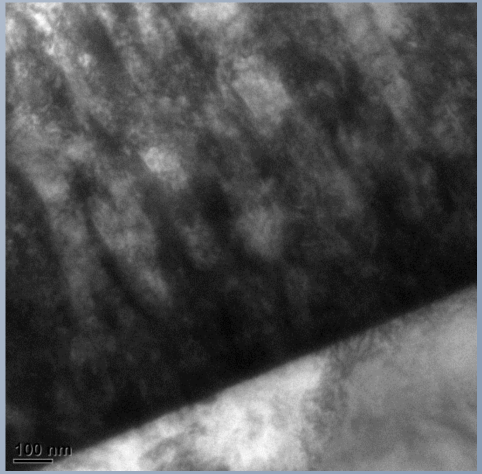


HiPIMS discharge

- ☐ Same hardware as for DCMS
- ☐ Pulsed Power supply
  - 1% duty cycle
  - Short pulses: 200 µs
  - High peak current (200 A vs 3 A for DCMS)
  - High peak power (80 kW peak for 1kW avg)
- ☐ Ionization of sputtered species
- ☐ Lower coating rate than DCMS



Seemingly larger surface features than in DCMS



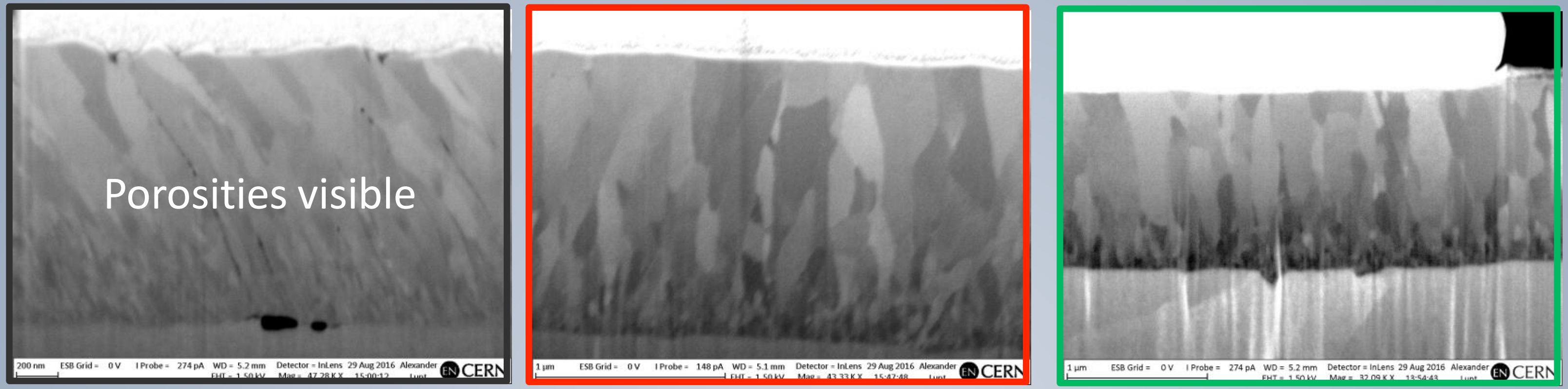
HiPIMS – Results at CERN

Photo:
Reidar Hahn

Grounded

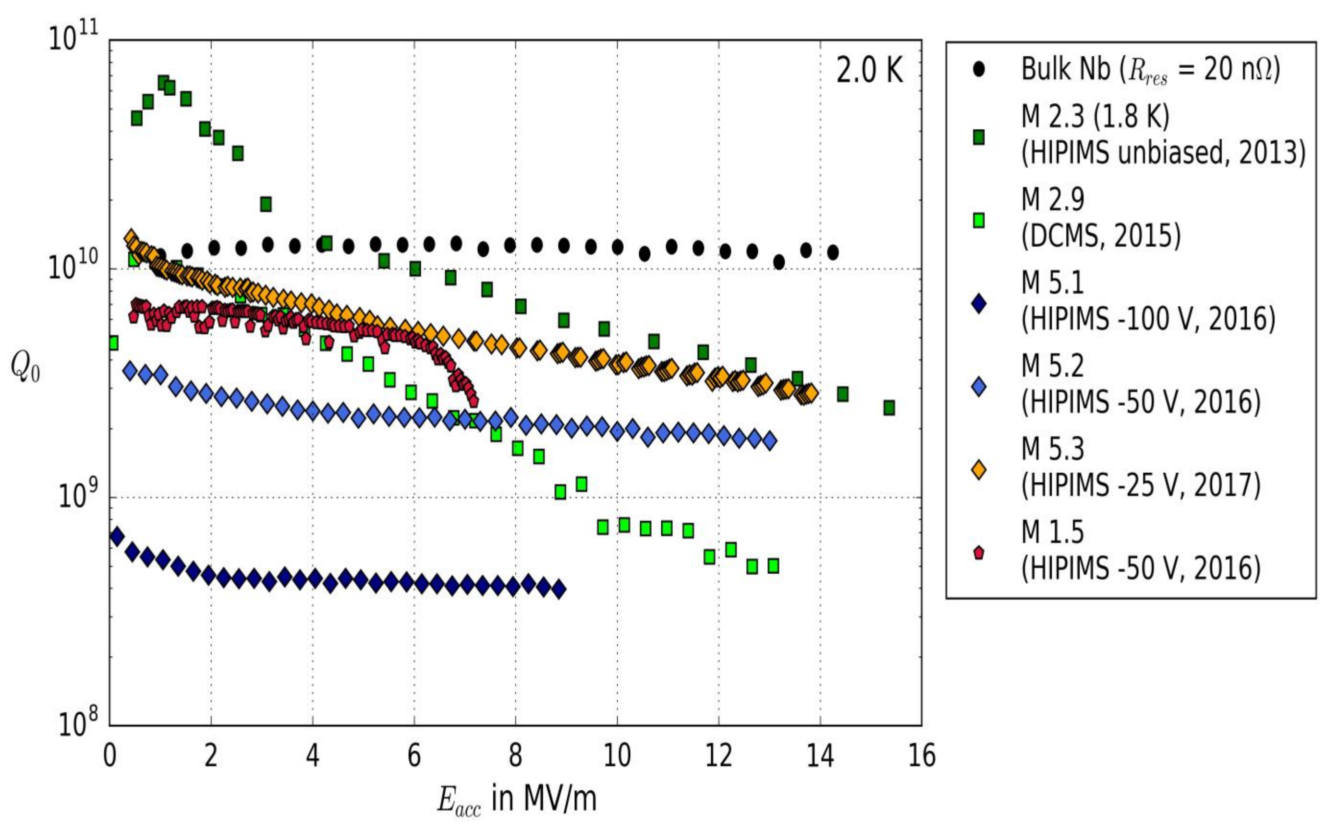
-50 V

-100 V



Porosities visible

FIB
Cross-sections
G. Rosaz (CERN)



