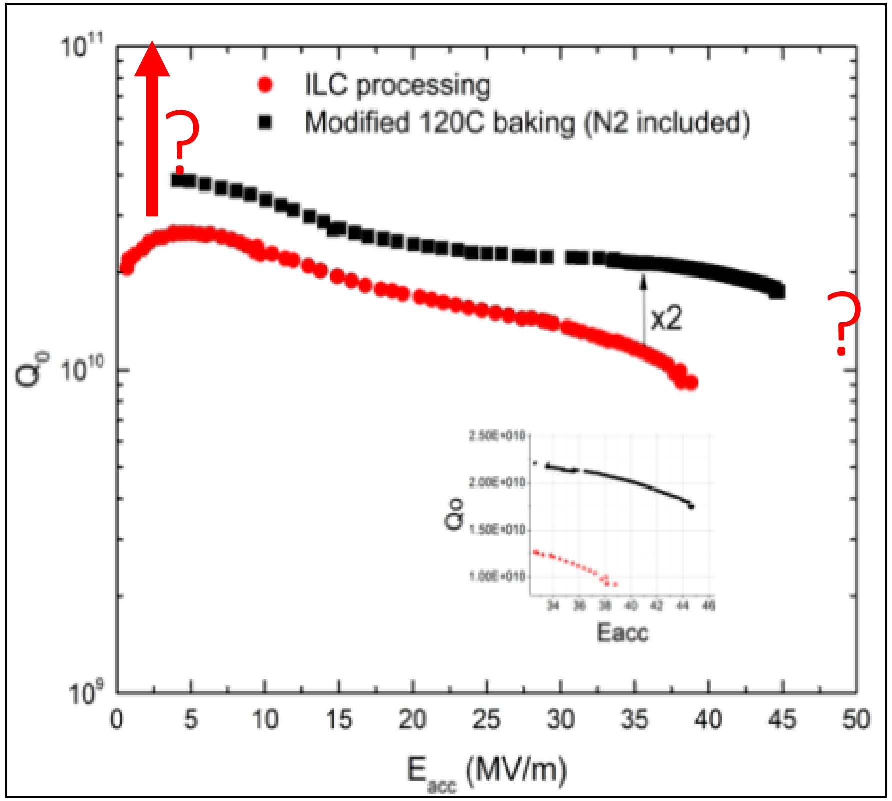
BEYOND BULK Nb

A-M VALENTE-FELICIANO

Why looking beyond bulk Nb?



A. Grassellino and S. Aderhold, TTC meeting, Saclay, France (2016)

So far Q(H) and E_{acc} of Nb cavities have been rising ...

Fundamental limits of Q(H) and the breakdown field?

Decrease of Q(H) is consistent with current pairbreaking effects

How close is Nb to the fundamental instability of the Meissner state?

Breakdown fields close to the de-pairing limit of 50 MV/m for Nb have been achieved
Best Nb cavities approaching their intrinsic limit at $H_{max} = H_C$

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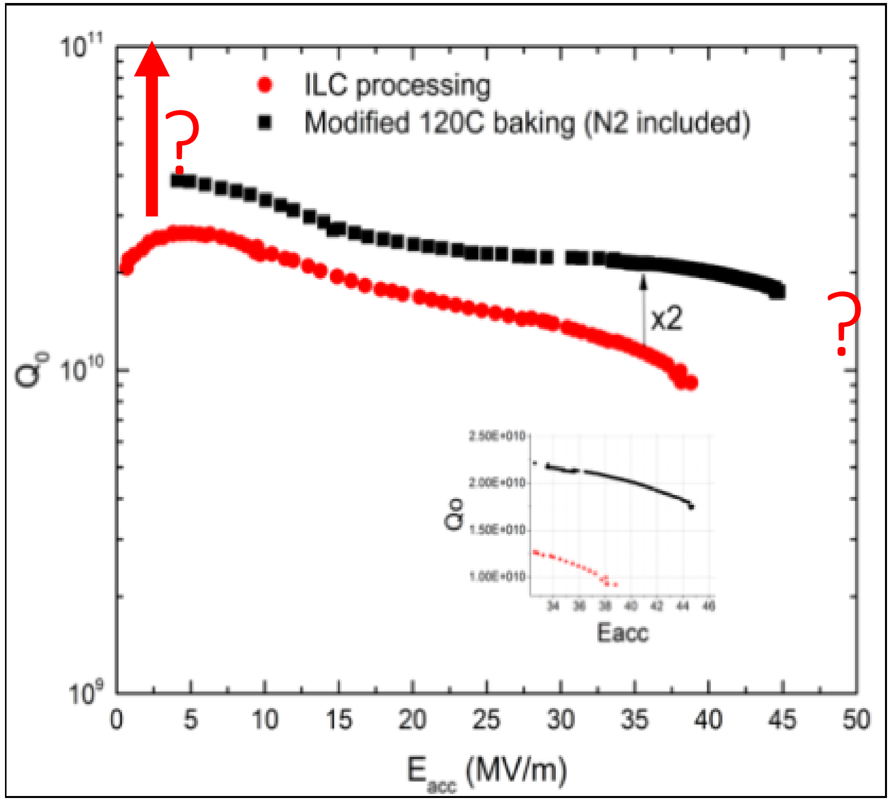

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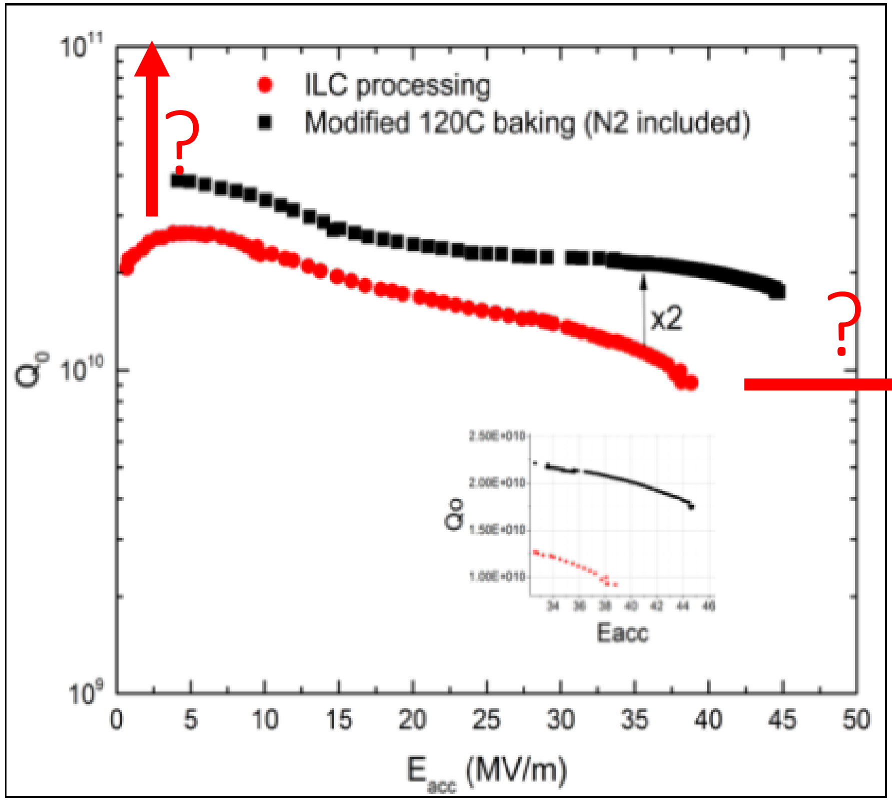

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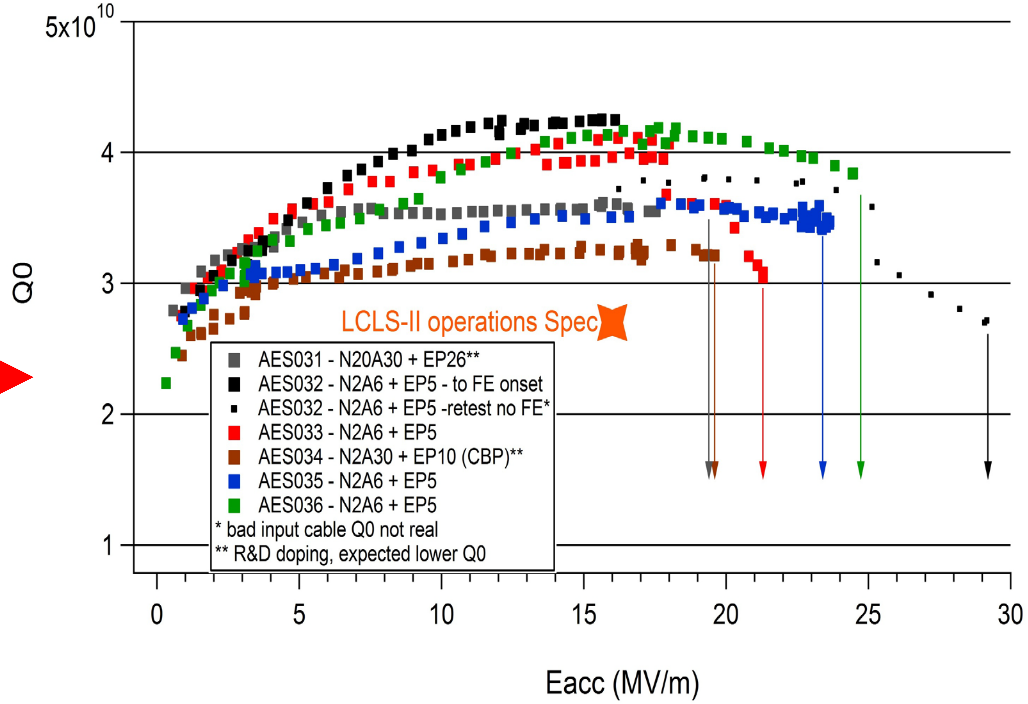


All cavities were tested with Stainless steel flanges which add 1.4 nΩ. Residual resistance with 1.4 nΩ has been subtracted from the data. –

Breakdown fields close to the de-pairing limit of 50 MV/m for Nb have been achieved

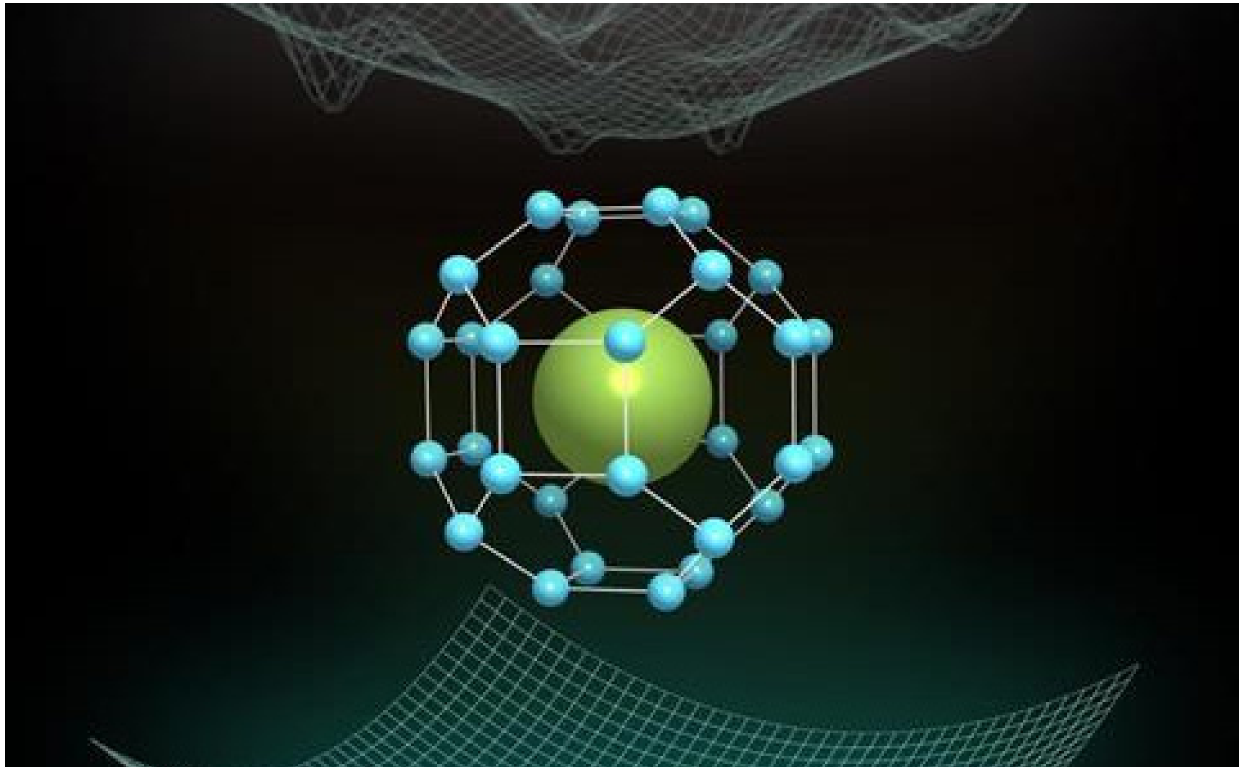
Best Nb cavities approaching their intrinsic limit at $H_{max} = H_C$

Recent improved cavity RF performance in Q with N doping/infusion

For further improvement, innovation needed

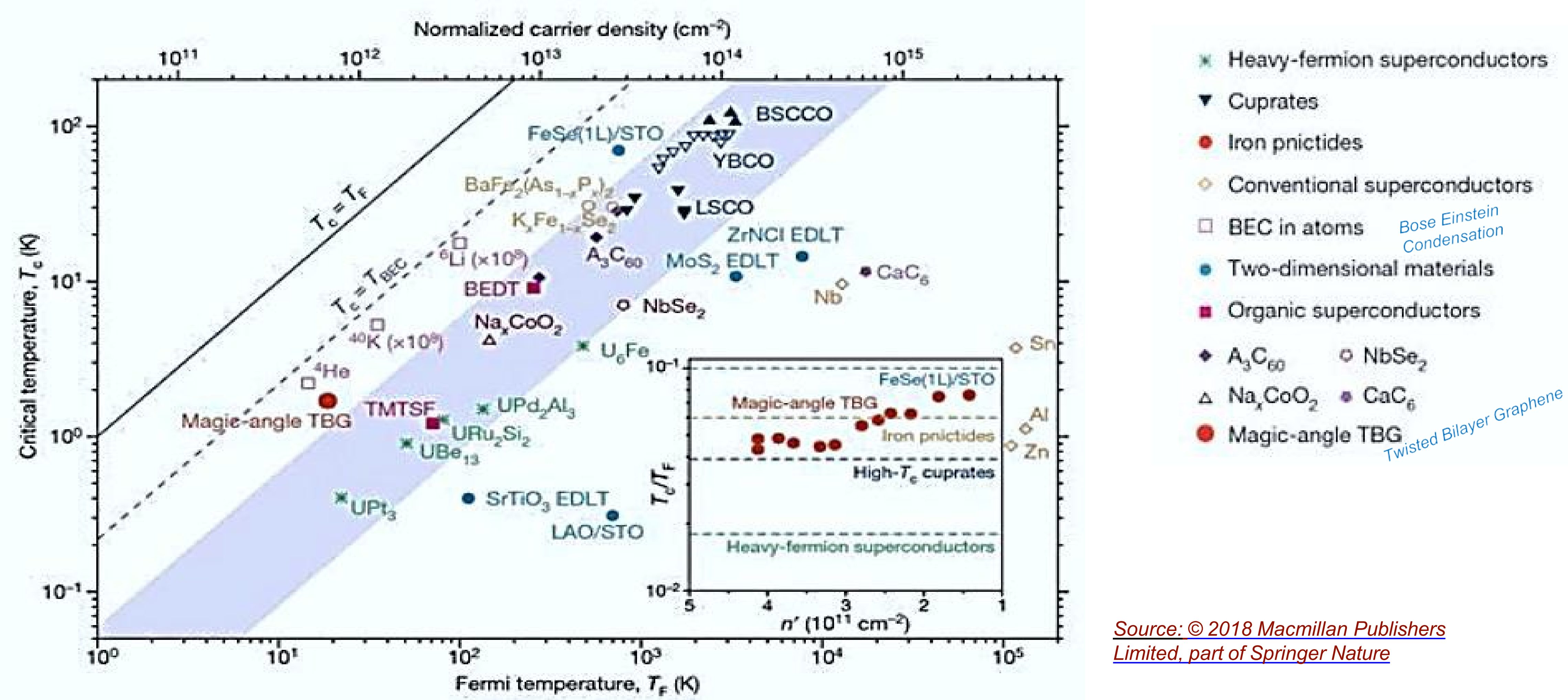
Possibilities to use higher performance superconductors other than bulk Nb?

RF SUPERCONDUCTOR: CHOICE CRITERIA ?



THOUSANDS OF SUPERCONDUCTORS …

Thousands of SC exist, ~10 are currently used for applications, only bulk Nb works well for SRF !!!



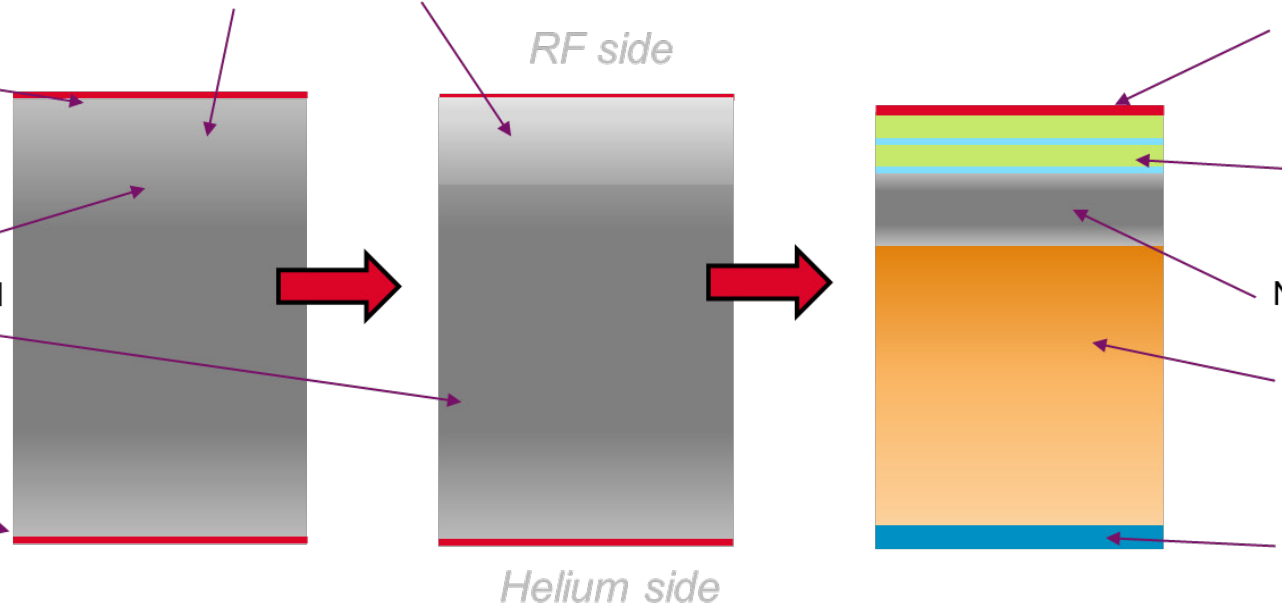
Bose Einstein Condensation

Twisted Bilayer Graphene

Source: © 2018 Macmillan Publishers Limited, part of Springer Nature

IDEAL SRF MATERIAL: TAILORED FOR APPLICATIONS

High RRR not required for superconductivity but for thermal stabilization in case of defects



Today: bulk & doped Nb

Native oxide
Unstable upon annealing

High purity Niobium
Optimized only for thermal conduction

Native oxide
Not optimized for thermal transfer

RF side

Helium side

Future ?

Protection, low secondary emission yield

High Tc SC
S-I-S multilayers

Niobium or…not

Structure, high thermal conductivity (Copper ?)