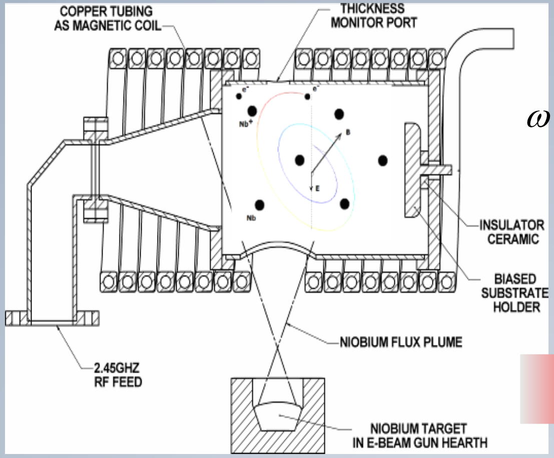
With substrate biasing, film densification with no porosities

- Q-slope looks flatter than DCMS
- Coating pressure & bias show strong impact on Q.
- Best up to now: $R_{res} = 25\ \mathrm{n\Omega}$.
- Substrate quality important (poor so far)!
- Tests ongoing

Photo:
Reidar Hahn

Jefferson Lab

Energetic condensation with ECR



$$\omega = \frac{eB}{m}$$

Generation of plasma - 3 essential components:

Neutral Nb vapor
RF power (@ 2.45GHz)
Static B ⊥ E_{RF} with ECR condition

No working gas

Singly charged ions (64eV) produced in vacuum

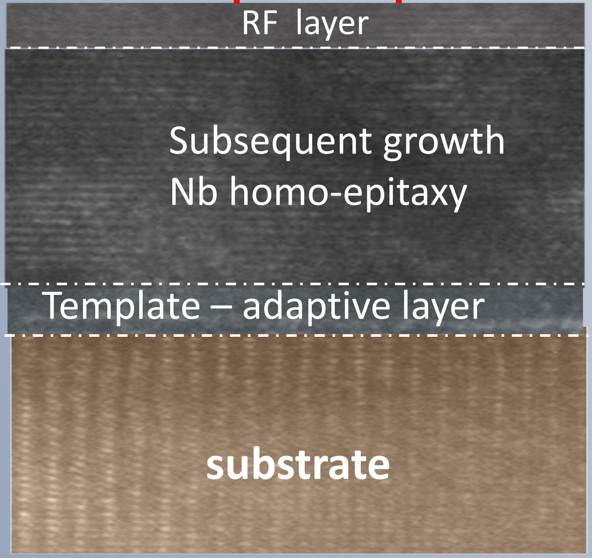
Controllable deposition energy with Bias voltage

Excellent bonding , No macro particles

Good conformality

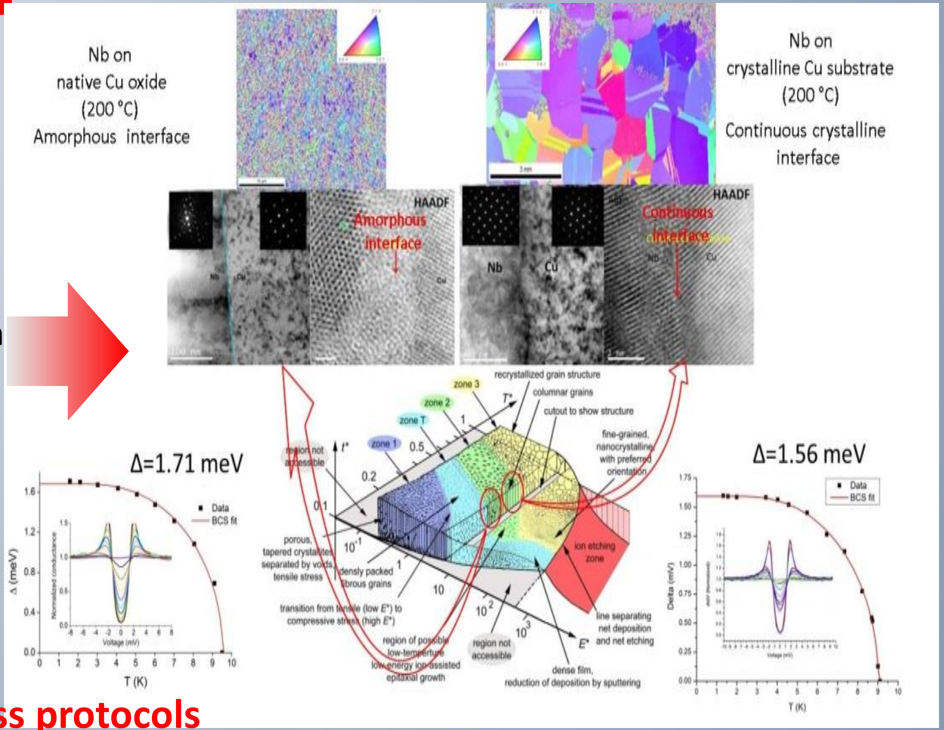
Engineering for optimum RF performance

Sequential phases for film growth



- ☐ Interface
- ☐ Film nucleation
- ☐ Growth of appropriate template for subsequent deposition
- ☐ Deposition of final surface optimized for minimum defect density.