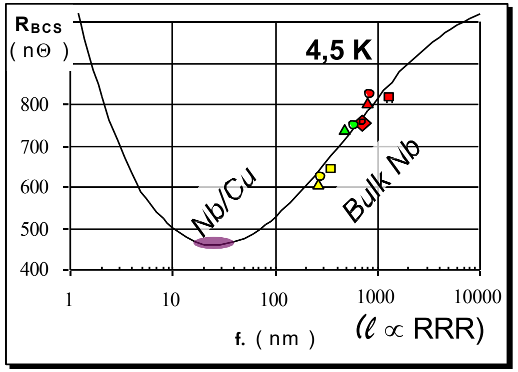
External layer, optimized for thermal transfer

“RF” layer optimized for superconductivity:

Low surface resistance (medium m.f.p.)

and/or *High H_P (high H_{C1} or high H_{SH})

**Depends on the application*



ULTIMATE LIMITS IN SRF

Niobium superconducting radiofrequency cavities

- ❑ **Performances**

$E_{acc} \alpha H_{RF}$

Q_0 (α $1/R_S$) α T_C => **Nb_3Sn, MgB_2, NbN…** *(but not YBCO)*

Limit = magnetic transition of the SC material @ H_{peak}

- ❑ **Superconductivity only needed inside :**

Thickness ~10 µm

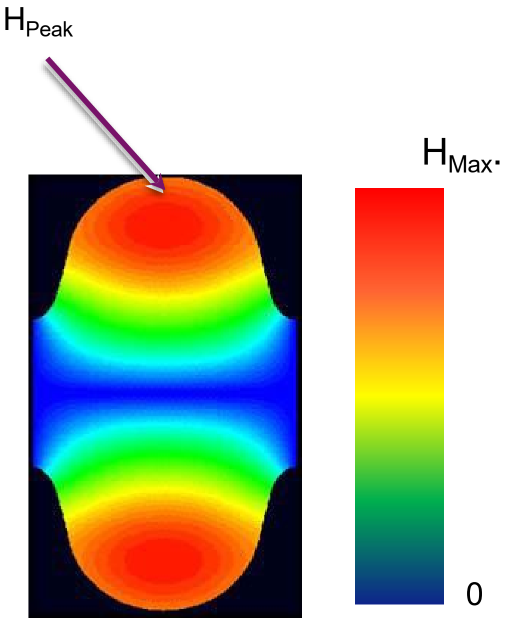
λ~ < 1 µm => thin films *(onto a thermally conductive, mechanically resistant material, e.g. Cu)*

- ❑ **Today :**

Thin films exhibit too many defects

Only Bulk Nb has high SRF performances *(high Q_0 and high E_{acc})*

- ❑ **Issues : getting "defect free" superconductors**



H field mapping in an elliptical cavity

(Yes but not all defects are detrimental... See doping !)

HIGH Q_0, E_{ACC} IN SRF => MEISSNER STATE !

❑ SC phase diagram

- All SC applications except SRF: mixed state w. vortex

  Vortices dissipate in RF !
- SRF => Meissner state mandatory !

❑ Limit ?

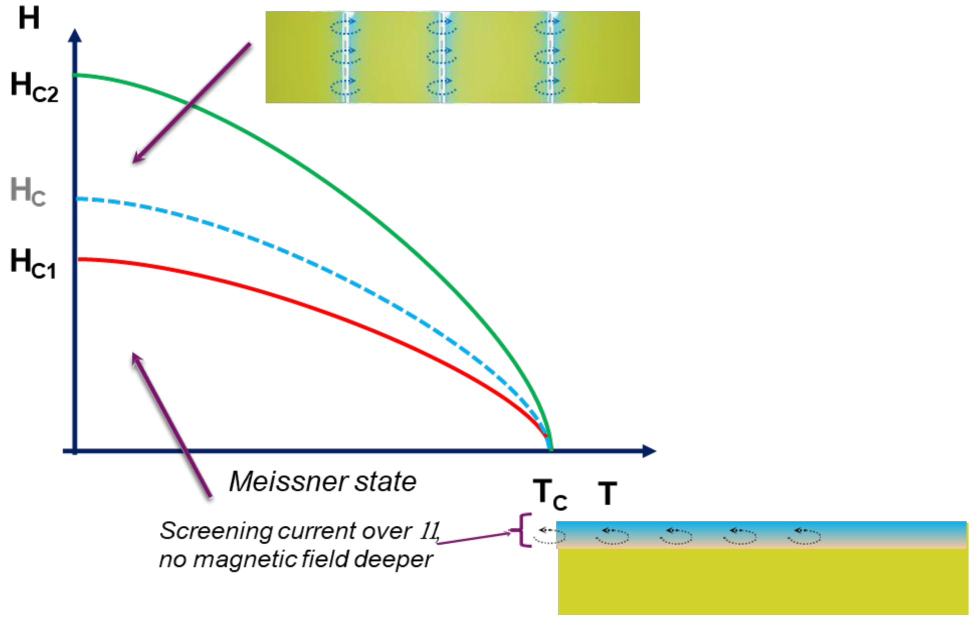
- H_{C1} = limit Meissner/mixed state
  - Nb: highest H_{C1} (180 mT)

Or

- H_{SH} "Superheating field": Metastable state favored by H // to surface

  Difficult to get in real life !

Mixed state w.Vortex (i.e. N. cond. flux line + screening currents)



❑ Surface resistance:

$$R_S = R_{BCS}(T) + R_{res}$$

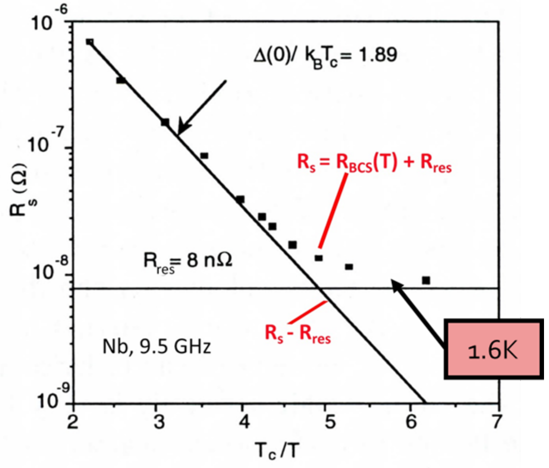
$$R_{BCS} = A(\lambda_L^4, \xi_F, \ell, \sqrt{\rho_n})\frac{\omega^2}{T}e^{-\Delta/kT}$$

Not one formula predicting R_{res} , at least $\propto \sqrt{\rho_n}$

Variety of phenomena involved

Intrinsic: Inhomogeneties, Metallic Inclusions within l, GB, Oxides

Extrinsic: Trapped Flux during cooling (can be avoided)



High T_c is better $T \ll T_C$ is better ($e^{-\Delta/kT}$)

Metallic character in NC state is better (ρ_n)

Dirty is better than high RRR (ℓ) ? *(e,g, doping, but more complex than that !)*

VORTEX PENETRATION WITH B //

Surface barrier

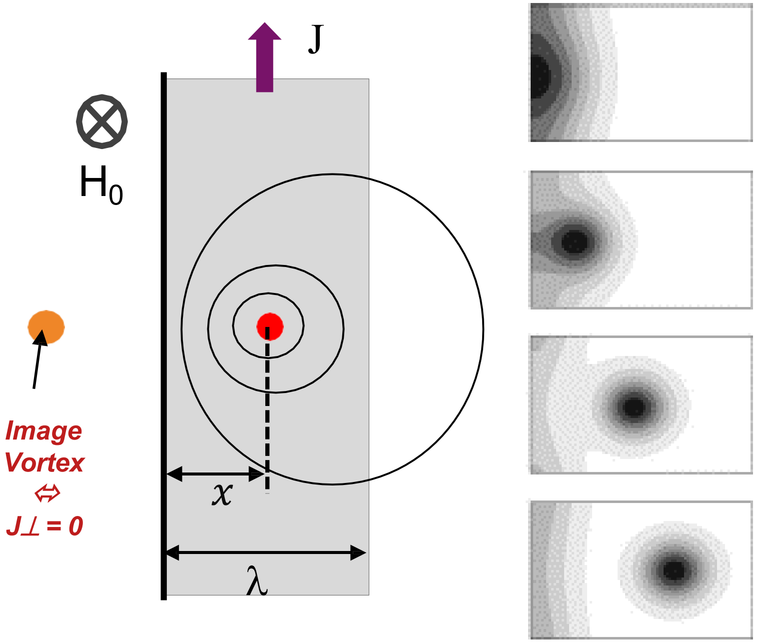
(Bean & Livingston, 1964)

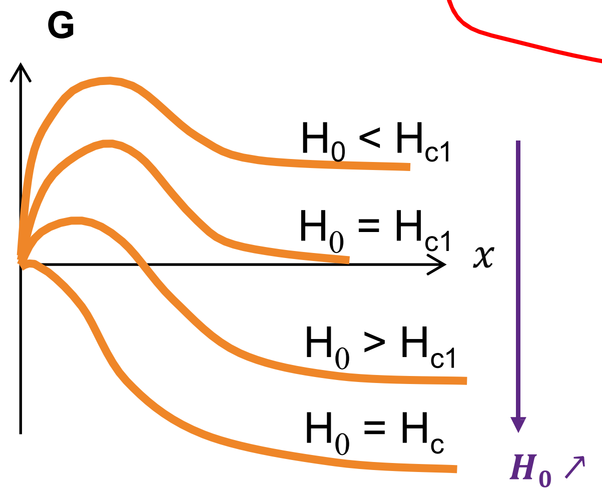
- Boundary condition. ($J_\perp = 0$) ≡ “image” vortices
  - Supercurrent tends to push Vx inside
  - Image antivortex tends to pull it out
- Before entering the material Vx have to cross a surface barrier:
  - Vx thermodynamic Potential :

$$G(x) = \phi_0 \left[H_0 e^{-x/\lambda} - H_v(2x) + H_{C1} - H_0 \right]$$

Meissner

Image





“Ideal surface”

- Barrier disappears only at $H_{SH} \sim H_C > H_{C1}$
- Rationale used to predict SRF limits

BUT

- If ∃ localized defect w.: $H_C^{local} \ll H_c^{bulk}$ (or $T_c^{local} \ll T_c^{bulk}$)

  => early penetration of 1 or several Vx there

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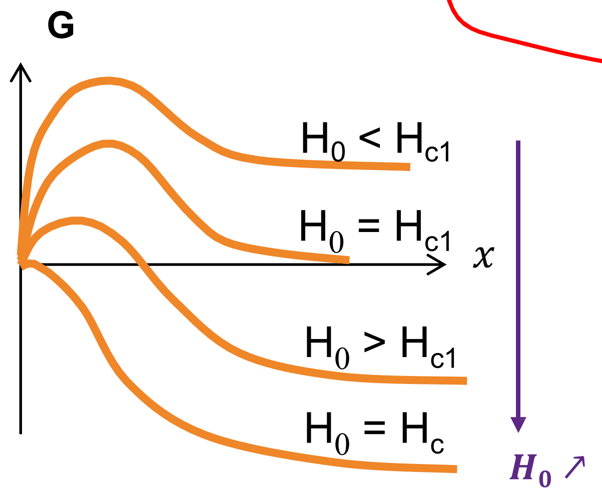

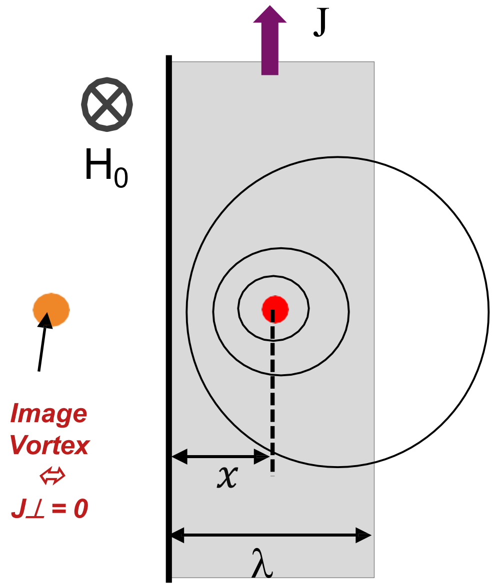

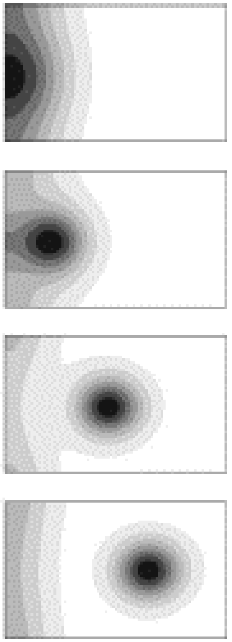

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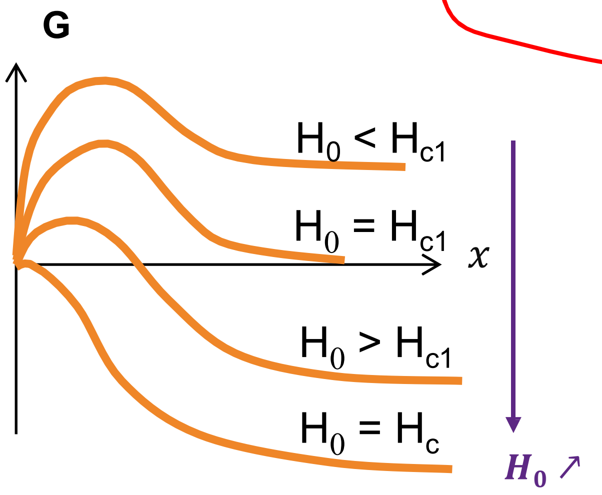

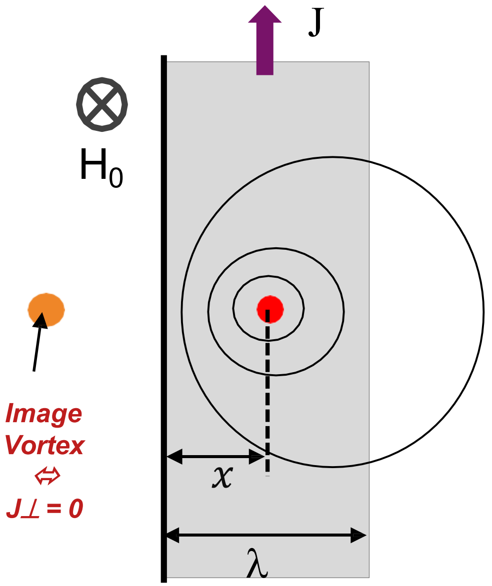

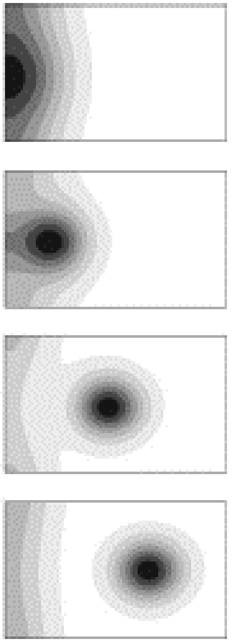

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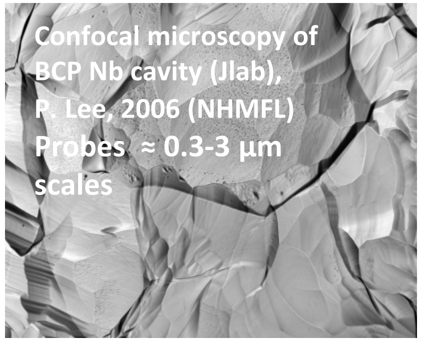
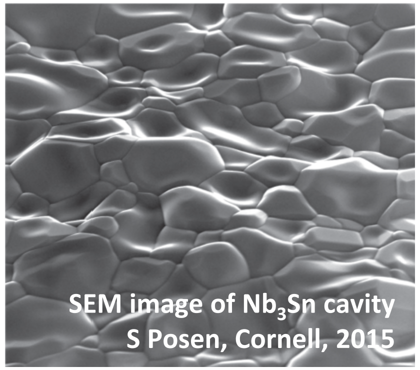


Confocal microscopy of BCP Nb cavity (Jlab), P. Lee, 2006 (NHMFL) Probes ≈ 0.3-3 µm scales



SEM image of Nb_3Sn cavity
S Posen, Cornell, 2015

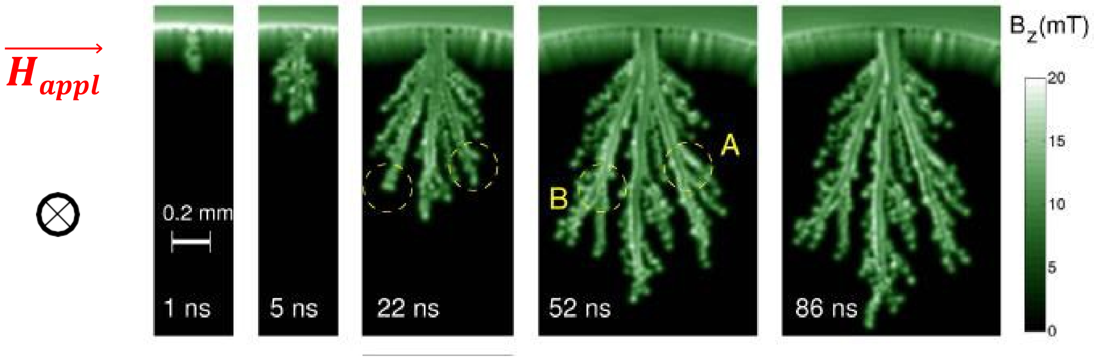
SUPERCONDUCTORS FOR SRF ?

Material	T_C (K)	ρ_n (μOcm)	μ_0H_{C1} (mT)*	μ_0H_{C2} (mT)*	μ_0H_C (mT)*	μ_0H_{SH} (mT)*	ll (nm)*	ξ (nm)*	Δ (meV)	Type
Pb	7.1		n.a.	n.a.	80		48			I
Nb	**9.23**	**2**	**170**	**400**	**200**	**219**	**40**	**28**	**1.5**	**II**
NbN	**17.1**	**70**	**20**	**15 000**	**230**	**214**	**200-350**	**<5**	**2.6**	**II**
NbTi			4-13	>11 000	100-200	80-160	210-420	5.4		
NbTiN	17.3	35	30	**15 000**			150-200	<5	2.8	II
Nb_3Sn	**18.3**	**20**	**50**	**30 000**	**540**	**425**	**80-100**	**<5**	**<5**	**II**
Mo_3Re	15	10-30	30	3 500	430	170	140			II
MgB_2	**39**	**0.1-10**	**30**	**3 500**	**430**	**170**	**140**	**5**	**2.3/7.2**	**II- 2gaps****
2H-$NbSe_2$	7.1	68	13	2680-15000	120	95	100-160	8-10		II- 2gaps**
~~**YBCO/Cuprates**~~	~~**93**~~		~~**10**~~	~~**100 000**~~	~~**1400**~~	~~**1050**~~	~~**150**~~	~~**0.03/2**~~		~~**d-wave****~~
Pnictides $Ba_{0.6}K_{0.4}Fe_2As_2$	**38**		**30**	**>50000**	**900**	**756**	**200**	**2**	**10-20**	**s/d wave****

* @ 0K
** 2D => orientation problems ?

WHAT IS THE ACTUAL LIMIT ($H_{fp}/H_{C1}/H_{SH}$) ?

- Avalanche penetration/flux jumps

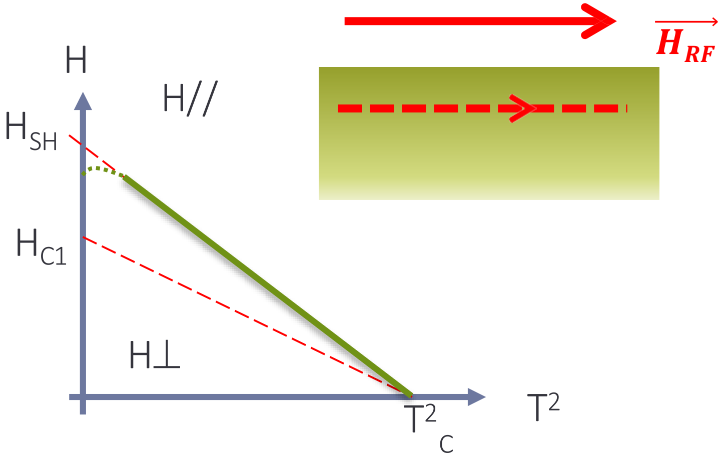


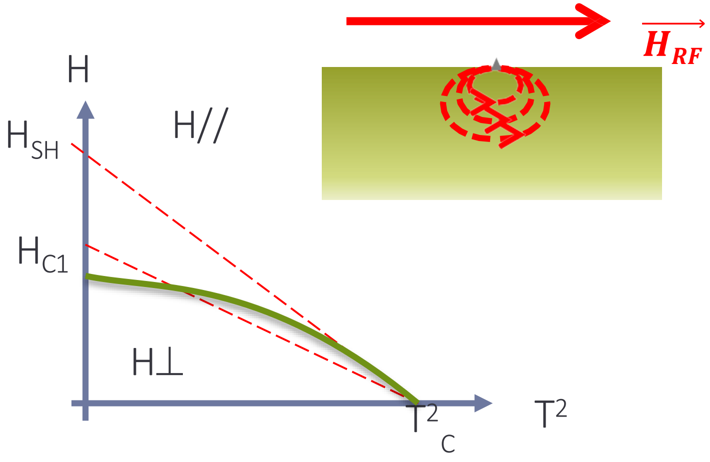
MgB$_2$: http://www.nature.com/srep/2012/121126/srep00886/full/srep00886.html?message-global=remove&WT.ec_id=SREP-20121127

- ~100 µm in 1 ns *(~RF period)*
- Compare with λ *field penetration depth)*
  - Nb : ~ 40 nm
  - MgB$_2$ ~ 200 nm
- Avalanche : high RF dissipation

- In real world, cavities behavior is dominated by a few number of defects

It is very important to measure the penetration field of samples in realistic conditions