Control over nucleation & subsequent growth, thus structure

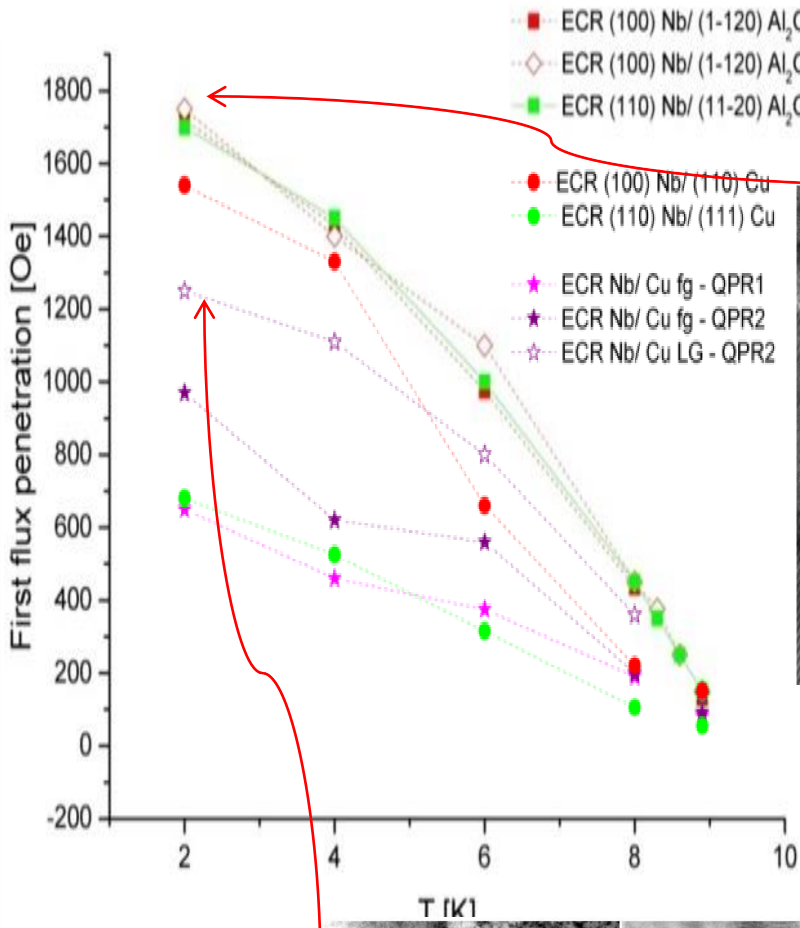


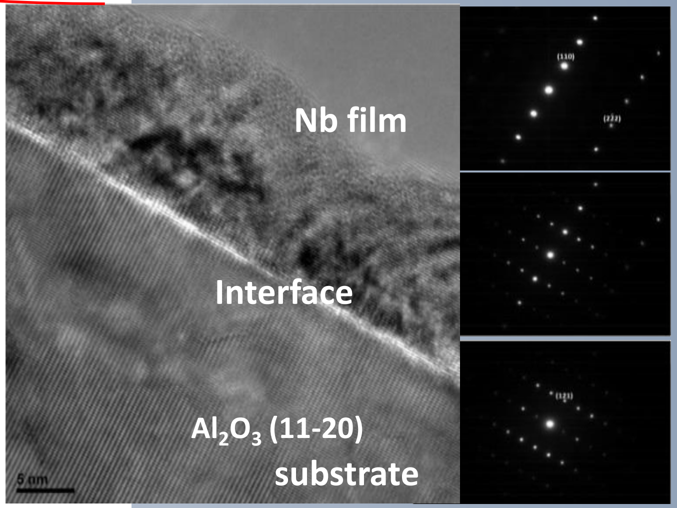
Full control over final SRF performance with strict process protocols

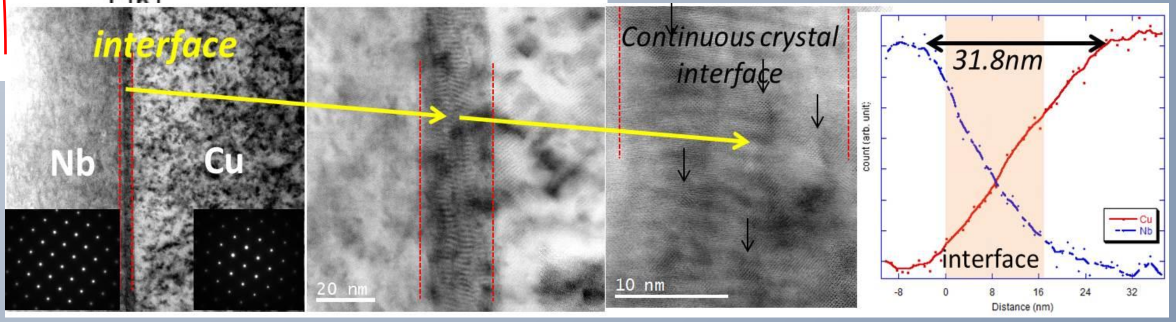

Photo:
Reidar Hahn

ECR Nb film properties

	Substrate	RRR max
Insulating	a-Al_2O_3	591
	r-Al_2O_3	725
	c-Al_2O_3	247
	MgO (100)	188
	MgO (110)	424
	MgO (111)	270
	Al_2O_3 ceramic	135
	AlN ceramic	110
	Fused Silica	84
Metallic	Cu (100)	181
	Cu (110)	275
	Cu (111)	245
	Cu fine grains	193
	Cu large grains	305





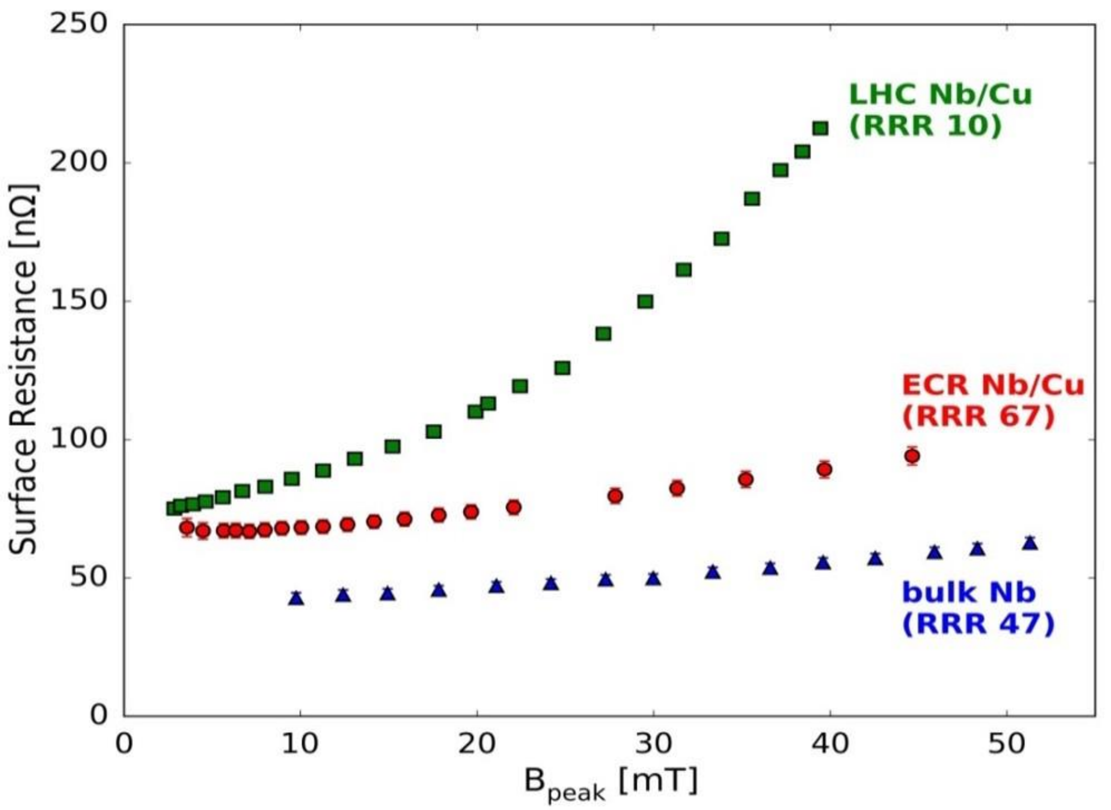


Full control of interface for enhanced adhesion


Photo:
Reidar Hahn

ECR sample coupon R_s measurements

	R_{res} [nΩ]	$\lambda(0\ \mathrm{K})$[nm]
400 MHz	46.6 ± 0.8	40 ± 2
800 MHz	79 ± 2	38 ± 1
1200 MHz	156 ± 11	38 ± 1



With $\lambda_L = 32\ nm$ and $\xi_0 = 39\ nm$: $\ell = (144 \pm 20)$ nm and $RRR = 53 \pm 7$.

A-M Valente-Feliciano, JLab
S. Aull, CERN

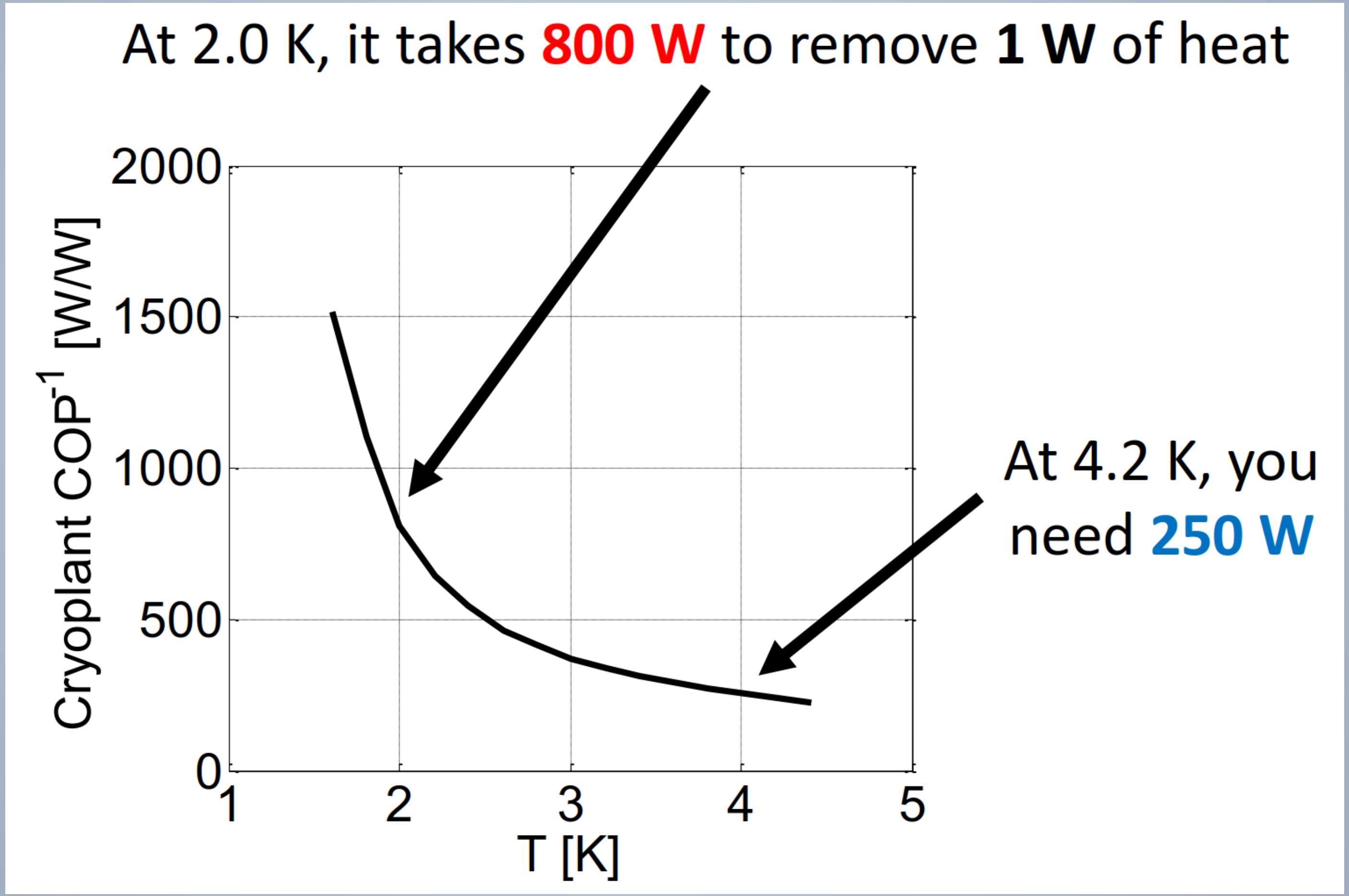
Nb_3Sn

Special thanks to D. Hall, M. Liepe (Cornell), S. Posen (FNAL)