EFFECTS OF LOCAL DEFECTS

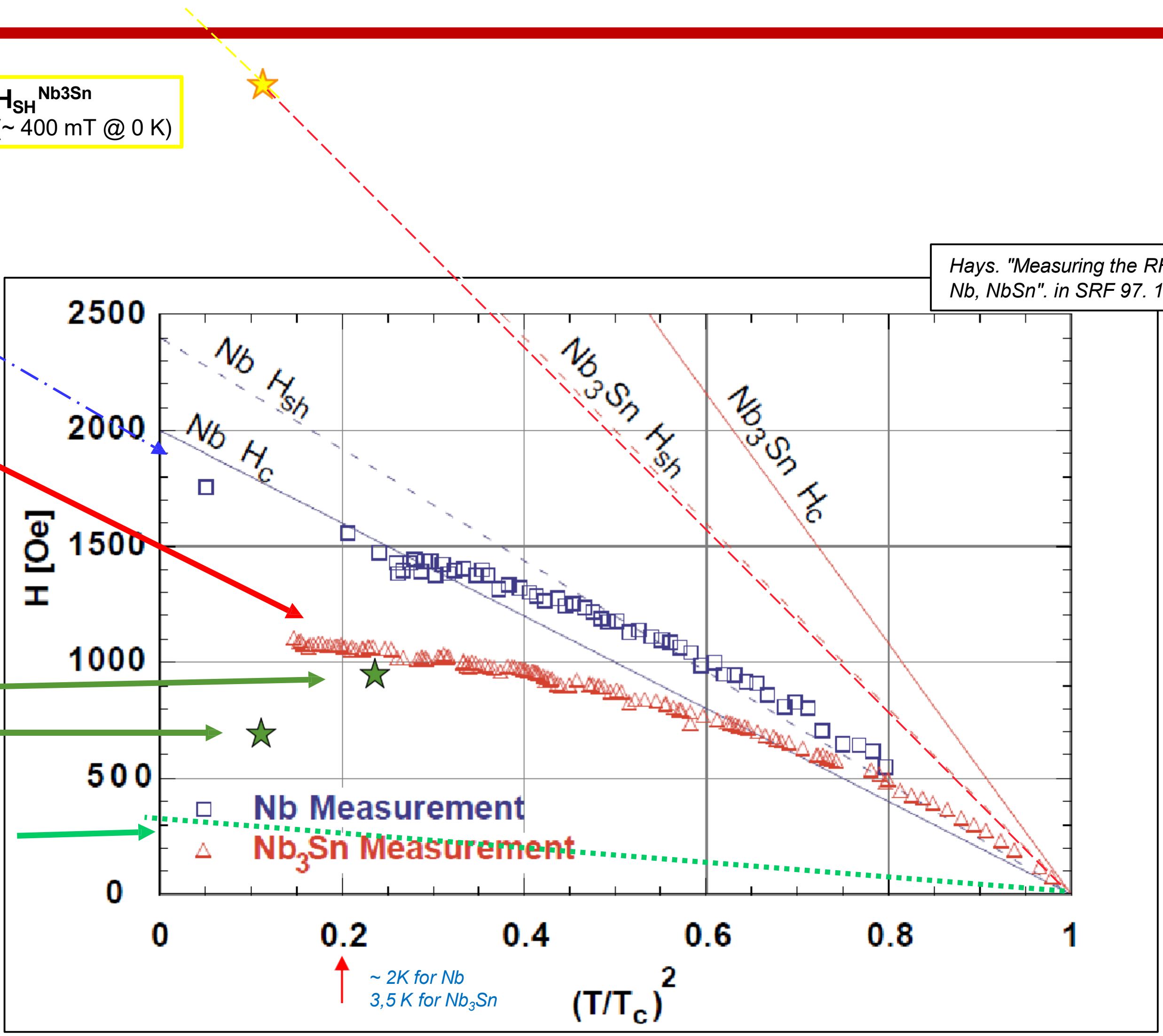
H_{SH}^{Nb3Sn}
(~ 400 mT @ 0 K)

Nb H_{C1}
(170 to 200 mT)

Cornell, 1997
pulsed

Recent results from Cornell & FNAL **CW**
Posen,
2019 (23 MV/m)
2015 (17 MV/m))

H_{C1}^{Nb3Sn} (~27mT)
(50 mT pour le bulk)



Hays. "Measuring the RF critical field of Pb, Nb, NbSn". in SRF 97. 1997.

~ 2K for Nb
3,5 K for Nb_3Sn

Nb_3Sn
vs Nb

$= H_c^0 \left(1-\left(\frac{T}{Tc}\right)^2\right)$

Dissipations :

$$\frac{1}{2}\iint R_s H^2 dS$$

Vortices enter more easily at lower temperature (counter intuitive !)?

@ T~T_C : H is low => low dissipations => easy to thermally stabilize

@ T<<T_C : H is high=> even if small defect => high dissipations => Favors flux jumps

=> We have to reduce defect density

(yes but which ones?)

SRF 2023 GRAND RAPIDS

Jefferson Lab

CHALLENGES TO FACE ON THE ROUTE TOWARDS OTHER SUPERCONDUCTORS: GENERALITIES

GENERAL ISSUES WITH SCs

Needed: high T_C, high H_{SH} (by default high H_{C1})

Metallurgy : started ~ 5000 Ys ago

- ☐ **Advantages of niobium: pure metal.**
  - Highest T_C of metallic SC, H_{C1}
  - Easy to form
  - Uniform composition, *no phase transition in the domain of interest*
  - Very large ξ: makes it less sensitive to small crystalline defects (e.g. GB)
- ☐ **Issues with alloyed, metallic SC compounds (e.g. NbTi)**
  - Higher T_Cs, but smaller H_{C1}, ξ
  - Still relatively easy to form (harder)
  - Usually several phases, not all of them SC
  - Risk of non homogeneity

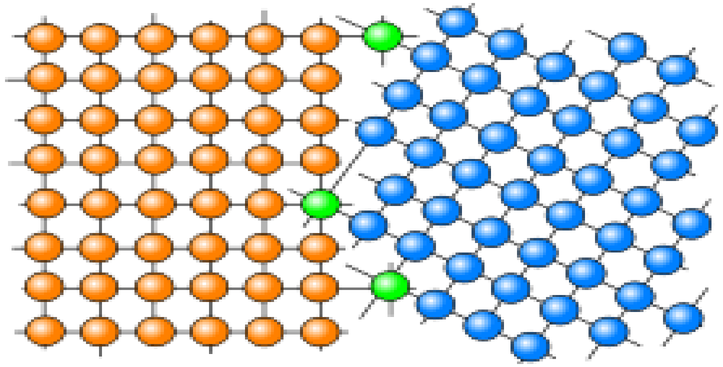
Chemistry : started ~ 200 Ys ago
Thin films techno. < 100Y

- ☐ **Issues with non metallic SC compounds**
  - Higher T_Cs, but smaller H_{C1}, ξ
  - Brittle, no forming is possible, only films *(OK for SRF, but a more complex fabrication route is needed)*
  - Usually several phases, not all of them SC
  - Risk of non homogeneity
- ☐ **Sometimes local disorder =>**
  - **≠ local composition,** *possibly non SC*
  - **Weak links** *e.g. NC grain boundaries*

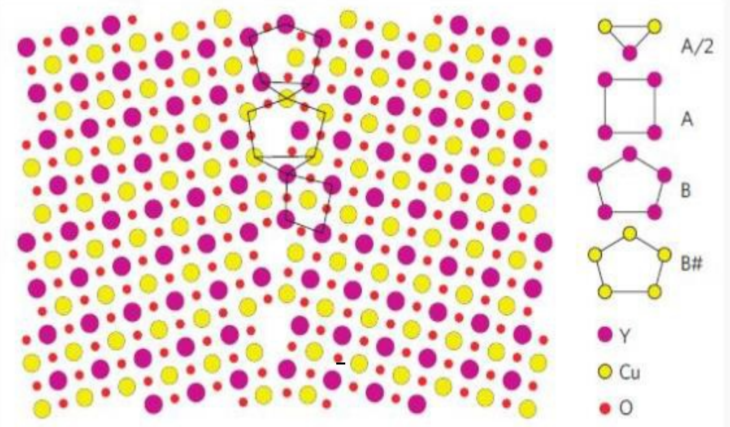
= main reason why HTC do not apply in SRF .

If you are a theoretician you prefer to talk about the "existence of nodes in the gap of d-wave superconductors" : both are related to Brillouin structure

EX. : Grain boundaries



Some nm ⟷ *Compare with ξ*



Top view of a (410) YBCO grain boundary calculated with molecular dynamics.

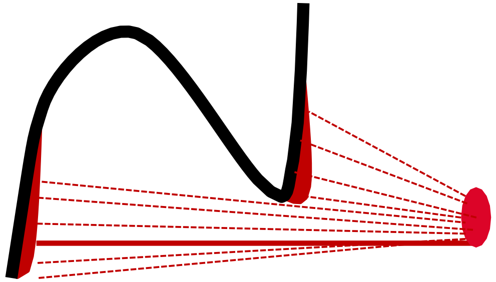
http://www.phys.ufl.edu/~pjh/grain-boundry.html

THIN FILMS DEPOSITION

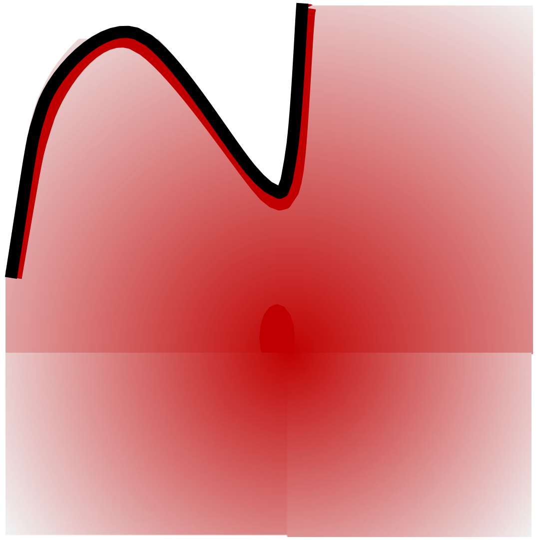
Nb : λ~50 nm => only a few 100s nm of SC necessary (the remaining thickness= mechanical support) **=> Make thin films !**

- **Advantages**
  - Thermal stability *(substrate cavity = copper, Aluminum,… W)*
  - Cost
  - Opens route to innovative materials
  - Optimization of R_{BCS} possible *(e.g. by playing with m.f.p)*
- **Disadvantages**
  - Fabrication and surface preparation of substrate *(at least)* as difficult as for bulk Nb
  - Steep Q_0 decrease often observed by increase of RF field *(sputtered niobium films, improved lately)*
  - Deposition of innovative materials is very difficult *(large parameters space to be explored)*
  - Most of the known SC have been optimized for wire applications *(low H_{C1}, defects, pinning centers…)* **=> most of the literature recipes are not fitted for SRF application** ☹ ☹ ☹

DEPOSITION TECHNIQUES: 3 MAJORS FAMILIES



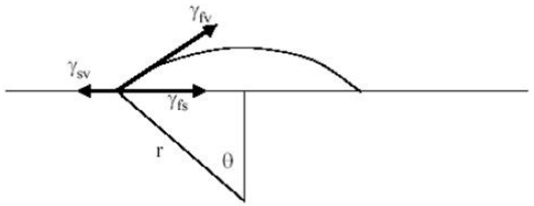
- **Physical deposition techniques (PVD, MS, DS…)**
  - line of sight techniques
  - issues: getting uniform thickness/structure internal stress and adhesion
  - limited for complex geometry
- **Thermal diffusion films**
  - limited compositions available
  - non uniform composition issues *(S shaped diffusion front, differential diffusion rate with substrate grain orientation)*



- **Chemical techniques CVD, ALD**
  - conformational even in complex shape
  - very quick for large surfaces
  - issues: get the proper crystalline structure
  - Required use of precursors introduces more impurities

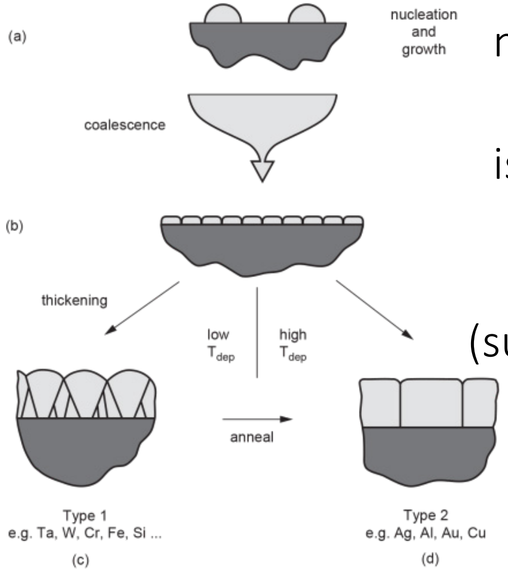
Thin Films Growth

Heterogeneous nucleation



$$\Delta G = \underbrace{a_3 r^3 \Delta G_v}_{\text{Volume of cap}} + \underbrace{a_1 r^2 \gamma_{vf}}_{\text{Cap surface area}} + \underbrace{a_2 r^2 \gamma_{fs}}_{\text{Projected Surface area}} - a_2 r^2 \gamma_{sv}$$

$$a_1 = 2\pi[1-\cos(\theta)]$$
$$a_2 = \pi \sin^2 \theta$$
$$a_3 = \pi[2 - 3\cos(\theta) - \cos^3(\theta)]$$



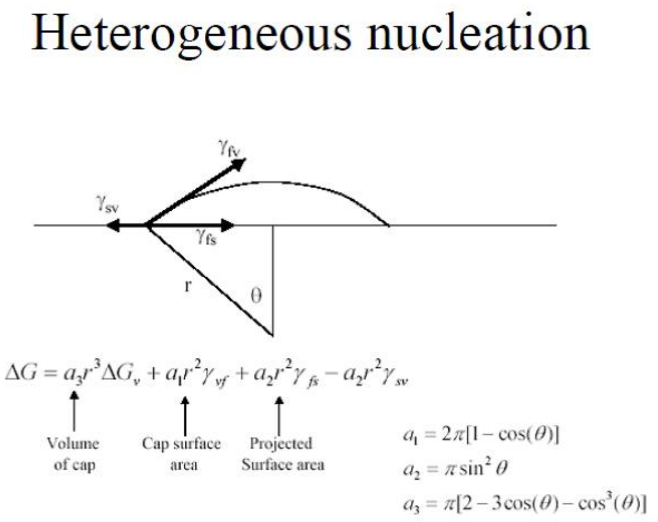
nucleation & island growth

island coalescence

continuous film
(subsequent growth).

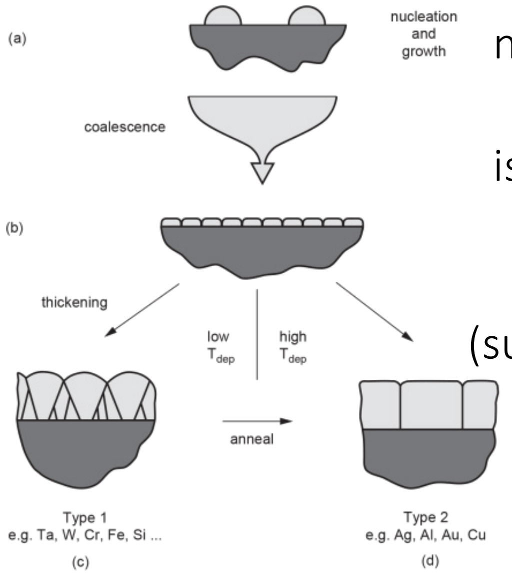
[C. Thompson]

Thin Films Growth



$$\Delta G = a_3 r^3 \Delta G_v + a_1 r^2 \gamma_{vf} + a_2 r^2 \gamma_{fs} - a_2 r^2 \gamma_{sv}$$

$$a_1 = 2\pi[1-\cos(\theta)]$$
$$a_2 = \pi \sin^2\theta$$
$$a_3 = \pi[2-3\cos(\theta)-\cos^3(\theta)]$$



nucleation & island growth

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[C. Thompson]

Control over the deposition process is exercised by only

3 first-order vapor parameters & 1 first-order substrate parameter

Vapor parameters	**Absolute arrival rates of film atoms**
	Partial pressures of background gases in the chamber
	Energies of the deposition fluxes.
Substrate parameter	Substrate **temperature T**.

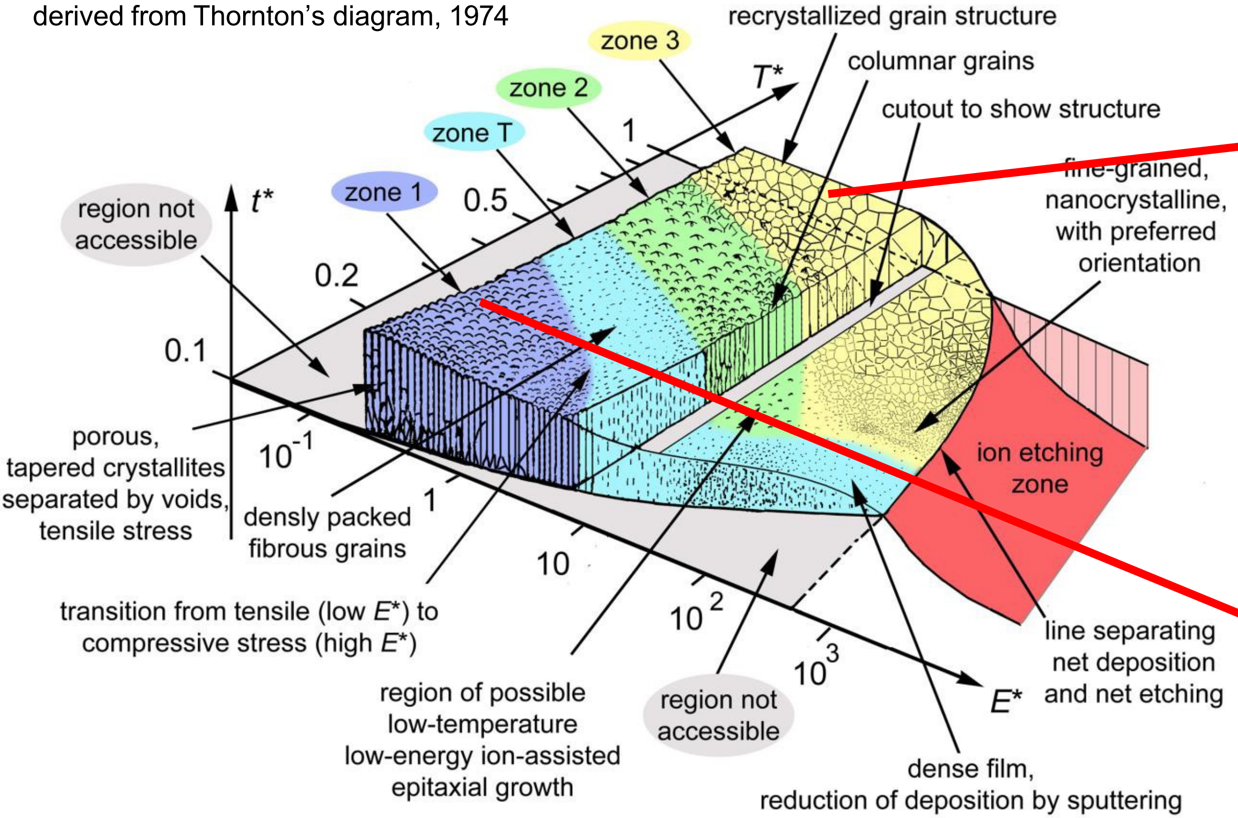
Without energetic atoms, only the substrate temperature influences the processes of physi- and chemisorption, thermal desorption, nucleation, nuclei dissociation, surface diffusion, and formation of specific nucleation sites.

SEARCH FOR BETTER STRUCTURE - Energetic Condensation

Condensing (film-forming) species : hyper-thermal & low energies (>10 eV).