Photo:
Reidar Hahn

The interest to move to higher T_{op}

- Cryogenic efficiency:


At 2.0 K, it takes **800 W** to remove **1 W** of heat

At 4.2 K, you need **250 W**


Photo:
Reidar Hahn

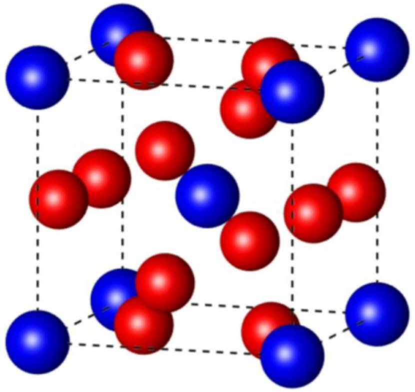
Nb_3Sn qualities

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 Δ/k_bT_c	1.8	2.2
λ at T = 0 K	50 nm	111 nm
ξ at T = 0 K	22 nm	4.2 nm
GL parameter κ	2.3	26

← **Lower losses**

← **Higher gradients**


Photo:
Reidar Hahn

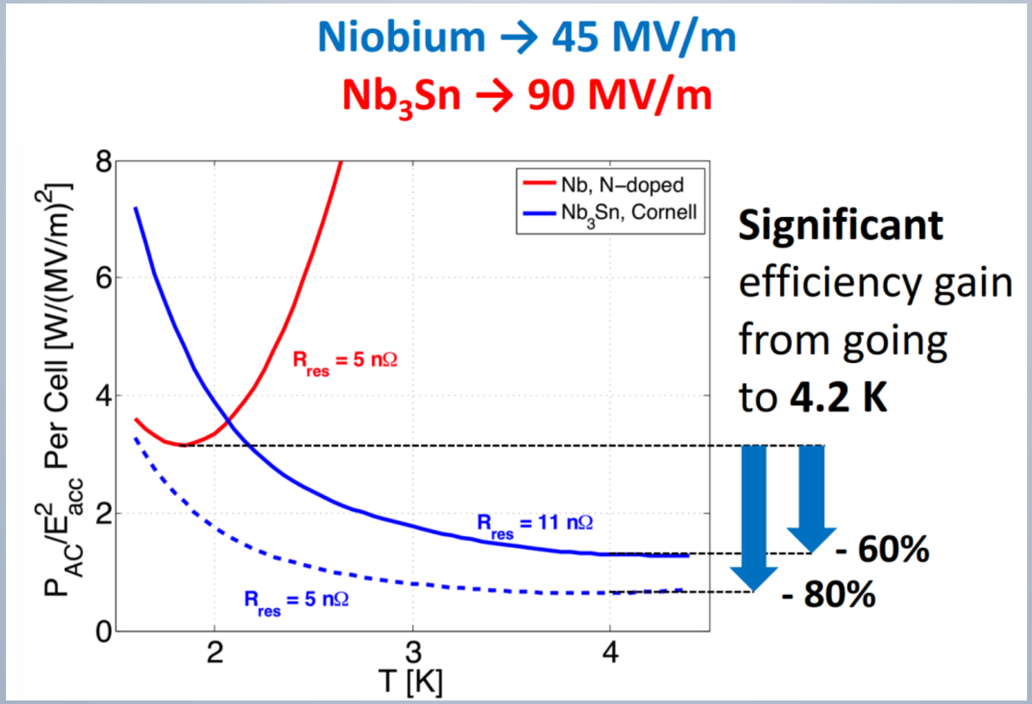
Effect of higher T_c

- BCS resistance:

$$R_s = \frac{A}{T} e^{-\frac{1.76\,T_c}{T}} + R_{res}$$

Higher critical temperature ⇒ lower BCS resistance, lower loss.

Potential:


Niobium → 45 MV/m

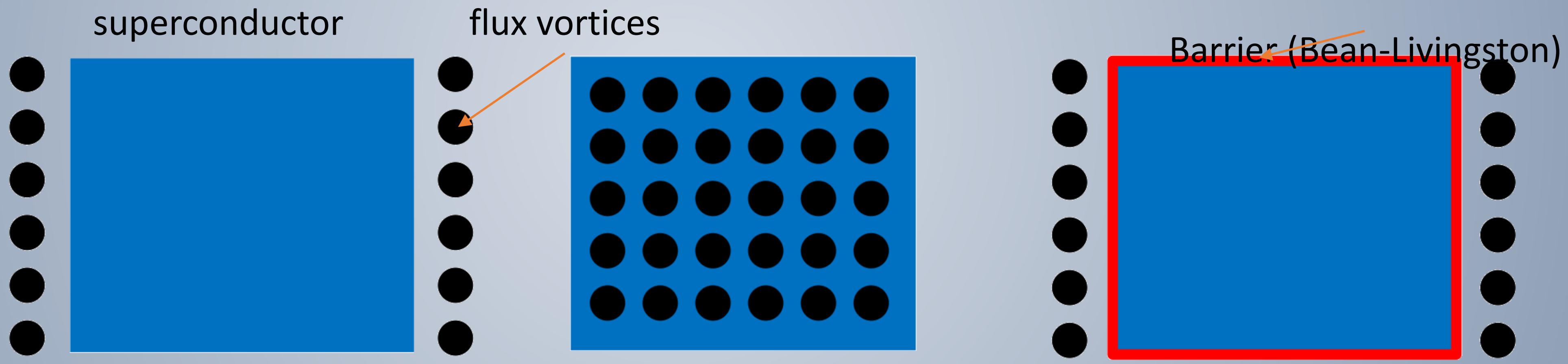
Nb_3Sn → 90 MV/m

Significant efficiency gain from going to **4.2 K**


Photo:
Reidar Hahn

Superheating field

- Type-II superconductor: flux lines can enter above H_{c1}, but cavities cannot operate in mixed state – the losses from vortex drag are too important.
- However, there are barriers that prevent vortices to enter even above H_{c1} and up to H_{sh}.



$H < H_{c1}$, Meissner state, all flux expelled

$H_{c1} < H$, Mixed state, not good for SRF!

$H_{c1} < H < H_{sh}$, barrier prevents flux vortices from entering

- The superheating field of Nb_3Sn is encouraging $425\ \mathrm{mT}$!


Photo:
Reidar Hahn

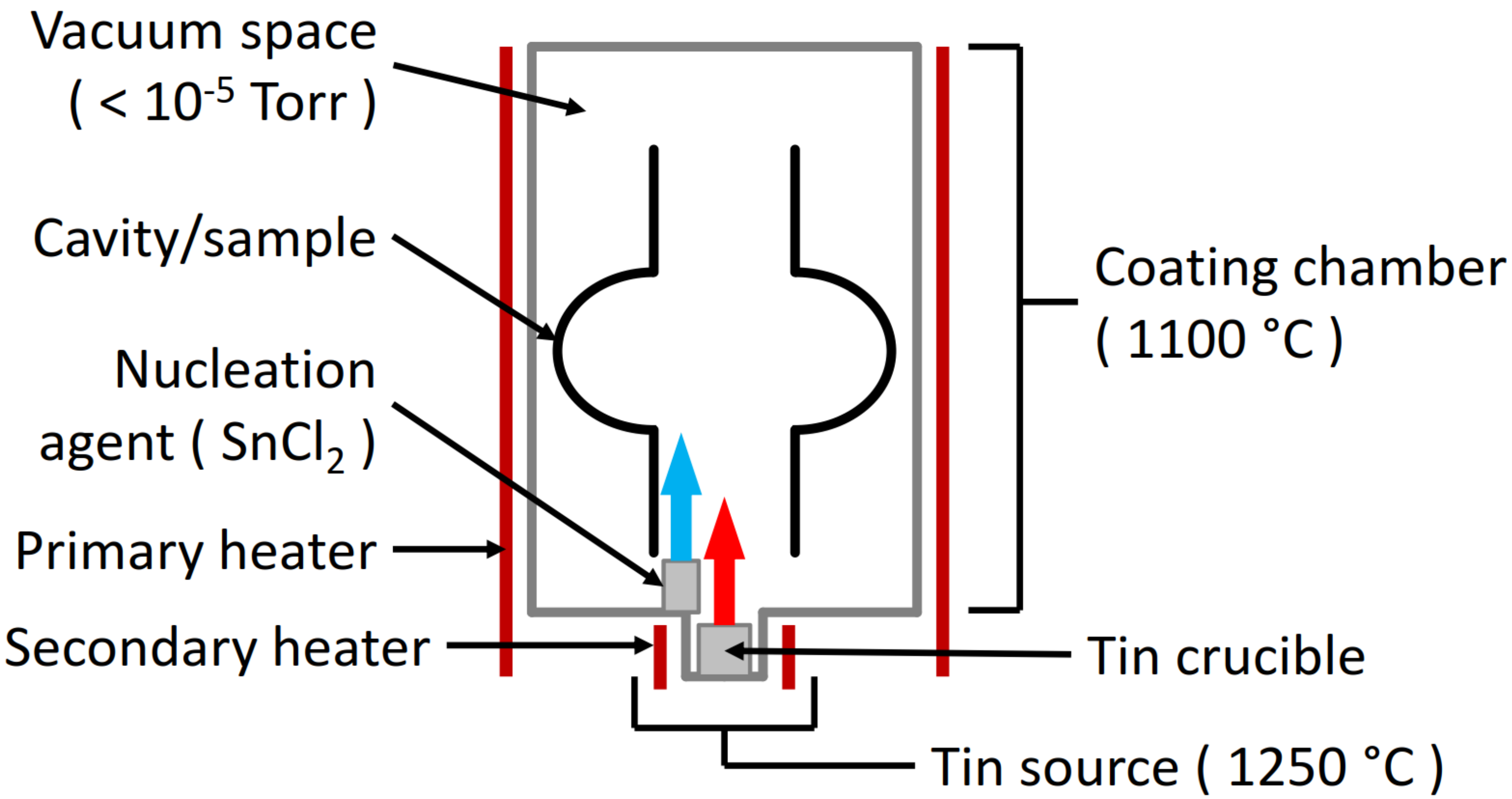
The challenges

- Nb_3Sn is very brittle
  → we cannot form it
- Nb_3Sn have a low thermal conductivity
  →if too thick, we would get thermal feedback.
- This led to the approach to grow a thin film on a Nb substrate using **vapour diffusion** technique.

Photo: Reidar Hahn

Vapour diffusion process

Coating furnace with separate **source hot-zone**



Vacuum space (< 10^{-5} Torr)

Cavity/sample

Nucleation agent ($SnCl_2$)

Primary heater

Secondary heater

Coating chamber (1100 °C)

Tin crucible

Tin source (1250 °C)