Generalized structure zone model (from A. Anders)

derived from Thornton's diagram, 1974



© Andre Anders, 2010

A. Anders, Thin Solid Films **518**, 4087 (2010).

Energetic deposition (HPIMS, CED, VAD…)
=> Bulk like films

Magnetron sputtering
=> A lot of defects
Cu limits annealing temperature recrystallization

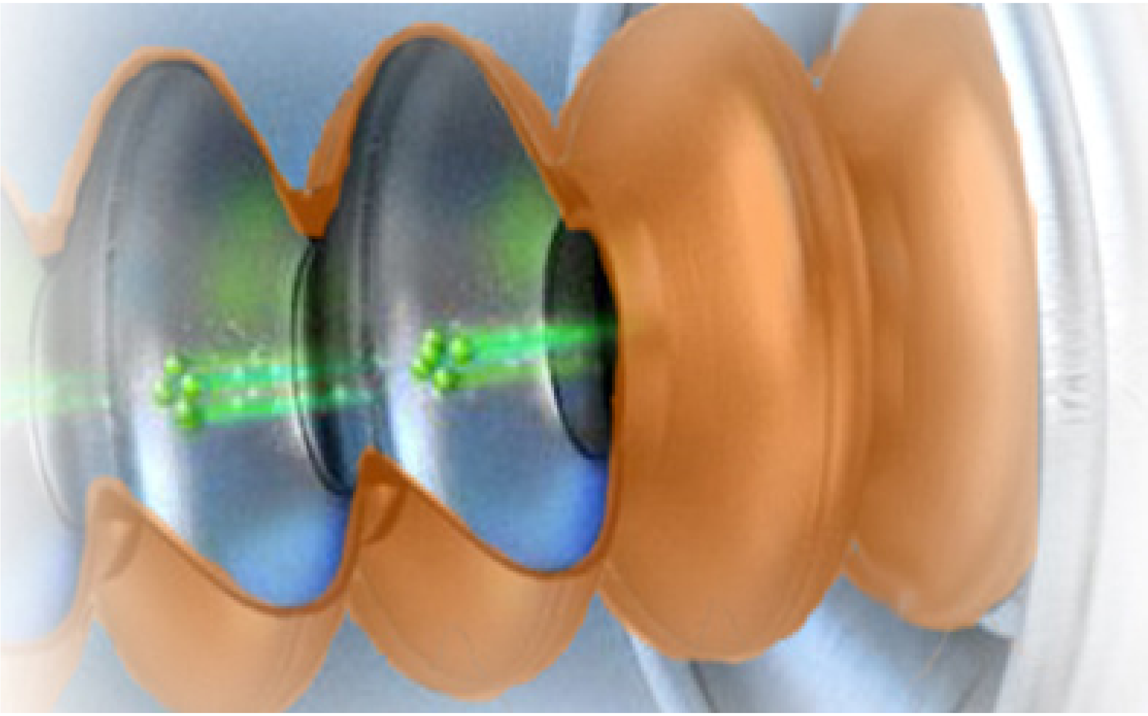
Additional energy provided by fast particles arriving at a surface ⇒number of surface & sub-surface processes ⇒changes in the film growth process:

- 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

Nb/Cu

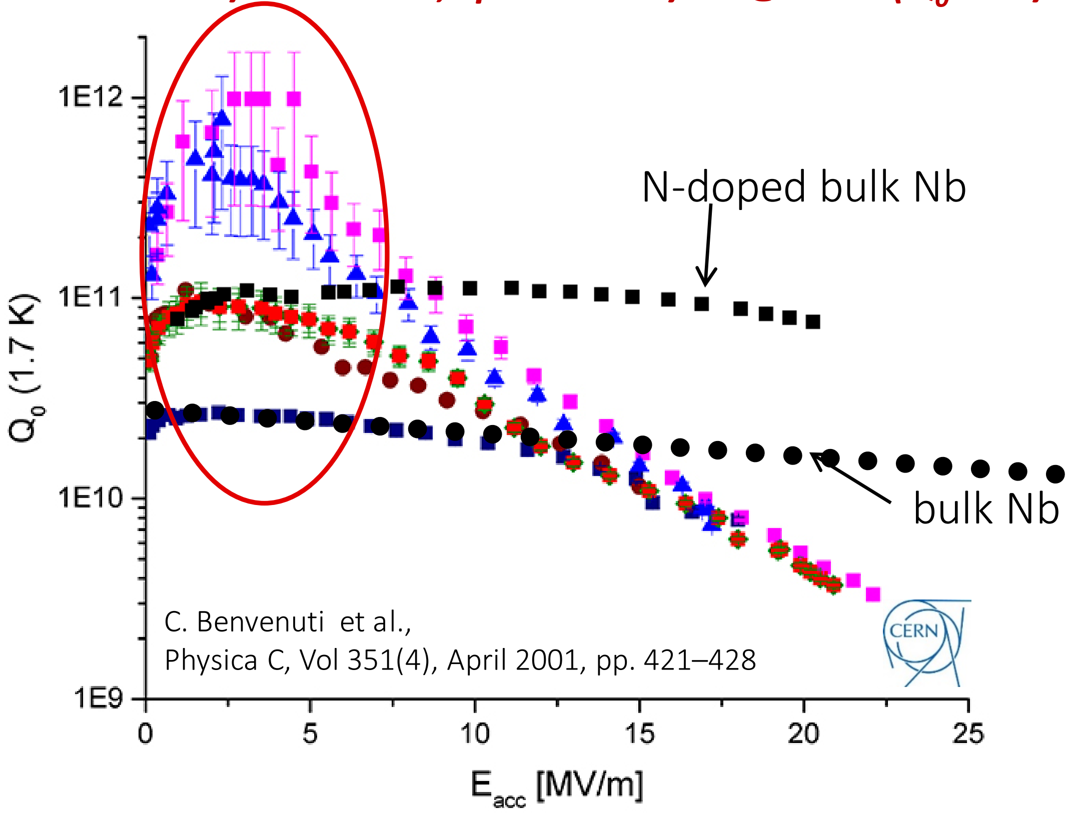


SPUTTERED Nb FILMS

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

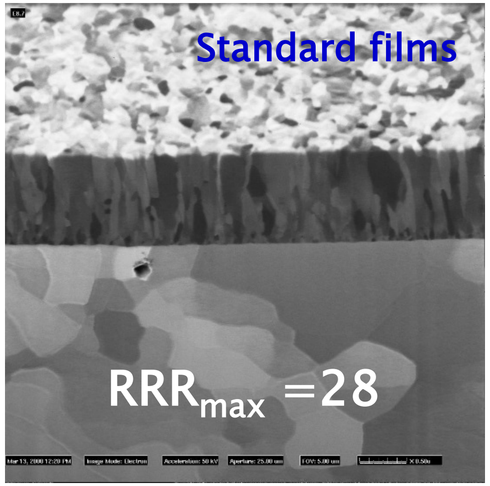
•CERN LEP 2	272 x 353MHz Nb/Cu 4-cell cavities
•LHC	16 x 400 MHz Nb/Cu 1-cell cavities
•INFN Legnaro	52 x 160 MHZ Nb/Cu QWR
•CERN HiE- ISOLDE	52 x 160 MHZ Nb/Cu QWR

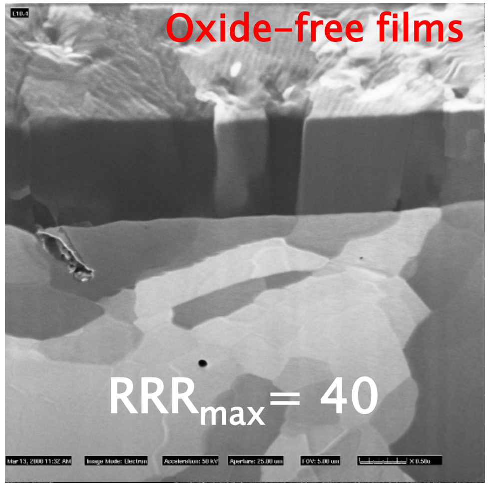
1.5 GHz Nb/Cu cavities, sputtered w/ Kr @ 1.7 K (Q_0=295/R_s)

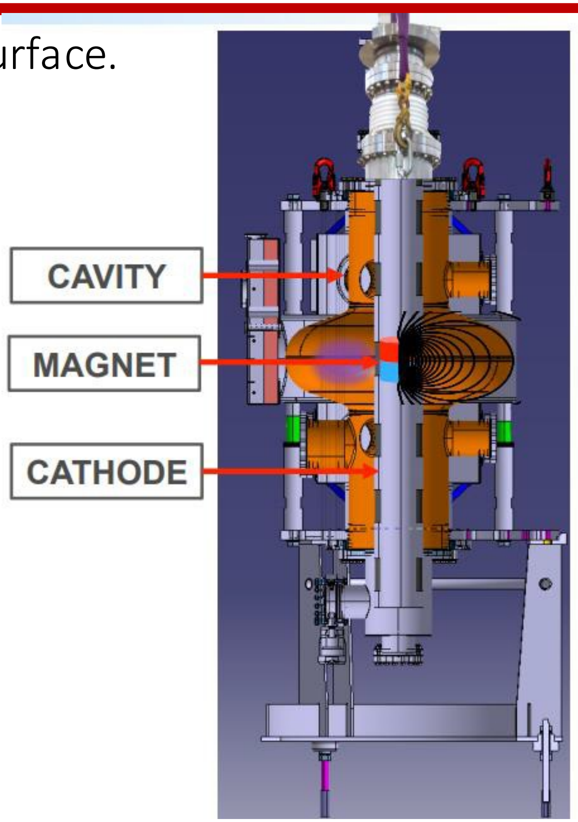


C. Benvenuti et al.,
Physica C, Vol 351(4), April 2001, pp. 421–428

High Q at low field BUT strong Q-slope







Possible origin of the slope

Depinning of trapped flux

Low H_{C1}

Early vortex penetration due to roughness

Current concentration due to porosities

(generating local electrical field)

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)

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(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.

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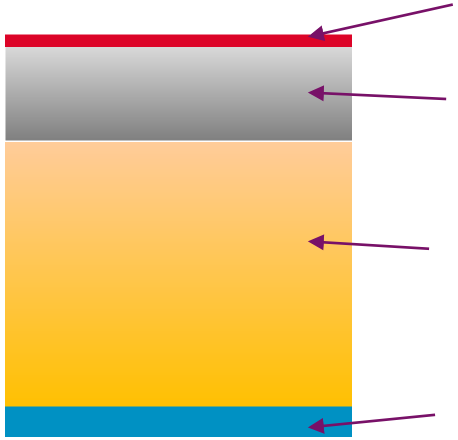
What are the differences between bulk and thin-film Nb in reference to the RF surface?

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)

SRF Thin Films for Next-Generation Cavities

**ALL film properties are a direct consequence of the film structure, defect/impurity content…
thus the technique, environment, substrate are key factors**



Protective Layer
e.g. oxide layer = diffusion barrier, or low secondary emission layer (↓ MP)

“RF” layer
Optimized for superconductivity:
Low surface resistance (medium m,f,p,)
and/or High H_P (high H_{C1} high H_{SH})

“thermal conducting” layer
Optimized for thermal transfer (high RRR, high m,f,p., not necessarily Nb)

“External” layer
Optimized for thermal transfer (low Kapitza resistance, e,g, anodization)

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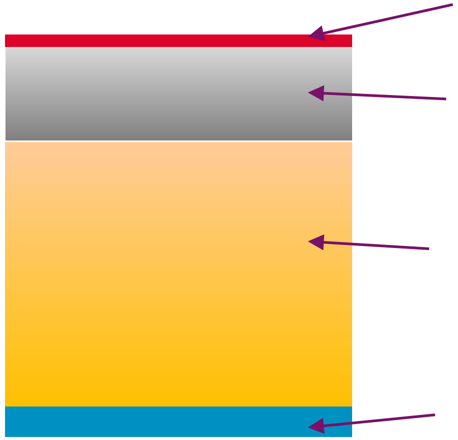

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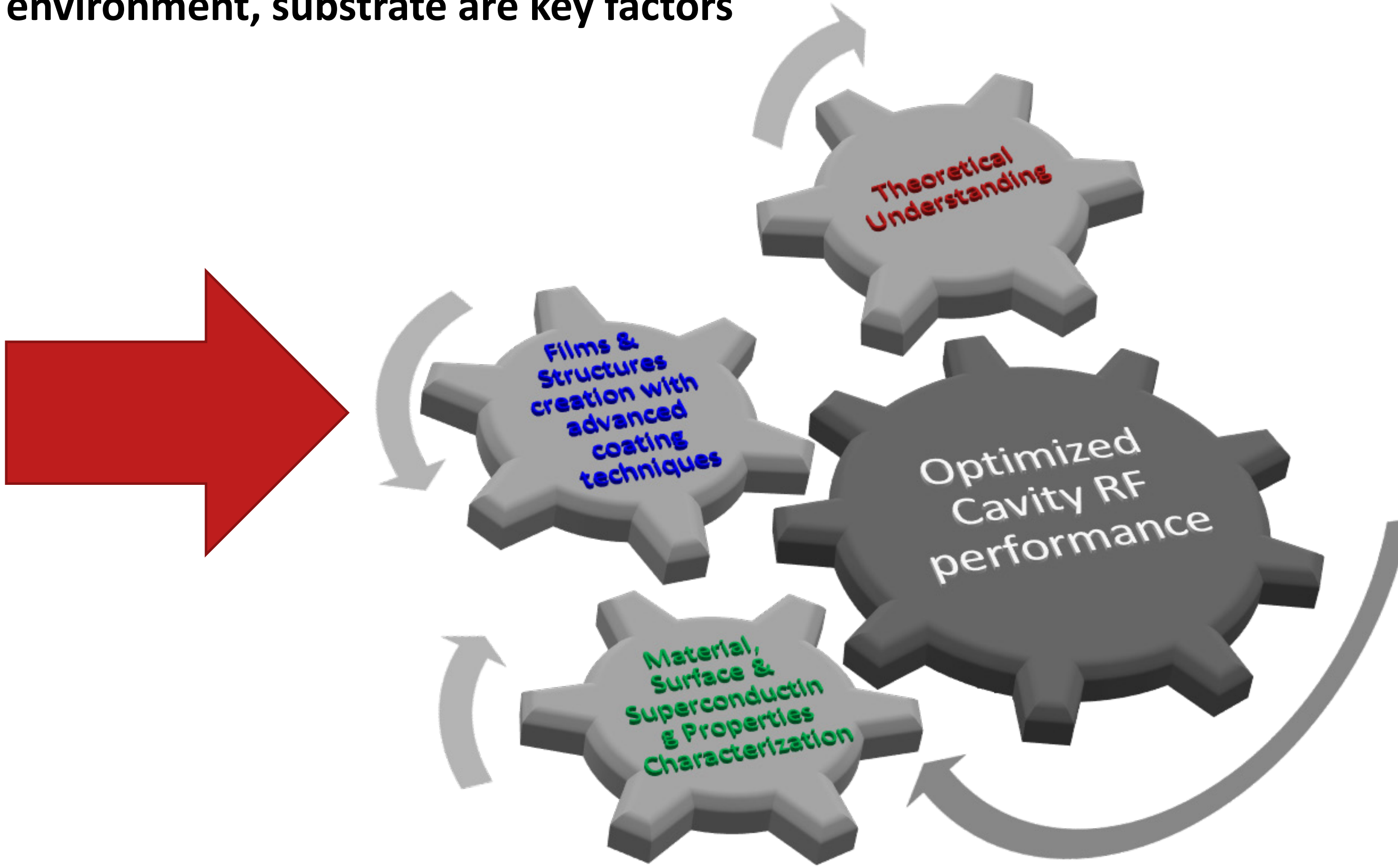
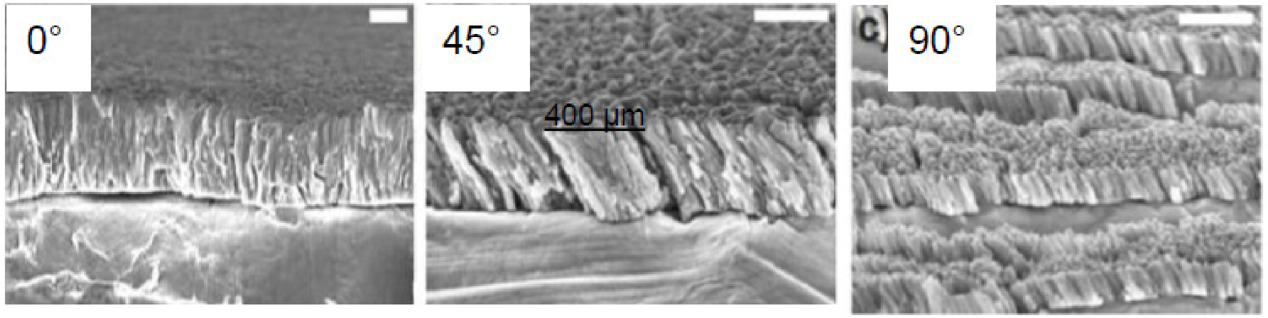


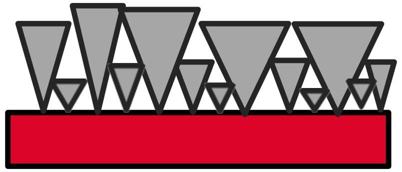
EXAMPLE OF QUALITY ISSUES OF FILMS

Magn. Sput. Nb

- ❑ Line of sight issues
  => porosities

[G. Rosaz]

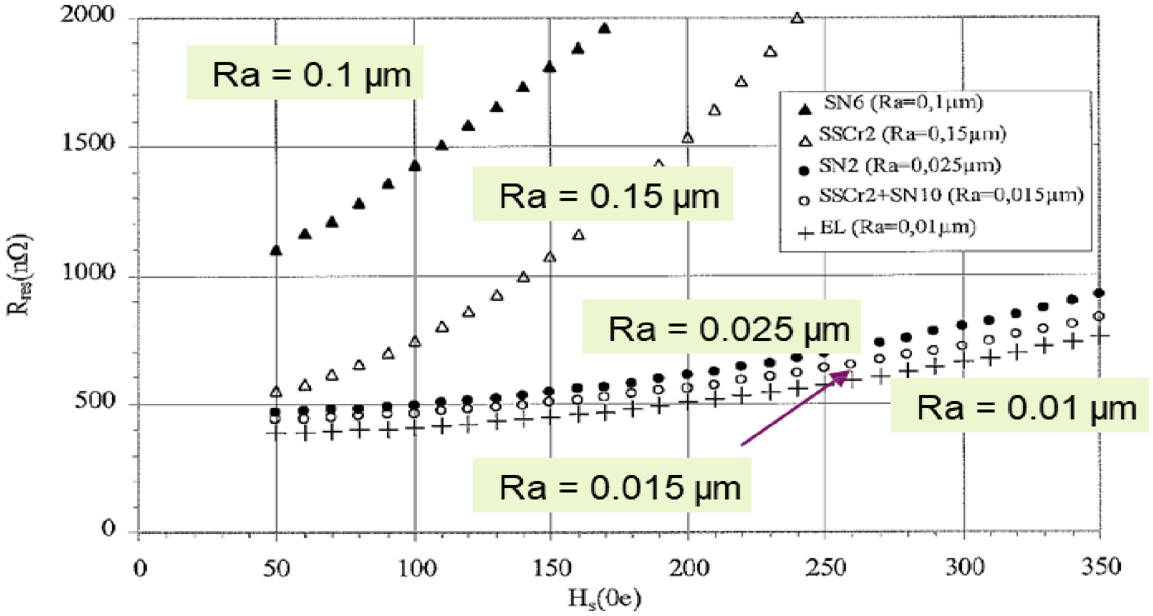




Inverted pyramid crystalline growth

- ❑ Internal stress
  - ○ Advantage: higher Tc *(up to a certain impurity concentration)*
  - ○ Disadvantage: adhesion issues
    (peel-off, delamination)
- ❑ High impurities content
  - ○ Nb = getter material *(nearly as good as Ti*
    => high interstitial content)
  - ○ Carrier gas incorporation *(Ar)*

- ❑ Sensitivity to Cu roughness *(the smoother, the better)*



Ra = 0.1 µm

Ra = 0.15 µm

Ra = 0.025 µm

Ra = 0.01 µm

Ra = 0.015 µm

[M. Ribeaudeau, PhD]

SUBSTRATE ISSUES

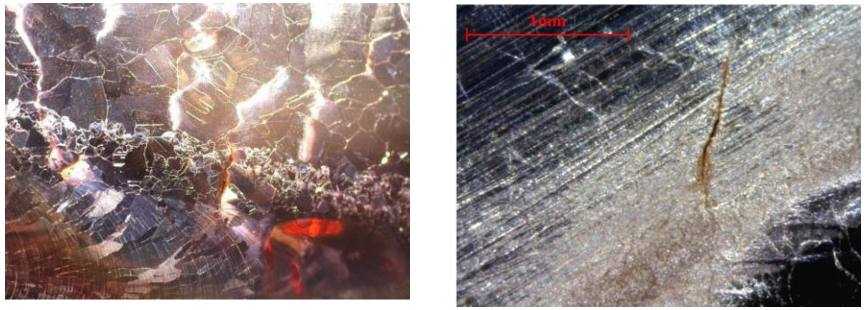
Cu and Nb not miscible (especially in presence of O)

Advantage: low interdiffusion

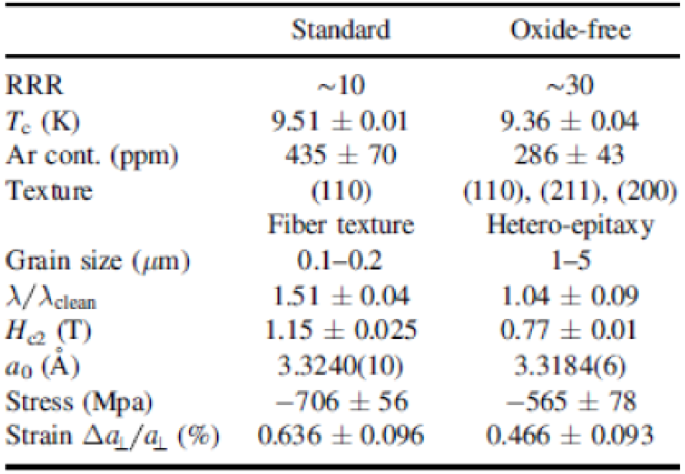
Disadvantage: adhesion issues (delamination)

Issues on Cu welding arreas

where



Best results are not always expected:

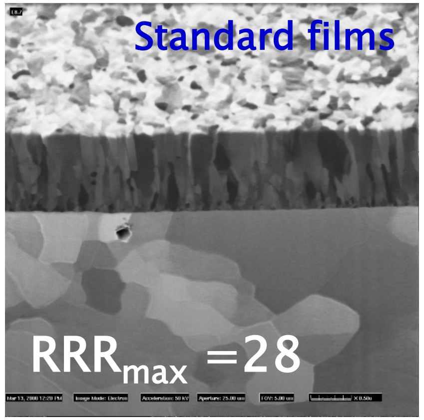


	Standard	Oxide-free
RRR	~10	~30
T_c (K)	9.51 ± 0.01	9.36 ± 0.04
Ar cont. (ppm)	435 ± 70	286 ± 43
Texture	(110) Fiber texture	(110), (211), (200) Hetero-epitaxy
Grain size (μm)	0.1–0.2	1–5
λ/λ_{clean}	1.51 ± 0.04	1.04 ± 0.09
H_{c2} (T)	1.15 ± 0.025	0.77 ± 0.01
a_0 (Å)	3.3240(10)	3.3184(6)
Stress (Mpa)	−706 ± 56	−565 ± 78
Strain $\Delta a_\perp/a_\perp$ (%)	0.636 ± 0.096	0.466 ± 0.093

Columnar grains, size ~ 100 nm

In plane diffraction pattern: powder diagram

(110) fiber texture ⊥ substrate plane



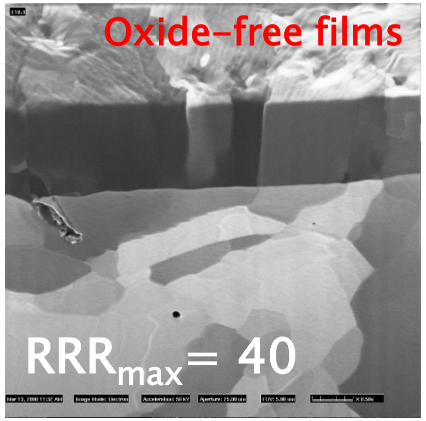
Courtesy: P. Jacob – EMPA

Equi-axed grains, size ~ 1–5μm

In plane diffraction pattern: zone axis [110]

Heteroepitaxy

Nb (110) //Cu(010) , Nb (110) //Cu(111),Nb (100) //Cu(110)



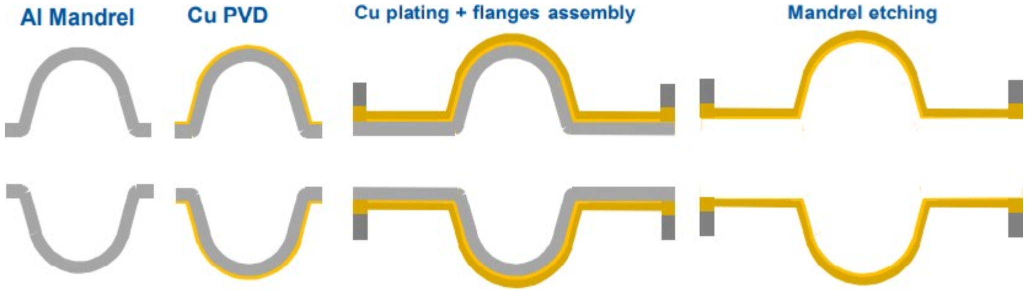
- ❑ Bulk like films did not perform better initially ! (but recent changes !!!)