Photo:
Reidar Hahn

Cornell’s coating furnace

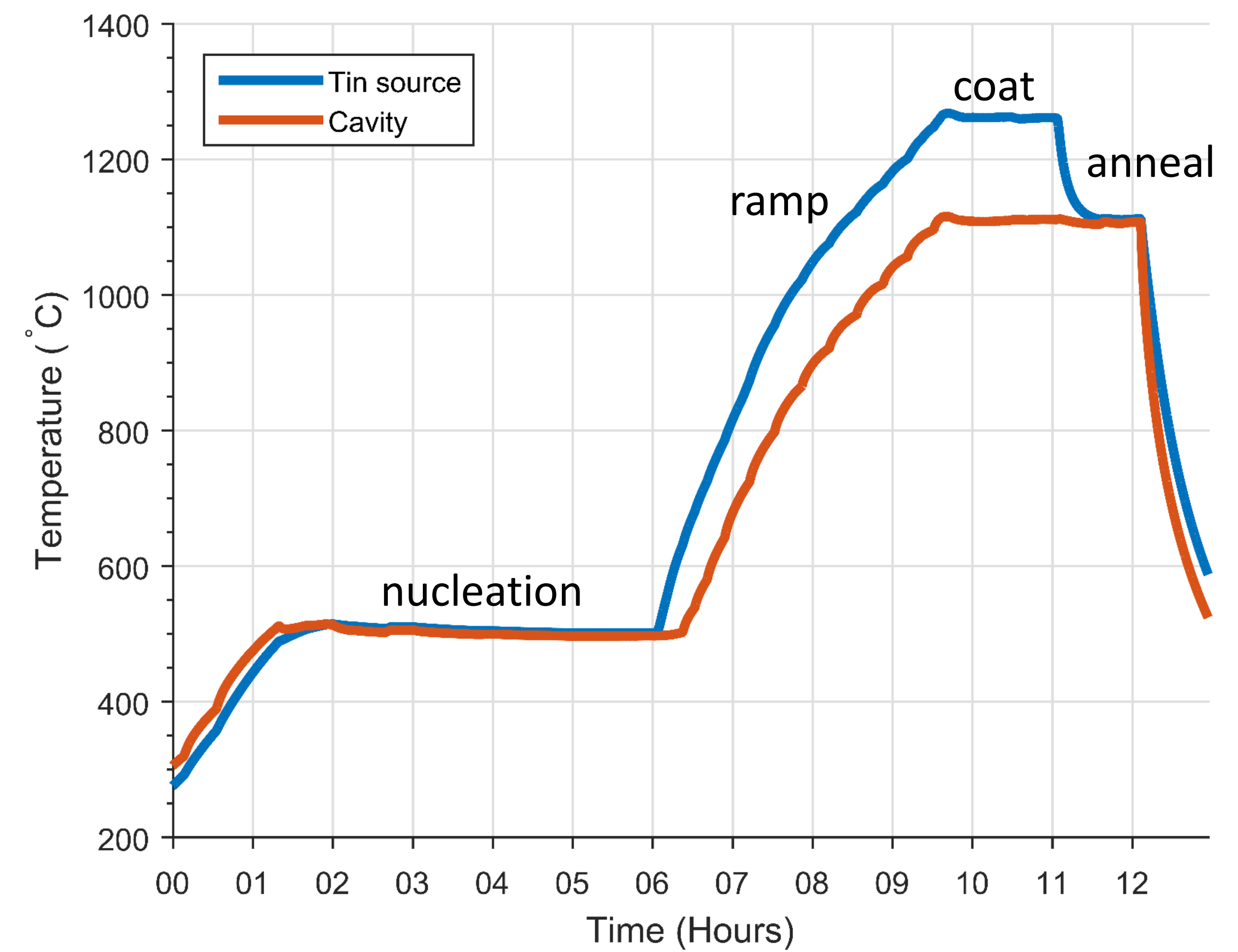
- Custom-built UHV furnace for coating **sample coupons** and **single-cell 1.3 GHz cavities**


Photo: Reidar Hahn

The successful heat cycle

Important details:

- The stoichiometry is very important (25% Sn!)
- **Nucleation:** The surface is seeded with tin to ensure uniform coating
- **Ramp:** The tin source is hotter than the chamber before coating begins



Nb_3Sn in cross-section

- Nb_3Sn forms a polycrystalline layer on the Nb surface, about 3 μm thick.