❑ New approaches:

Bulk machining

Electroplating

Laser surfacing …

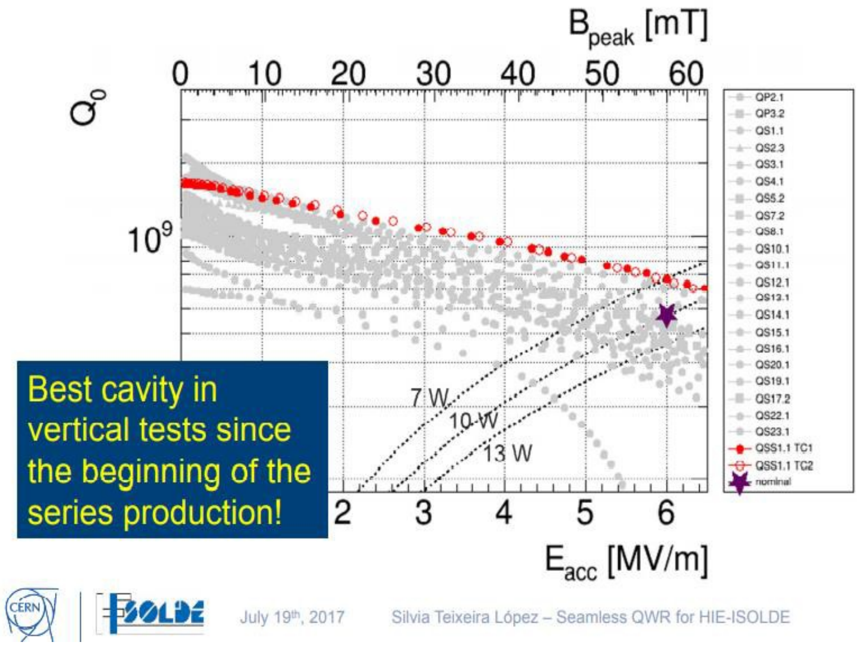


Courtesy: G. Rosaz, K. Scibor - CERN

Machined cell

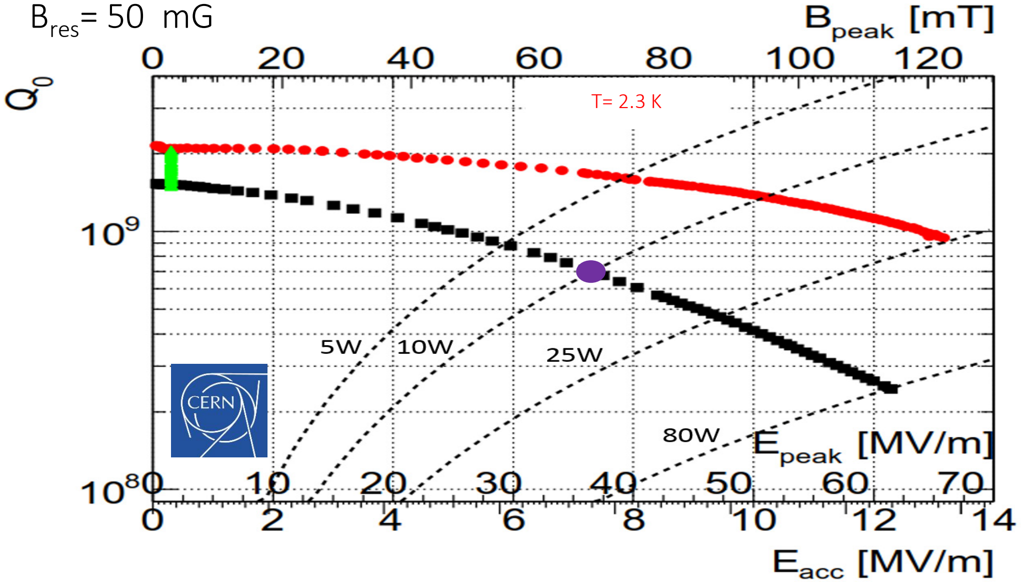
E-beam welded to cut-offs

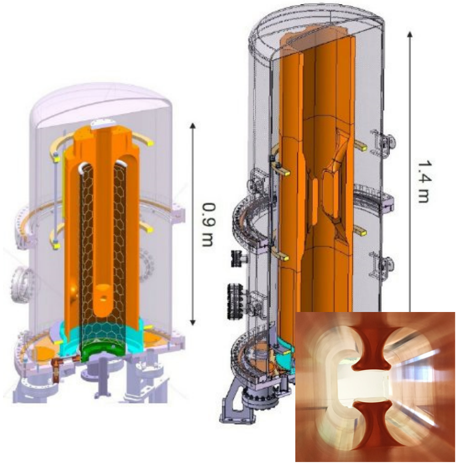
SEAMLESS HIE-ISOLDE CAVITY



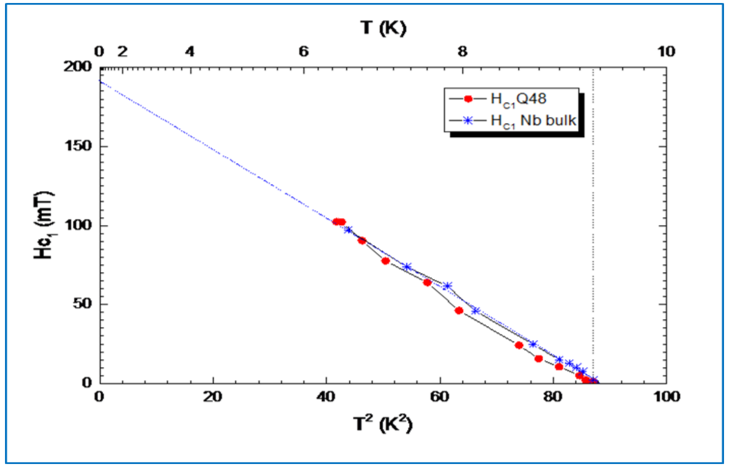
Best cavity in vertical tests since the beginning of the series production!

July 19th, 2017 Silvia Teixeira López – Seamless QWR for HIE-ISOLDE

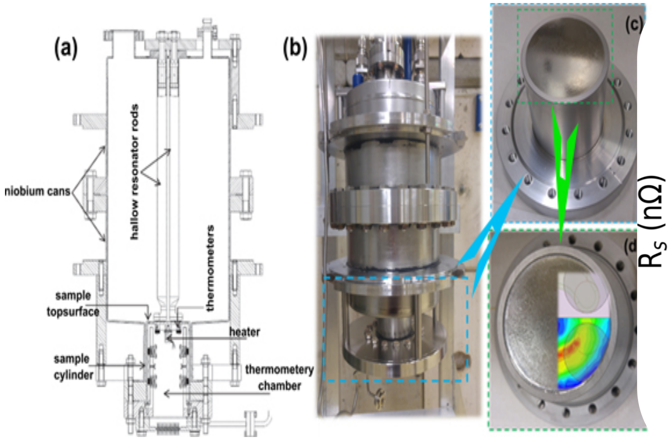


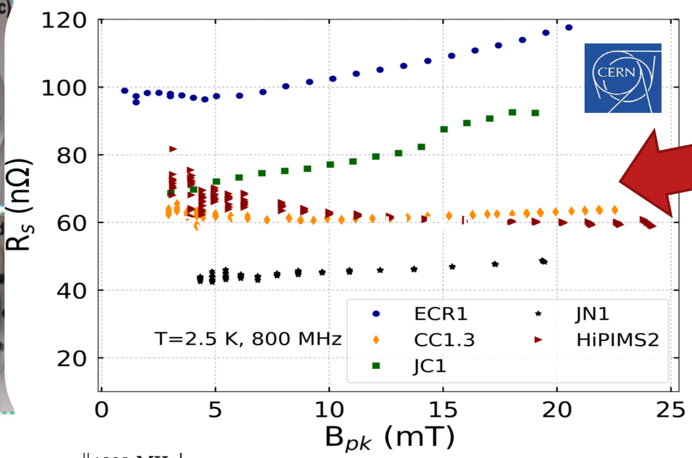


- ❑ Local magnetometry on a sample deposited in the same condition
- ❑ First evidence of a bulk-like behavior for a thin film !!!!

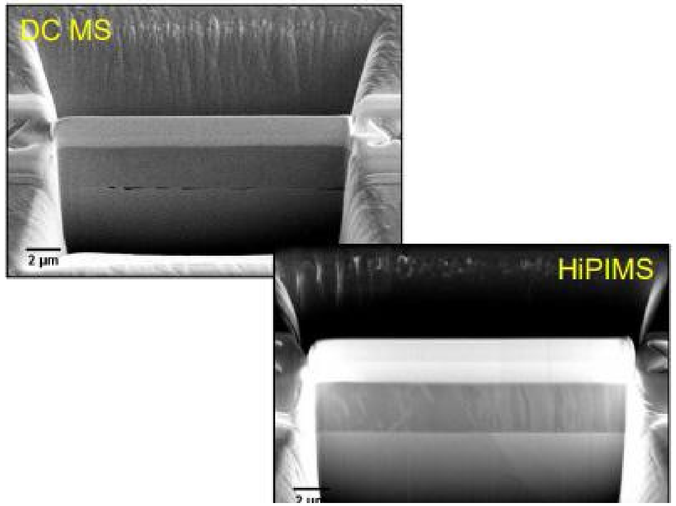


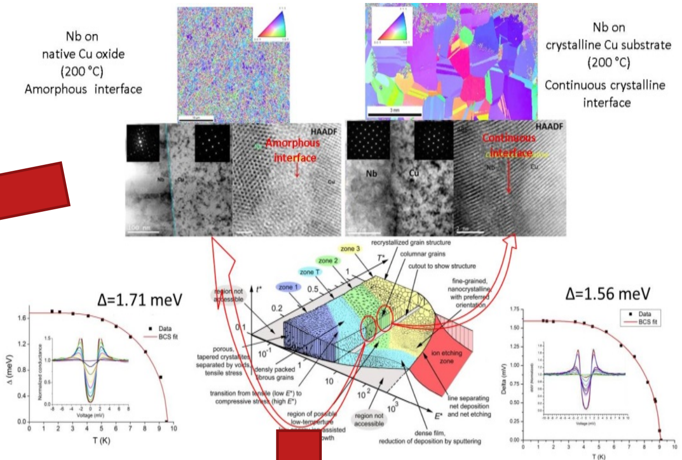
FILM DENSIFICATION /MITIGATION OF THE Q-SLOPE

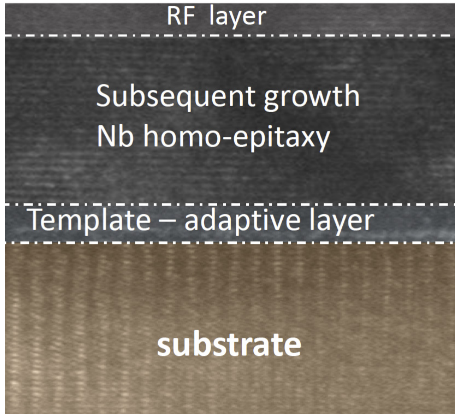


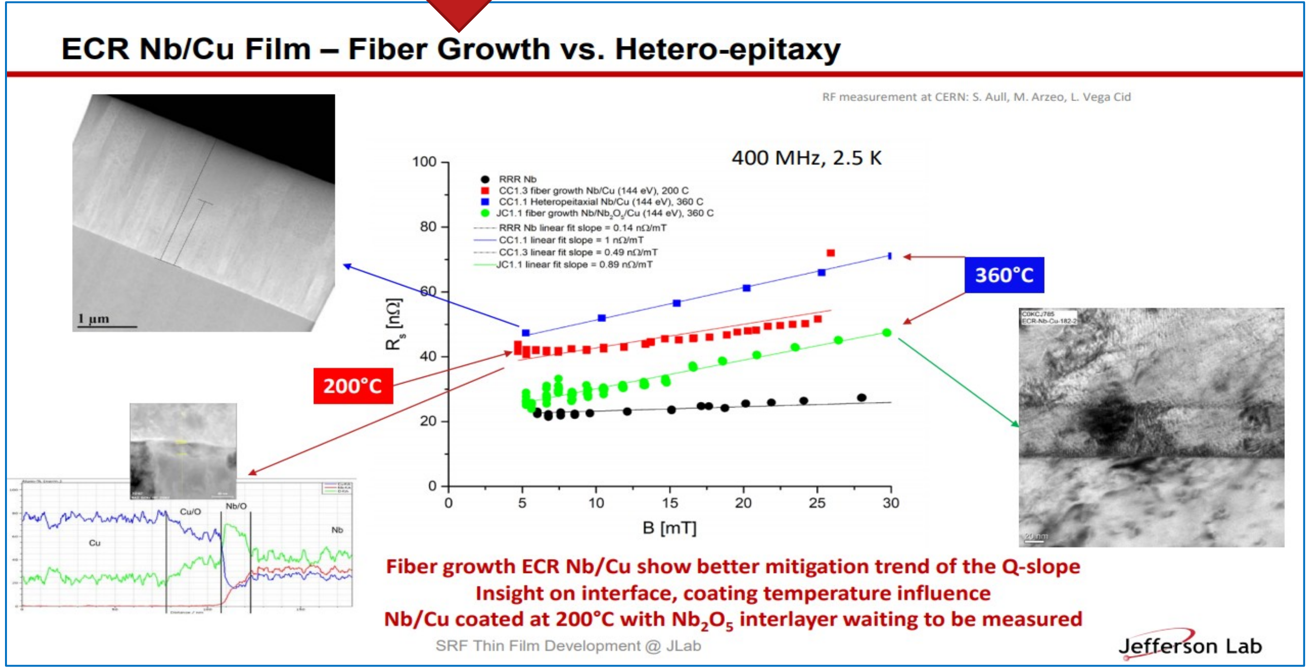


Sample	400 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	800 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)	1200 MHz R_{s0} (nΩ)	R_{s1} (nΩ/mT)
ECR	19.7	0.84	65.8	1.14	126.2	1.35
HiPIMS	19.8	0.11	n/a*	n/a*	100.9	0.3
bulk Nb	21.2	0.13	42.1	0.32	120.1	0.69









ECR Nb/Cu Film – Fiber Growth vs. Hetero-epitaxy

RF measurement at CERN: S. Aull, M. Arzeo, L. Vega Cid

Fiber growth ECR Nb/Cu show better mitigation trend of the Q-slope

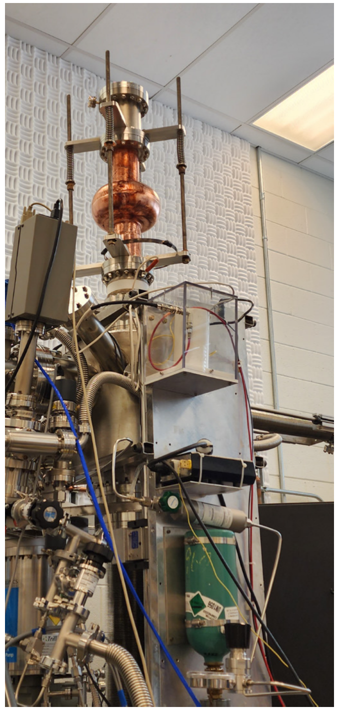
Insight on interface, coating temperature influence

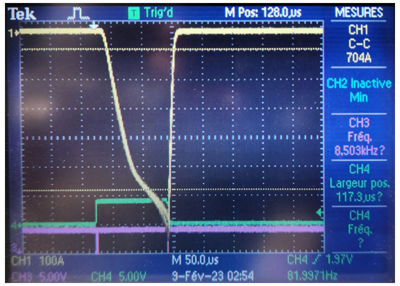
Nb/Cu coated at 200°C with Nb_2O_5 interlayer waiting to be measured

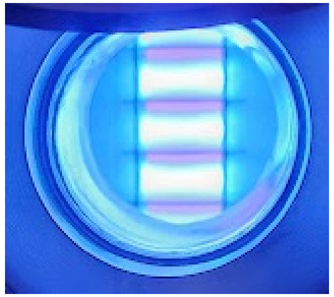
SRF Thin Film Development @ JLab

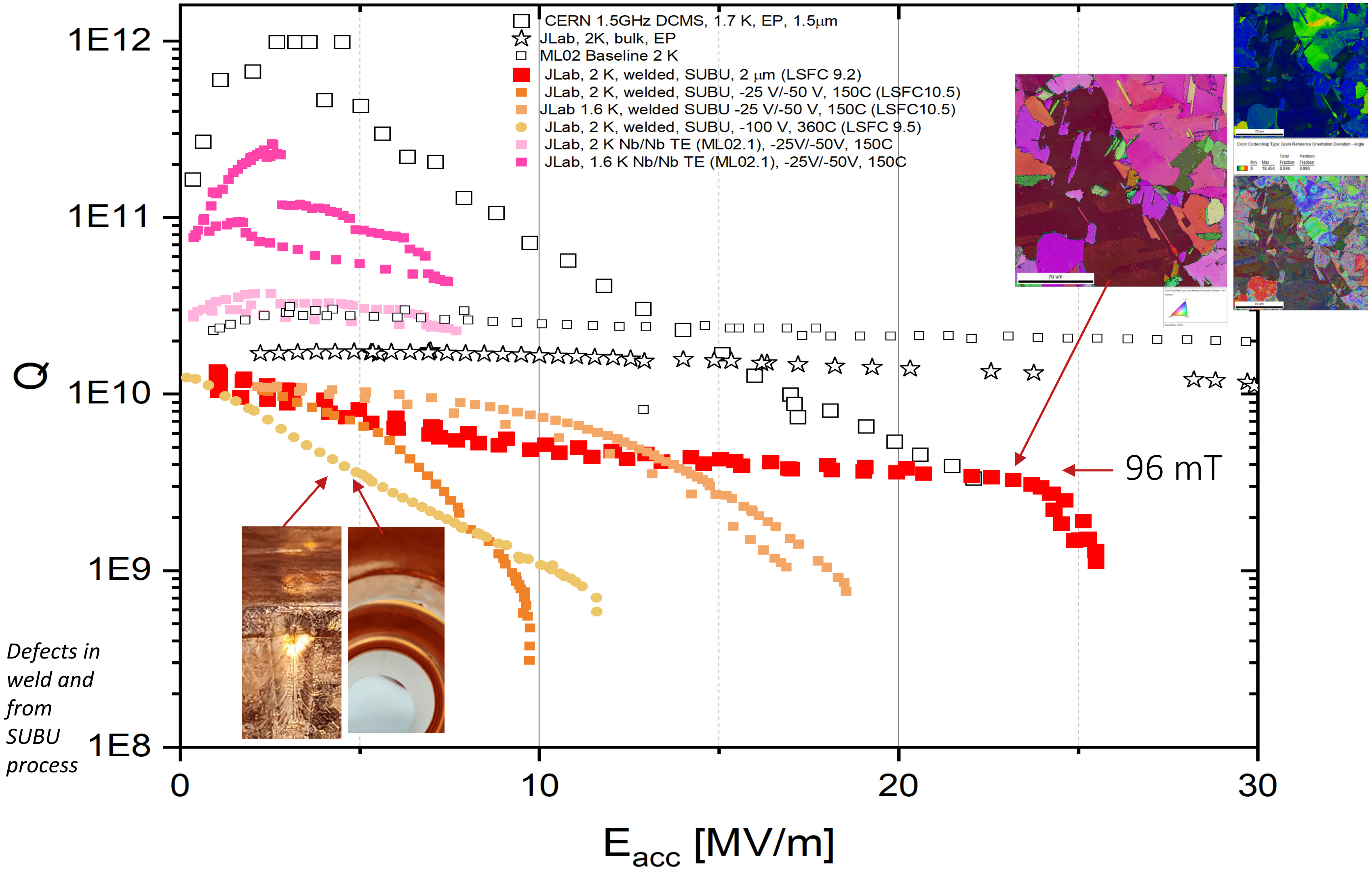
Development of Nb/Cu Cavities by Energetic Condensation

Development of Nb/Cu SRF Surfaces Development (HiPIMS & ECR)





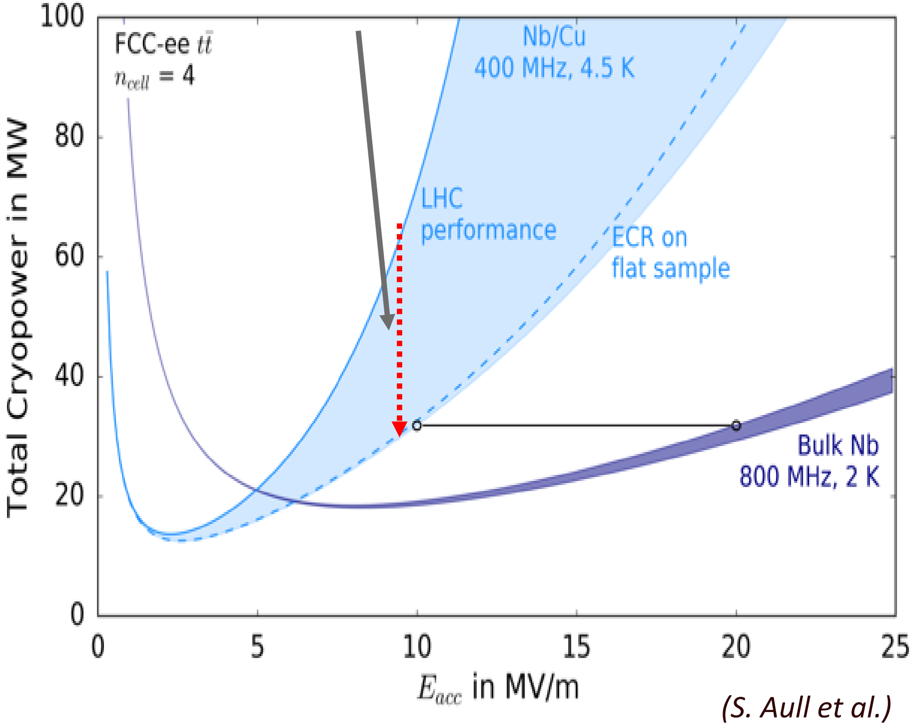




Defects in weld and from SUBU process

Tailored Nb films via energetic condensation

- **Tune thin film structure and quality** with ion energy and substrate temperature on a variety of substrates (amorphous, polycrystalline and single crystal)
- **Achieve film structures and properties only achievable at higher temperature** with classic coating methods
- **Tune RRR values** from single digits to **bulk Nb values** →No intrinsic limitations
- **Lower impurity (H) content** than bulk Nb
- **Good adhesion to the substrate** (delamination threshold : function of ion energy and temperature)
- **Tailoring interface** with high energy and subsequent growth at energy minimizing defect creation can **contribute to lower R_s and mitigate Q-slope.**



(S. Aull et al.)

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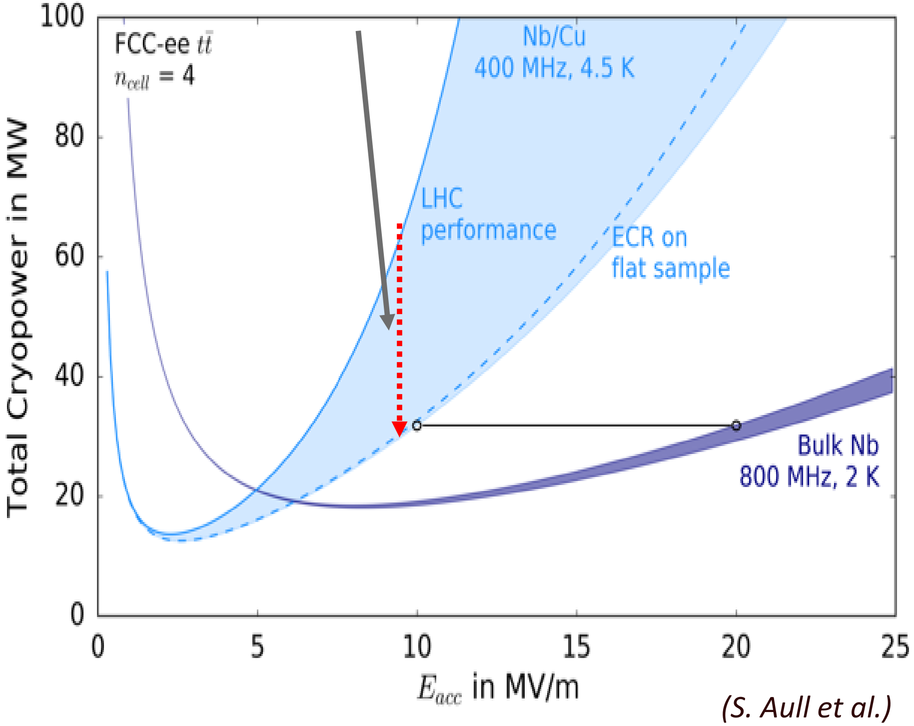

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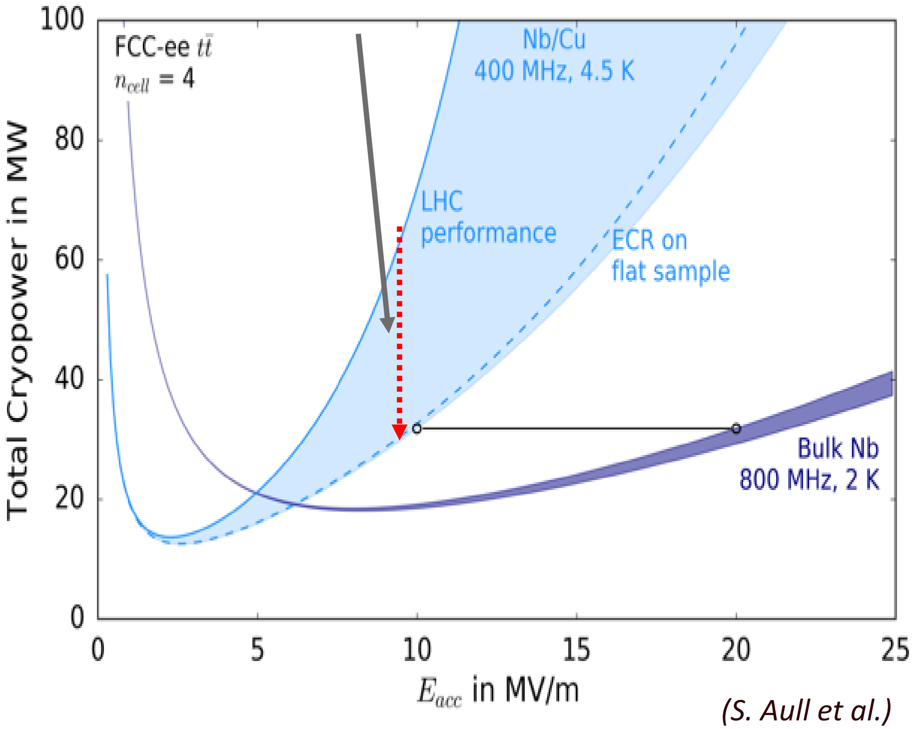


(S. Aull et al.)

- **Basic material processes exist**
  - proof-of-principle demonstrations for modest field applications
- **Principal challenges at present**
  - **Establish adequate process controls**
  - **Address technical challenges with scale-up**

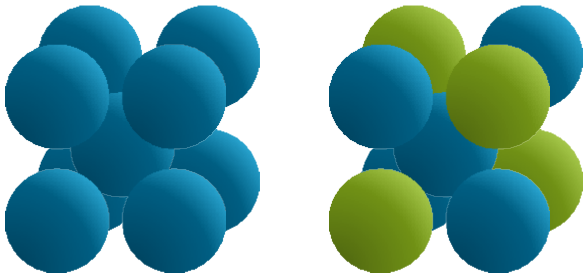
  (Though not fundamental, these require serious resource investment to establish "industrial" capability).
  - Resources drive the timeline.
- **Develop cavity coating & refine process parameters in parallel on smaller scales.**
- Done right, reasonable stepping stone to truly "engineered surface", with all the benefits of high Q, high field, low cost, high reliability systems.

OTHER SUPERCONDUCTORS

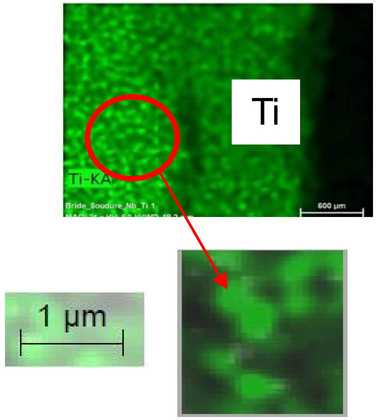
MOST COMMON SUPERCONDUCTORS

- **A2** (e.g. NbTi, Transition metal alloys, BCC structures)
- **B1** (e.g. NbN, NbTiN, Transition metal carbide or nitride, NaCl structures)
- **A15** (e.g. Nb_3Sn, Compounds, NaCl structures)
- **2-D SC** (Compounds, anisotropic)
  - MgB_2
  - Cuprates, Pnictides
  - (others TaS_2, organic…)
- **SPECIAL SRF: METAMATERIALS** (Multilayers)

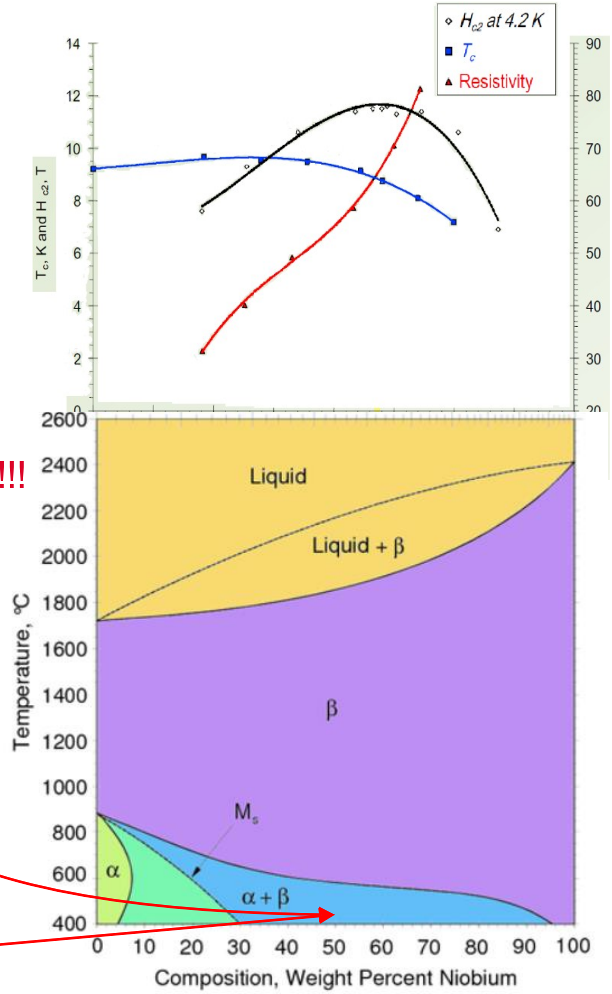
A2 SC ALLOYS: e.g. NbTi



BCC pure metal and solid solution alloy



Ti precipitates (∅ ~0,4 µm)
NC Metal => RF dissipation !!!!



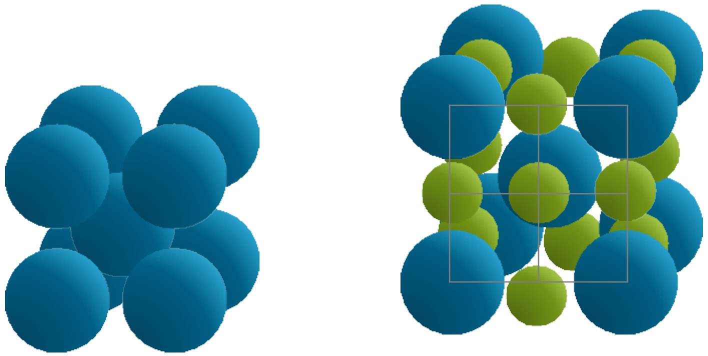
- NbTi widely used in coils
- Available alloys range around 45-55 % Ti
- Ti is not fully miscible inside Nb (Ti precipitates J at low T when [Ti] > 5 W%)

=> no RF !!!

Ti ∅ = Nb ∅
Ti precipitates in a niobium matrix (with a few Nb replaced by substitutional Ti) => ~ same T_C, same H_C as Nb, but not same ℓ => high K

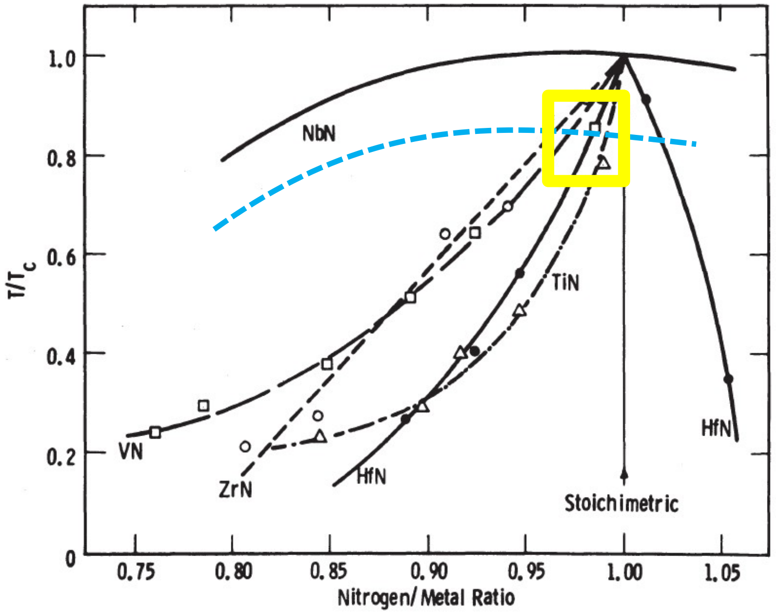
http://www.dierk-raabe.com/titanium-alloys/biomedical-titanium-alloys/

B1 SC COMPOUNDS: e.g. NbN, NbTiN



BCC pure metal + smaller atoms (N, C) in interstitial location => NaCl structure

https://link.springer.com/content/pdf/10.1007%2F978-1-4757-0037-4.pdf



. 20 Critical temperature versus nitrogen-to-metal ratio for various B1-structure nitrides of the transition metals (data assembled by Hulm and Blaugher).

NbN cubic phase : T_C ~17-18 K

NbTiN stabilization of cubic (SC) phase NbN

not too sensitive to local variation of composition !

Solid solution => relatively easy fabrication *(thermal diffusion, reactive sputtering…)*

Good model SC

Widely used for JJ and SC electronics

Also a material of choice for the development of multilayers (see below)

NbTiN RF Results

INFN : reactive sputtering with Ar/N_2 in DC Triode Magnetron Sputtering @ 600˚C and 200˚C

($Nb_{1-x}Ti_x$)N films with 1-x<0.5 present a lower calculated surface impedance, lower critical fields and better surface properties than NbN, especially when deposited at low temperatures.

R. Di Leo et al. J. of Low Temp. Phys, vol 78, n1/2, pp41-50, 1990

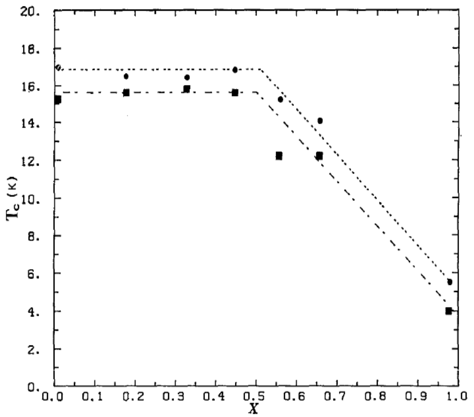


Fig. 1. Superconducting critical temperature T_c as a function of the titanium composition (x) for the ($Nb_{1-x}Ti_x$)N films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares).

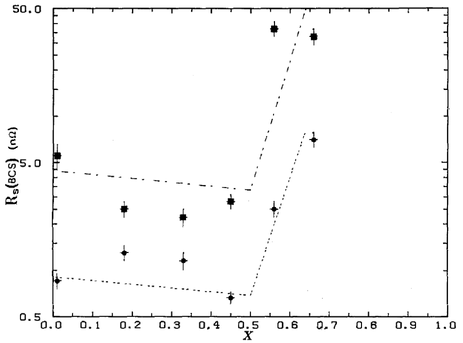


Fig. 3. Calculated BCS surface impedance R_s(BCS) as a function of the titanium composition (x) for the ($Nb_{1-x}Ti_x$)N films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares). The continuous lines correspond to the values of the lines through the data in Figs. 1 and 2.

Reactive Magnetron Sputtering:

CEA Saclay :

NbTiN films deposited on 12 cm copper disks by magnetron sputtering and tested in a cylindrical TE_{011} cavity

reached RF field levels of 35 mT

low residual surface resistance (< 100 nΩ at 4 GHz) with a very small BCS resistance

4 cavities deposited but no RF measurement due to film blistering on large area of the cavity.

Rs slope significantly decreased when coating with bias ranging from -50V to -100V

P. Bosland et al.

S. Cantacuzène et al.

CERN:

Samples and six 1.5 GHz Cu cavities coated by reactive cylindrical magnetron sputtering

Best cavity result for thicker film (4.3µm) and lower deposition temperature (265˚C)

Rs = 330nΩ @ 4.2K

M. Marino, Proceedings of the 8th Workshop on RF Superconductivity, October 1997, Abano Terme (Padua), (Rep) 133/98, vol.IV, p.1076

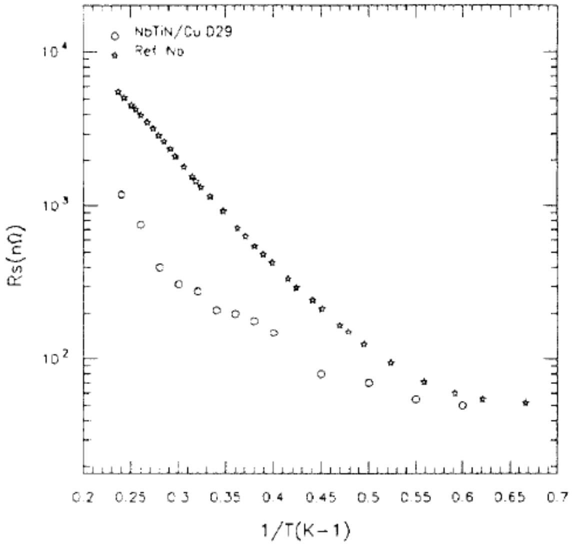
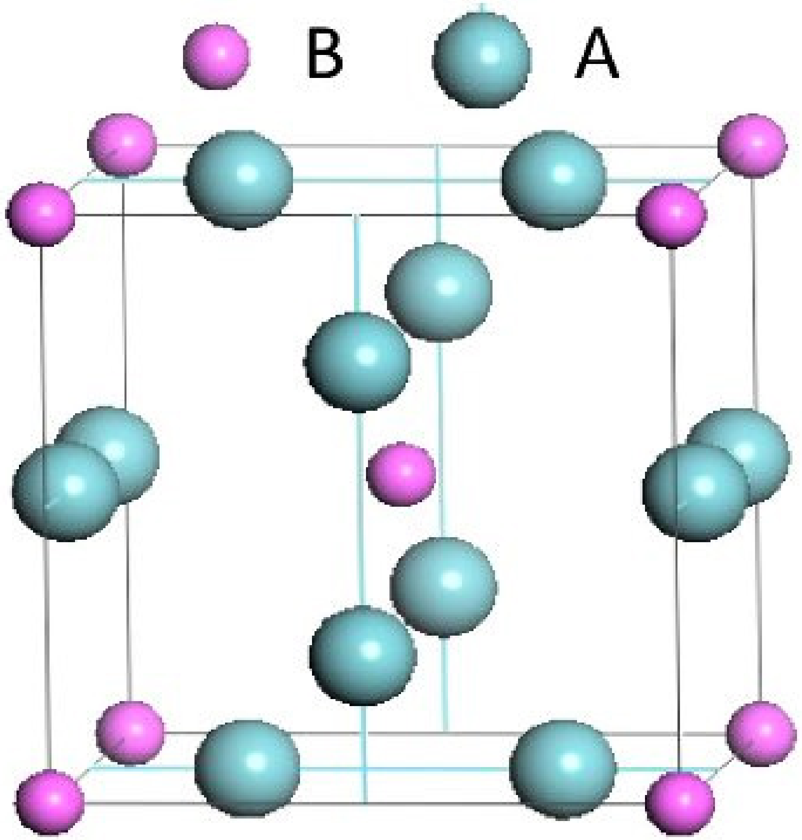


Figure 3 Surface resistance vs temperature for a NbTiN sample, at 4 GHz.