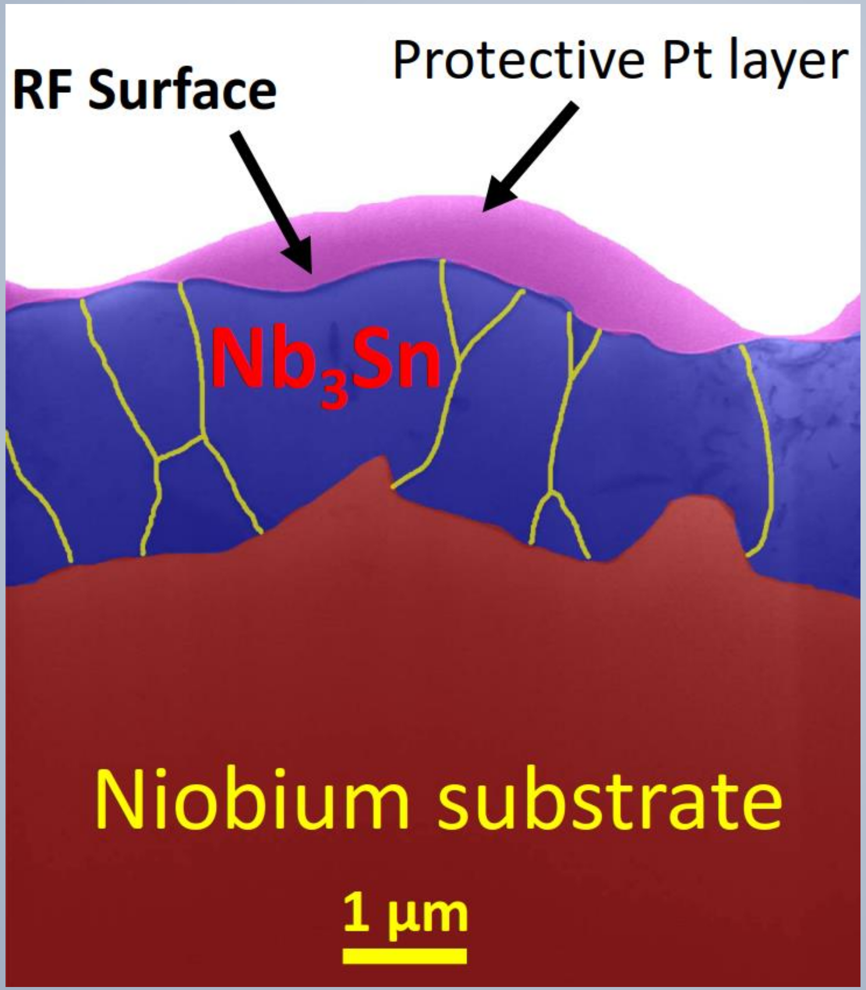
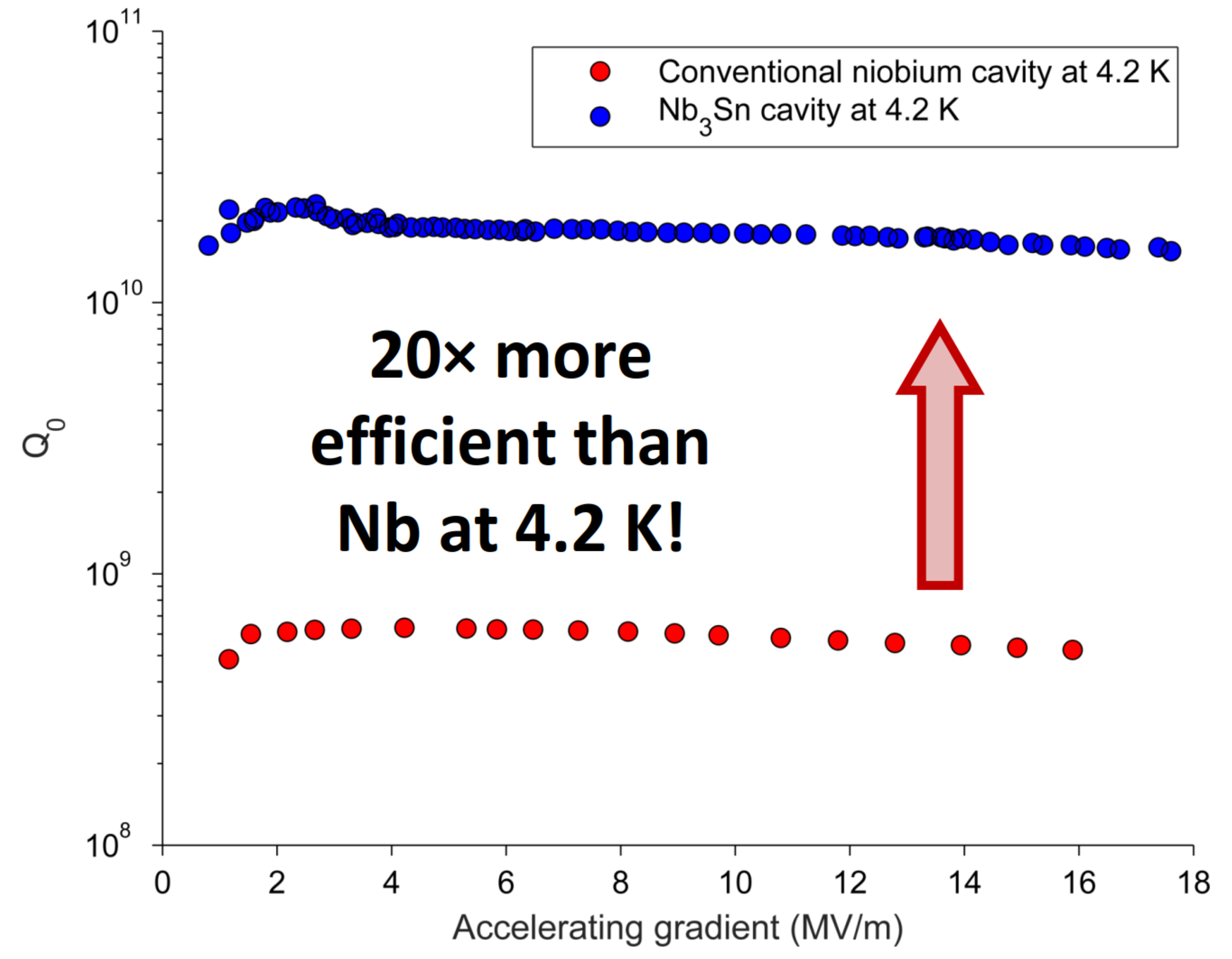



Photo:
Reidar Hahn

Testing the real cavity (at 4.2 K)

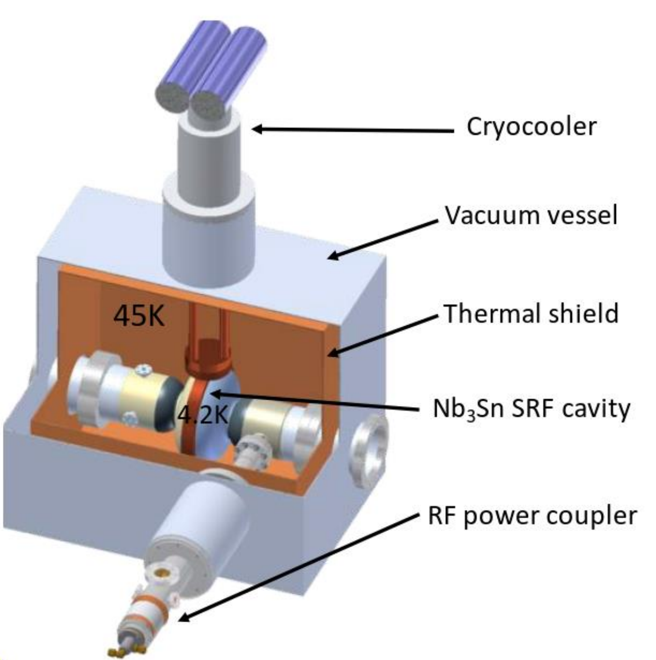


20× more efficient than Nb at 4.2 K!


Photo:
Reidar Hahn

Dreaming of future applications

- Compact light sources
- Cargo scanning
- Food sterilisation
- Polymer cross-linking



Cryocooler based miniaturized accelerator

Fast cargo scanning

End of “Recent progress and future trends in SRF technology “

Thank you very much!


Photo:
Reidar Hahn

End of EuCAS Short Course on Superconducting RF

Thanks you for your attention – please ask questions!