A15 COMPOUNDS



A15 COMPOUNDS : HIGH T_c

compound	T_C (K)	compound	T_C (K)	compound	T_C (K)	compound	T_C (K)
Ti_3Ir	4.6	V_3Os	5.15	Nb_3Os	0.94	Cr_3Ru	3.43
Ti_3Pt	0.49	V_3Rh	0.38	Nb_3Rh	2.5	Cr_3Os	4.03
Ti_3Sb	5.8	V_3Ir	1.39	Nb_3Ir	1.76	Cr_3Rh	0.07
		V_3Ni	0.57	Nb_3Pt	10	Cr_3Ir	0.17
Zr_3Au	0.92	V_3Pd	0.08	Nb_3Au	11		
Zr_3Pb	0.76	V_3Pb	3.7	Nb_3Al	20.3	Mo_3Re	15
		V_3Au	3.2	Nb_3Ga	18.9	Mo_3Os	11.68
		V_3Al	9.6	Nb_3In	8	Mo_3Ir	8.1
		V_3Ga	15.4	Nb_3Ge	23	Mo_3Pt	4.56
		V_3In	13.9	Nb_3Sn	18.3	Mo_3Al	0.58
		V_3Si	17.1	Nb_3Bi	2.25	Mo_3Ga	0.76
		V_3Ge	7			Mo_3Si	1.3
		V_3Sn	4.3	Ta_3Ge	8	Mo_3Ge	1.4
		V_3Sb	0.8	Ta_3Sn	6.4		
				Ta_3Sb	0.72		

[after Due-Hugues]

Phases with proper stoichiometry (A_3B) not stable in normal condition (RT to Cryogenic temp)
=> Quenching necessary

- **Among the Nb and V based high Tc (15 – 20 K)**
- **Nb_3Ga and Nb_3Ge do not exist as stable bulk materials at 3:1 stoichiometry**
- **Nb_3Al exists only at high temperature causing excessive atomic disorder**

Production of above materials need non equilibrium processes

- **V_3Ga, V_3Si & Nb_3Sn are stable bulk material and have high T_c**
- **Nb_3Sn =Special interest for SRF since the 1980's**

- **Another A-15 compound holding promise is Mo_3Re (Tc=15K)**

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Ti_3Sb	5.8	V_3Ir	1.39	Nb_3Ir	1.76	Cr_3Rh	0.07
		V_3Ni	0.57	Nb_3Pt	10	Cr_3Ir	0.17
Zr_3Au	0.92	V_3Pd	0.08	Nb_3Au	11		
Zr_3Pb	0.76	V_3Pb	3.7	Nb_3Al	20.3	Mo_3Re	15
		V_3Au	3.2	Nb_3Ga	18.9	Mo_3Os	11.68
		V_3Al	9.6	Nb_3In	8	Mo_3Ir	8.1
		V_3Ga	15.4	Nb_3Ge	23	Mo_3Pt	4.56
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- **Nb_3Sn =Special interest for SRF since the 1980's**

- **Another A-15 compound holding promise is Mo_3Re (Tc=15K)**

❑ **Extreme brittleness !!!**

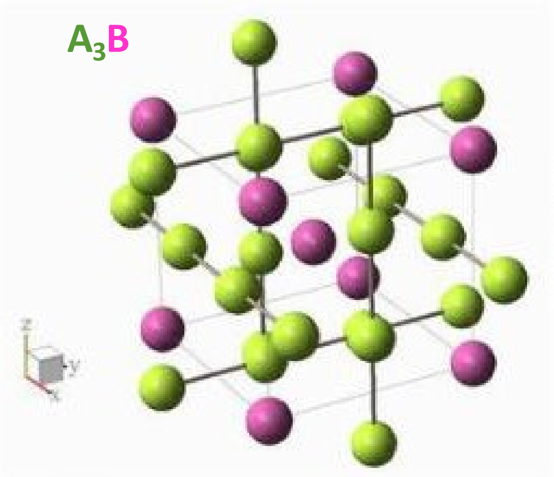
❖ cannot be plastically formed

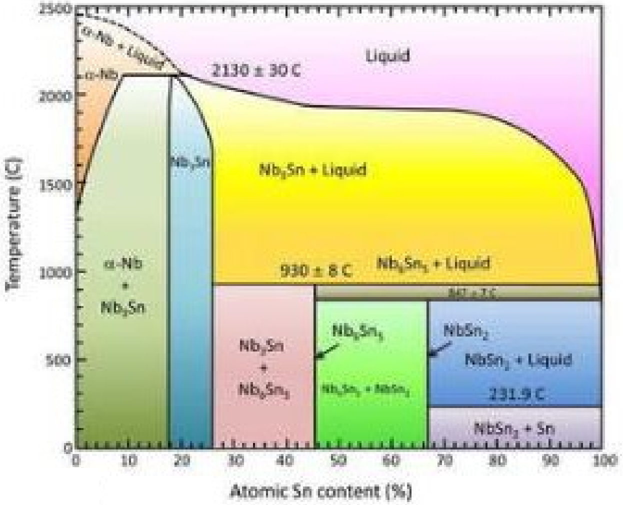
❖ thin/thick film route only !

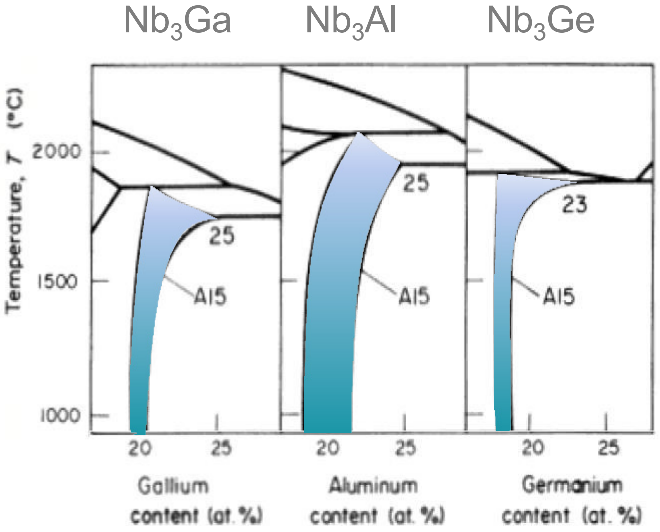
nm

µm

A15 COMPOUNDS : NARROW DOMAIN OF SC





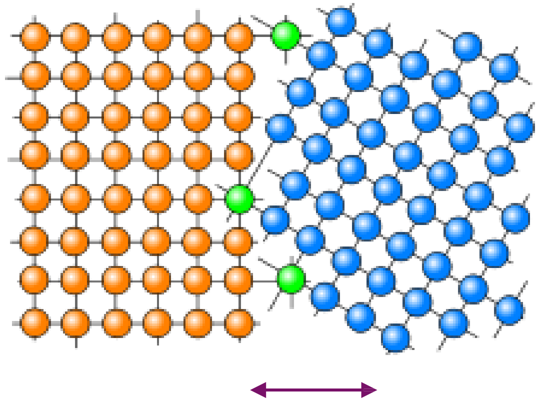


B *atoms occupy corners and center of BCC structure*

A *atoms form orthogonal chains bisecting the faces of the BCC unit cell.*

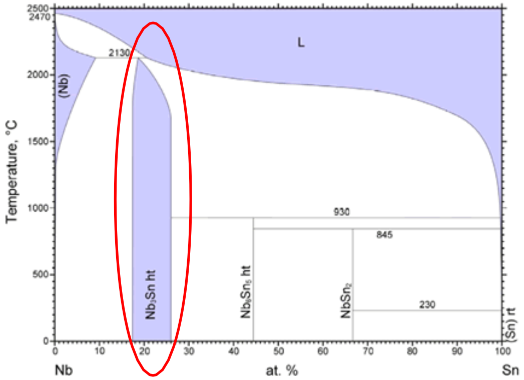
Linear Chain Integrity is crucial for Tc (long-range order required)

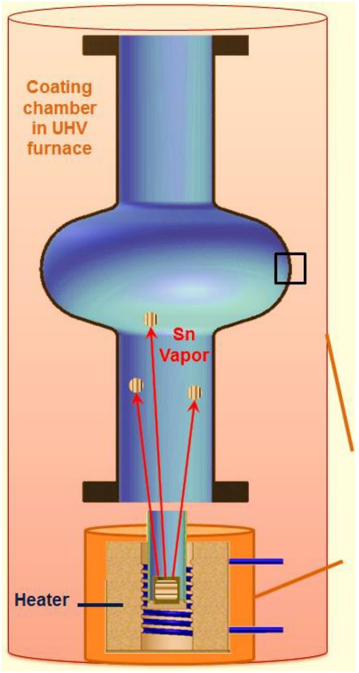
- **Narrow range of concentration for the SC phase:**
  - Highest T_C area is even narrower
  - Difficult to get uniform SC phase everywhere*
  - Special issues at grain boundaries: “intrinsic” local deviation of stoichiometry*
  - In Nb_3Sn wires : GB exhibit degraded SC => weak links, pinning centers



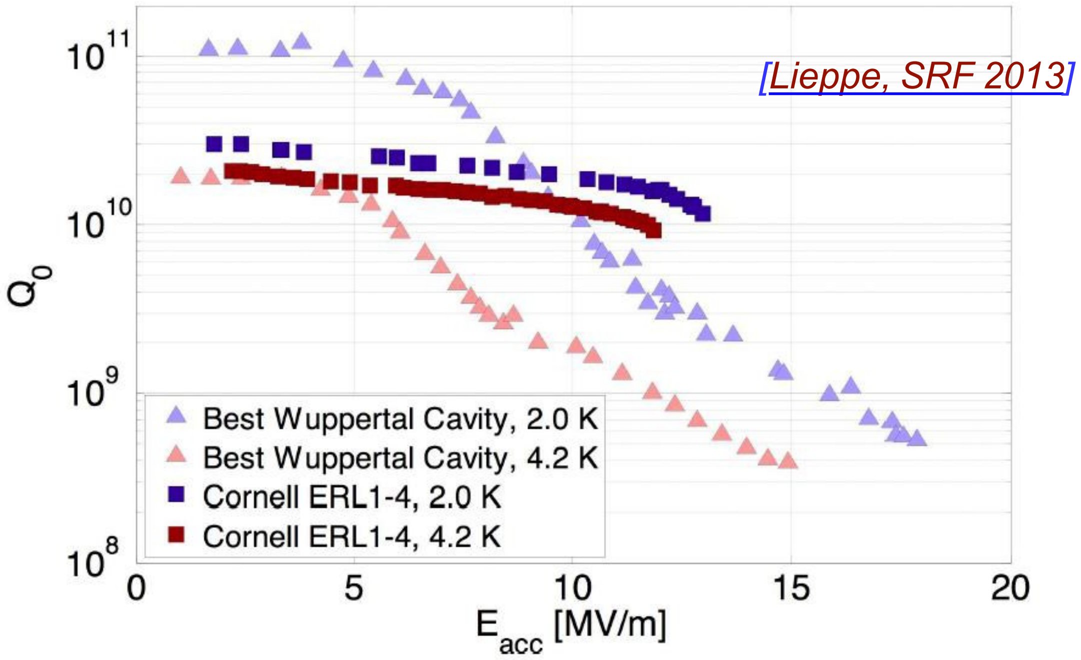
Compare with ξ

NB$_3$SN ON NB (thermal way)





Pioneer work: Wuppertal, Cornell



[Lieppe, SRF 2013]

- @ 4,2 K: Q_0 x 20 compare to Nb, @ 2K ~ the same
- Limited in E_{acc} , best results today ~20 MV/m
- Important developments: FNAL, JLAB, CERN, PKU….

EFFECTS OF LOCAL DEFECTS

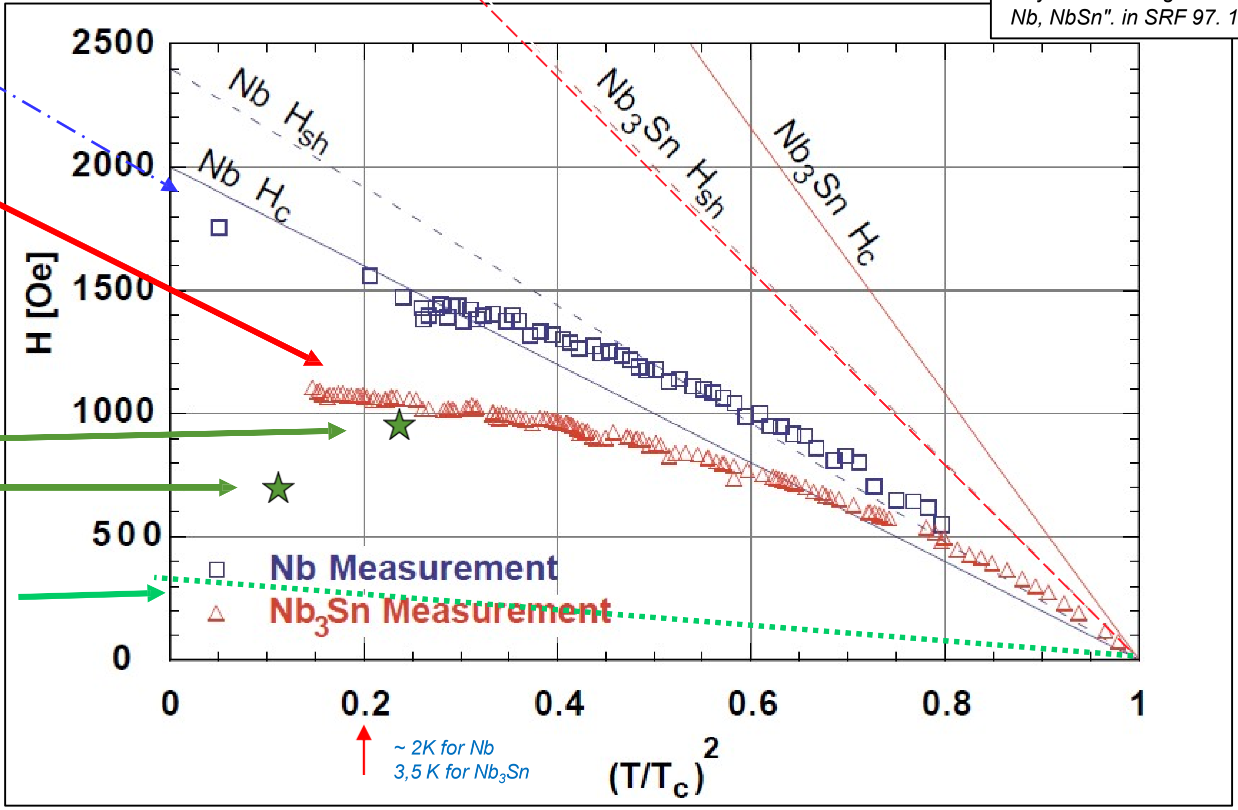
H_{SH}^{Nb3Sn}
(~ 400 mT @ 0 K)

Nb H_{C1}
(170 to 200 mT)

Cornell, 1997
pulsed

Recent results from Cornell & FNAL **CW**
Posen,
2019 (23 MV/m)
2015 (17 MV/m))

H_{C1}^{Nb3Sn} (~27mT)
(50 mT pour le bulk)

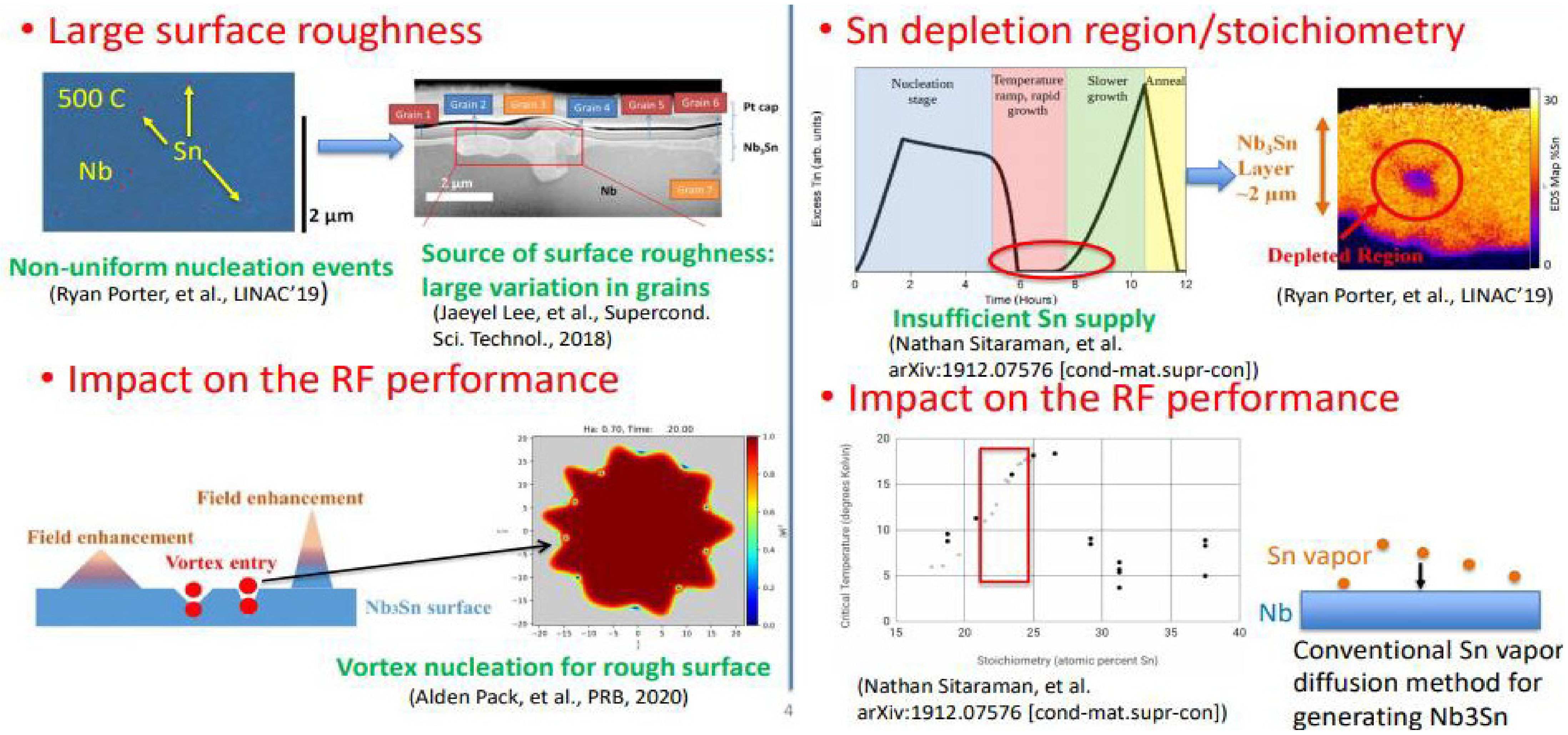


Hays. "Measuring the RF critical field of Pb, Nb, NbSn". in SRF 97. 1997.

Nb_3Sn
vs
Nb

=> We have to reduce defect density **(yes but which ones?)**

Issues with Nb$_3$Sn by vapor diffusion



- Large surface roughness

Non-uniform nucleation events
(Ryan Porter, et al., LINAC'19)

Source of surface roughness: large variation in grains
(Jaeyel Lee, et al., Supercond. Sci. Technol., 2018)

- Impact on the RF performance

Vortex nucleation for rough surface
(Alden Pack, et al., PRB, 2020)

- Sn depletion region/stoichiometry

Insufficient Sn supply
(Nathan Sitaraman, et al. arXiv:1912.07576 [cond-mat.supr-con])

(Ryan Porter, et al., LINAC'19)

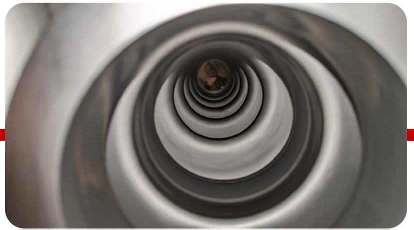
- Impact on the RF performance

(Nathan Sitaraman, et al. arXiv:1912.07576 [cond-mat.supr-con])

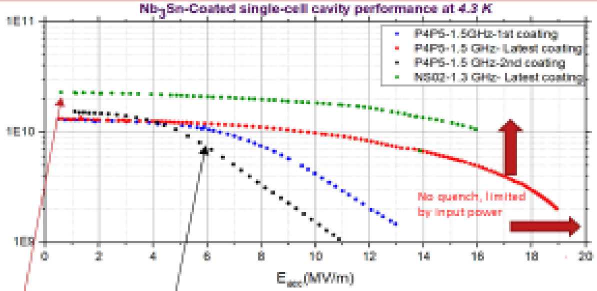
Conventional Sn vapor diffusion method for generating Nb3Sn

https://indico.jlab.org/event/405/contributions/7865/attachments/6613/8979/Zeming%20Sun_Thin%20film%20workshop%20slide.pdf

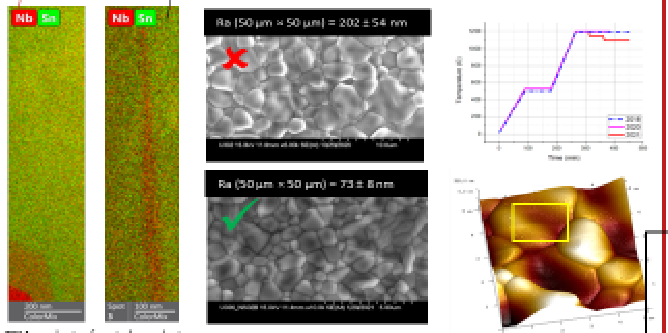
Developments around Nb_3Sn



Material studies and development of Nb_3Sn-coated cavities



Witness sample analysis correlating RF performance and coating parameters

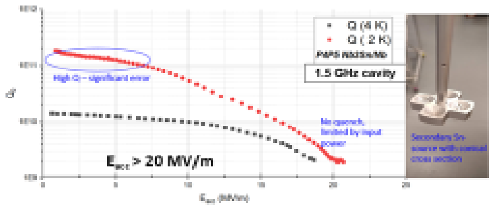


TEM analysis of grain boundaries with and without Q-slope

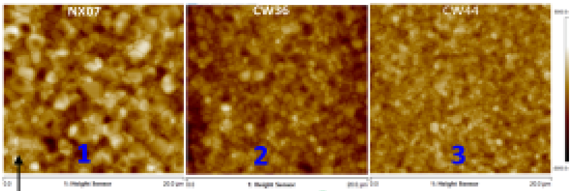
Grain size and roughness

Recurrent Sn residues contributing to residual resistance

- Coating with small grain sizes, smoother surfaces, and thinner (~ 1 μm) thinner coating with no Sn segregation or deficient grain boundary correlate with better-performing cavities.
- Further coating process optimization to enhance cavity performance is in progress.



Several cavities reached to ~ 20 MV/m, material studies and surface improvement is in progress to maintain high Q at high E_{acc}.

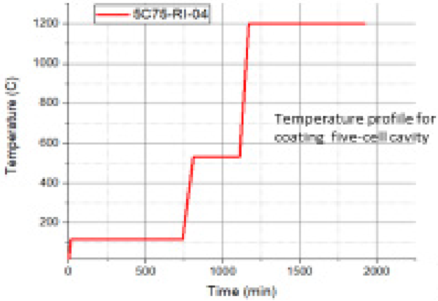


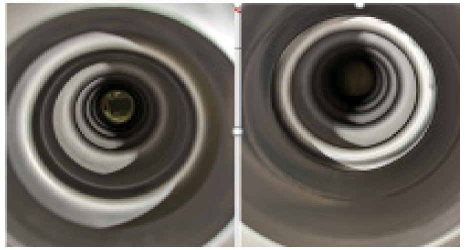
Expt	1200 C	1150 C	1100 C	Ra (nm)	Grain size (um)	Thickness (um)
00	38 min	45 min	85 min	85.4± 3.1	1.15	-
01	10 min	45 min	85 min	69± 3	0.93	2.07*
02	10 min	45 min		40± 1	0.75	1.0 +/- 0.2
03	10 min			27± 2	0.55	0.75
04	10 min		85 min	43.5± 1.5	0.6	1.02

- Several temperature profiles are identified to control roughness and thickness.
- Cavity coatings with selected profiles are in progress for potential improvement in RF performance.

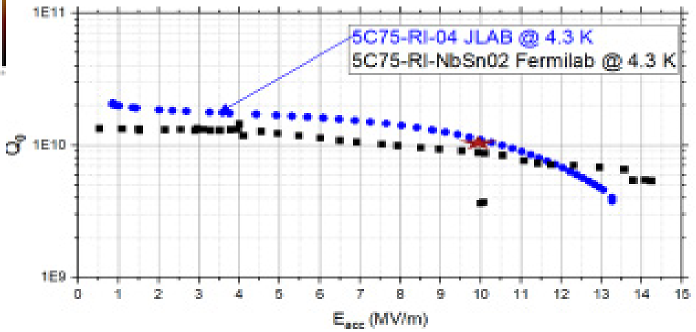
Jefferson Lab

Multi-cell cavity coating and Nb_3Sn QCM

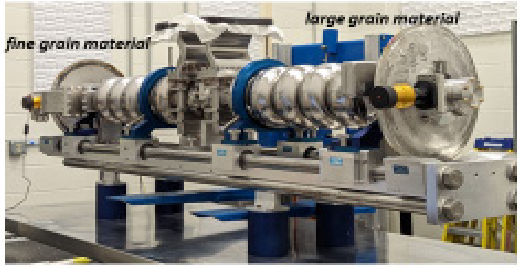




- Spec: 1E10 @ 10 MV/m
- One cavity was coated at Fermilab and another at Jlab.
- Cavity assembled in the pair and subjected to disassembly because of a leak, and assembled again with some degradation in the cavity performance
- Ready to be installed into a quarter module; test in the UITF later this year.



- Original C75 cavity made of ***large grain material***
- Limited by multipacting (no quench)

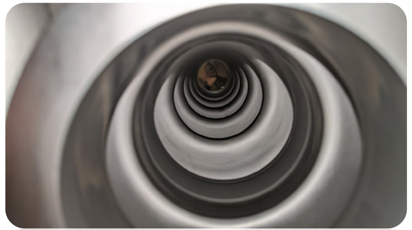


Based on G. Eremeev's ECA, Jlab cavity work supported by R&D fund.

Jefferson Lab

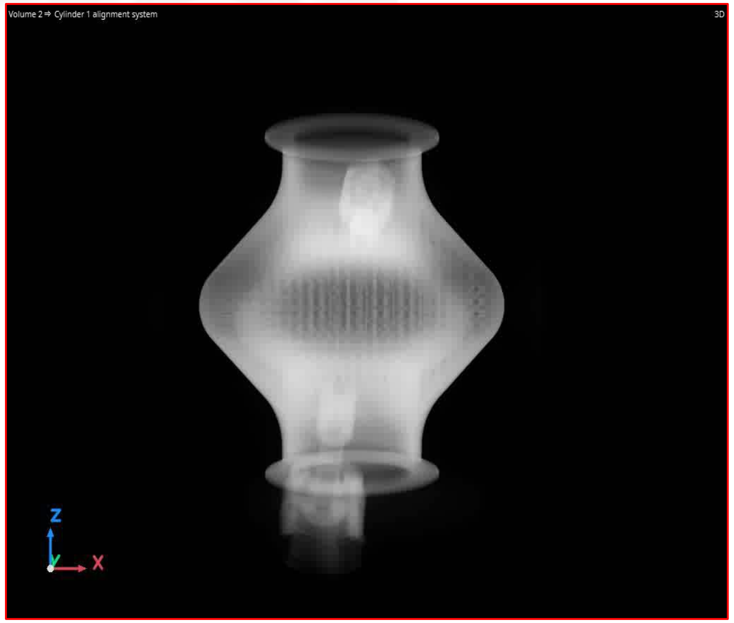
U. Pudasaini

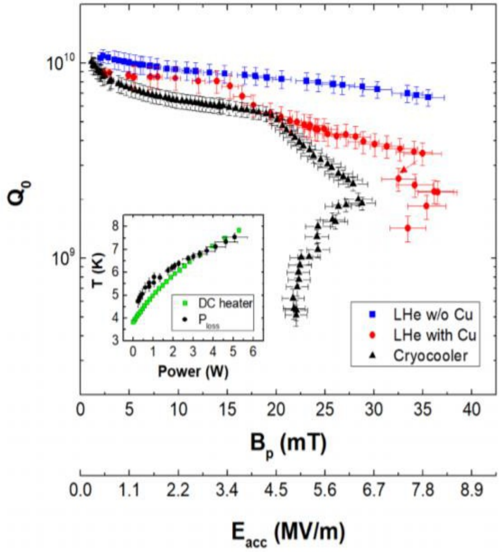
Developments around Nb$_3$Sn



Compact Accelerators for Societal Needs

Courtesy G. Ciovati et al.



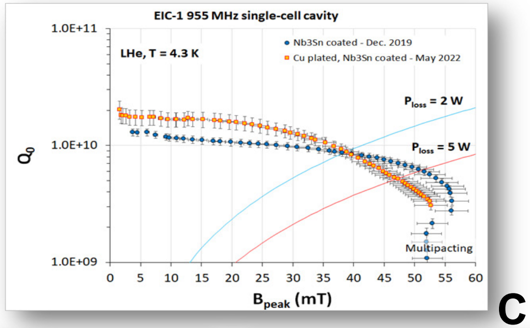


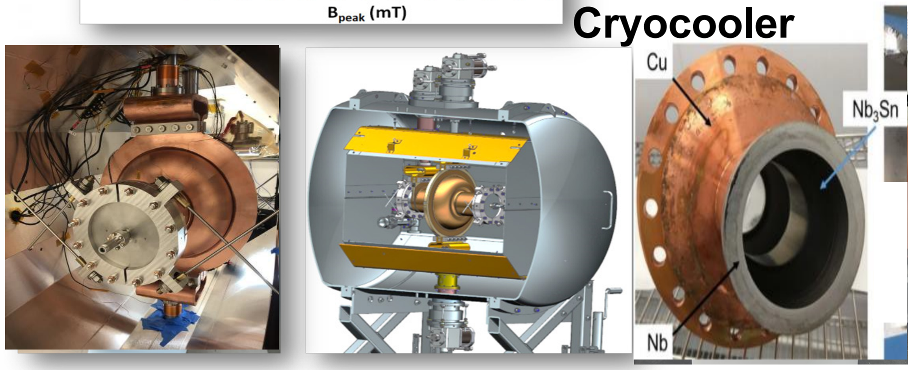
3D add. Fabrication with cooling circulating capillary integrated in the walls (thermosiphon approach)

- Reduced He volume
- Efficient cooling

General Atomics

Development of conduction-cooled SRF cavities





Horizontal Test Cryostat for conduction-cooled SRF cavities

G. Ciovati et al., "Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators", arXiv:2302.07201 [physics.acc-ph], 2023

A15 Compounds – Preparation Methods

Nb3Sn: Other Deposition Methods

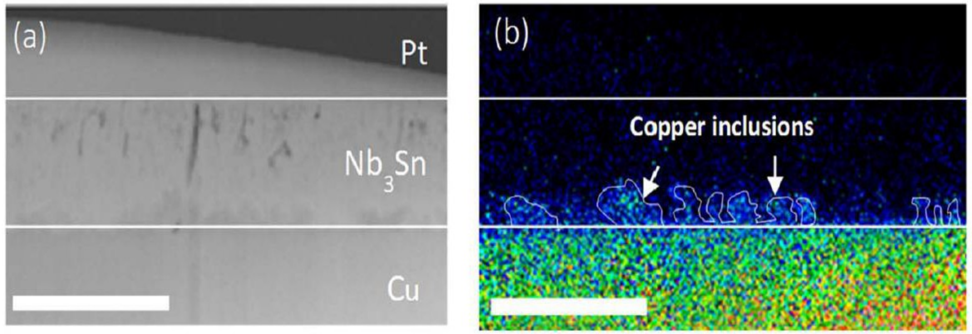
❑ Sputtered Nb_3S films on copper

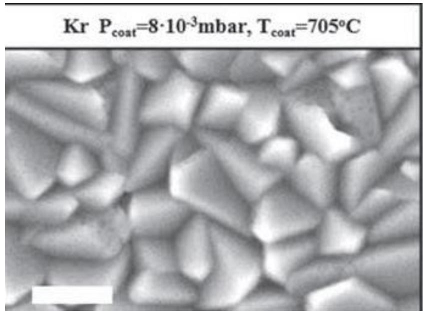
- Activities at Cern, STFC, Jlab, Cornell,,,
- RT deposited films : right composition but no A15 structure
- Heating of substrate (CERN)
- And/or post annealing

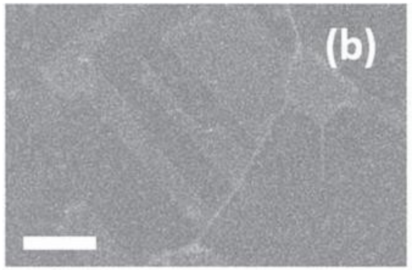
❑ Other issues

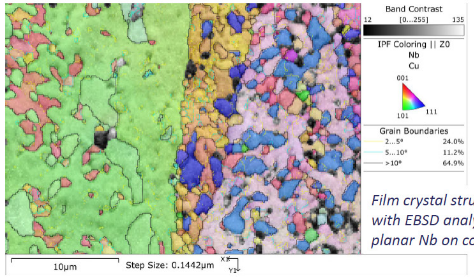
- Cracks on the layer *(due to differential dilatation coef)*
- Diffusion of copper in the layer
- Carrier gas incorporation *(Ar, Kr)*
- Sn evaporation at higher temperature (> 1000°C)

Supercond. Sci. Technol. **32** (2019) 035002 E A Ilyina *et al*



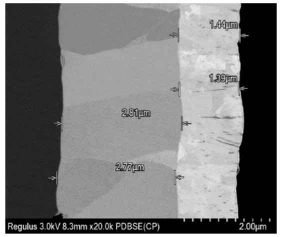






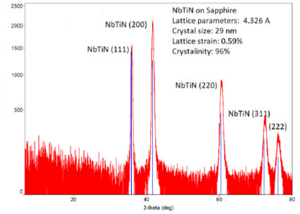
Film crystal structure with EBSD analysis of planar Nb on copper

X-section SEM of Nb_3Sn with a Nb underlayer as double structure on Cu



Science and

O.B. Malyshev | FCC week



XRD analysis of NbTiN deposited on copper

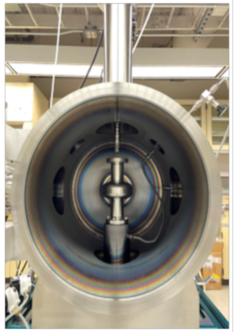
Courtesy of R. Valizadeh (STFC)

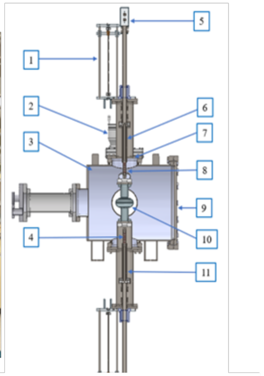
12

Cylindrical Magnetron Sputtering of Nb_3Sn coating (2.6 GHz Nb SRF cavity)

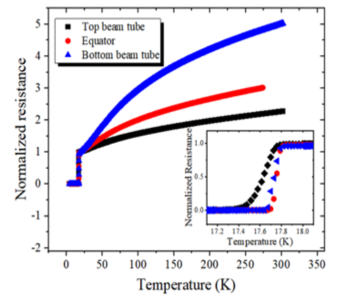
HEP Stewardship

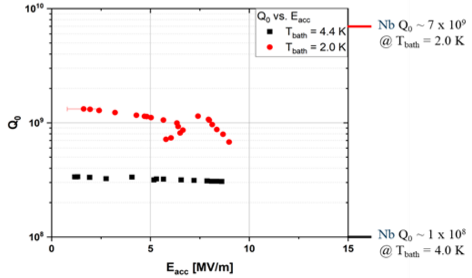

50 nm Nb
25 nm Sn
50 nm Nb
25 nm Sn
50 nm Nb
25 nm Sn
200 nm Nb
Nb substrate





Courtesy S. Sharifuzzaman et al.





Results

(Q_0) of 3.2 x 10^8 at E_{acc} = 5 MV/m at T_{bath} = 4.4 K

(Q_0) of 1.1 x 10^9 at E_{acc} = 5 MV/m at T_{bath} = 2.0 K

Nb3Sn: Other Deposition Methods

❑ Electrochemical deposition + diffusion through copper

- Proposed at FNAL
- Inspired from wire fabrication
- Not expensive !!!!

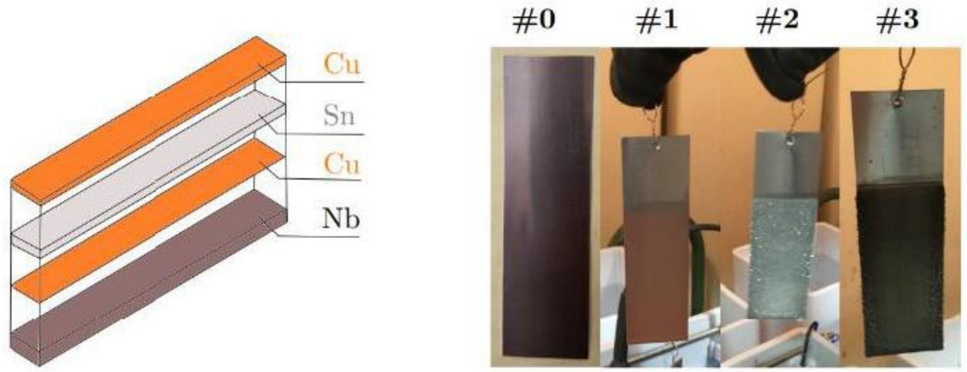
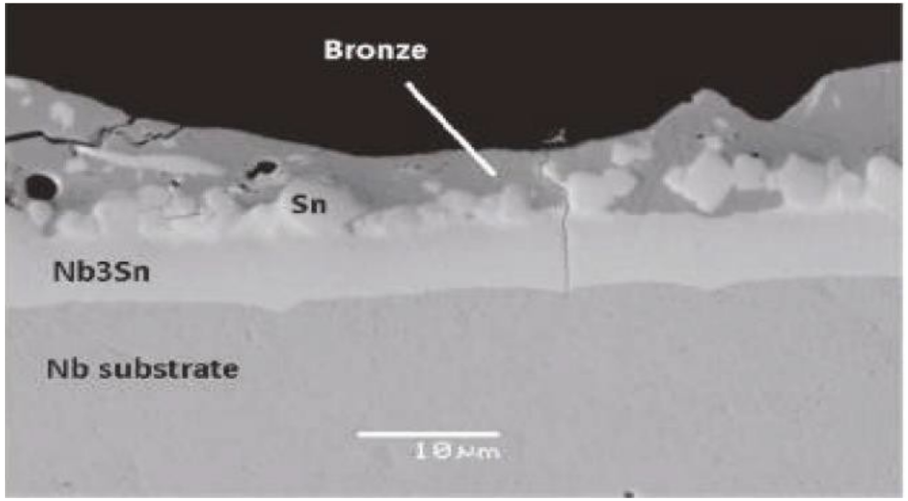


Fig. 3: Sequence of deposited layers (left), and pictures of sample at each deposition step (right).



- Multilayer is heated => solid state diffusion
- Cu lowers the formation Tp° of A15 phase and suppresses the unwanted $NbSn_2$ and Nb_6Sn_5 phases.

❑ Bronze Route

- Nb deposition on CuSn
- Heat treatment to diffuse Sn into Nb
- Not expensive !!!!

Current landscape for developments around Nb_3Sn

…non-exhaustive list

Method	Sn vapor/ liquid diffusion	Sputtering ! target	Co-sputtering	Sequential sputtering + annealing	Bronze routes (electrochemical deposition + annealing)
substrate	Nb only	Nb or Cu	Nb or Cu	Nb or Cu	Nb or Cu
Activities at	Cornell FNAL Jlab INFN KEK	Cornell Cern Jlab INFN STFC FSU	STFC* Peking U. Darmstadt Wisconsin U.*	IMP Jlab ODU FNAL	IMP Cornell FNAL FSU E2P

* In Multilayer structures

- NB : work on V_3Si also in progress

OTHER A15 COMPOUNDS

S. Deambrosis et al., Physica C 441 (2006) 108-113

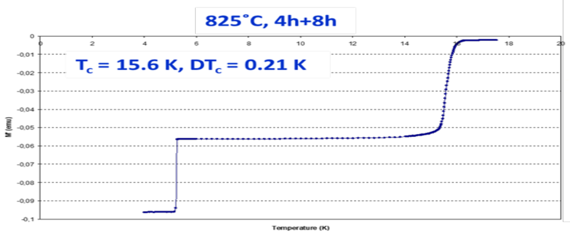
Highly ordered compound, RRR~80 achievable, max Tc (17.1K) when stoichiometric composition (25at.% Si)

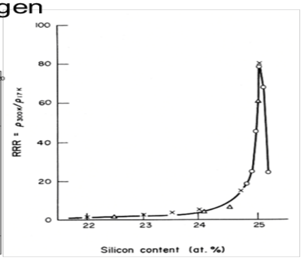
V_3Si layers by silanization of V substrate and Thermal Diffusion

V substrate heated to get SiH_4 decomposition and Silicon diffusion

Film grown by silanization with p (SiH_4) ~ 10^{-3}-10^{-4} mbar

Annealing in vacuum to get rid of hydrogen

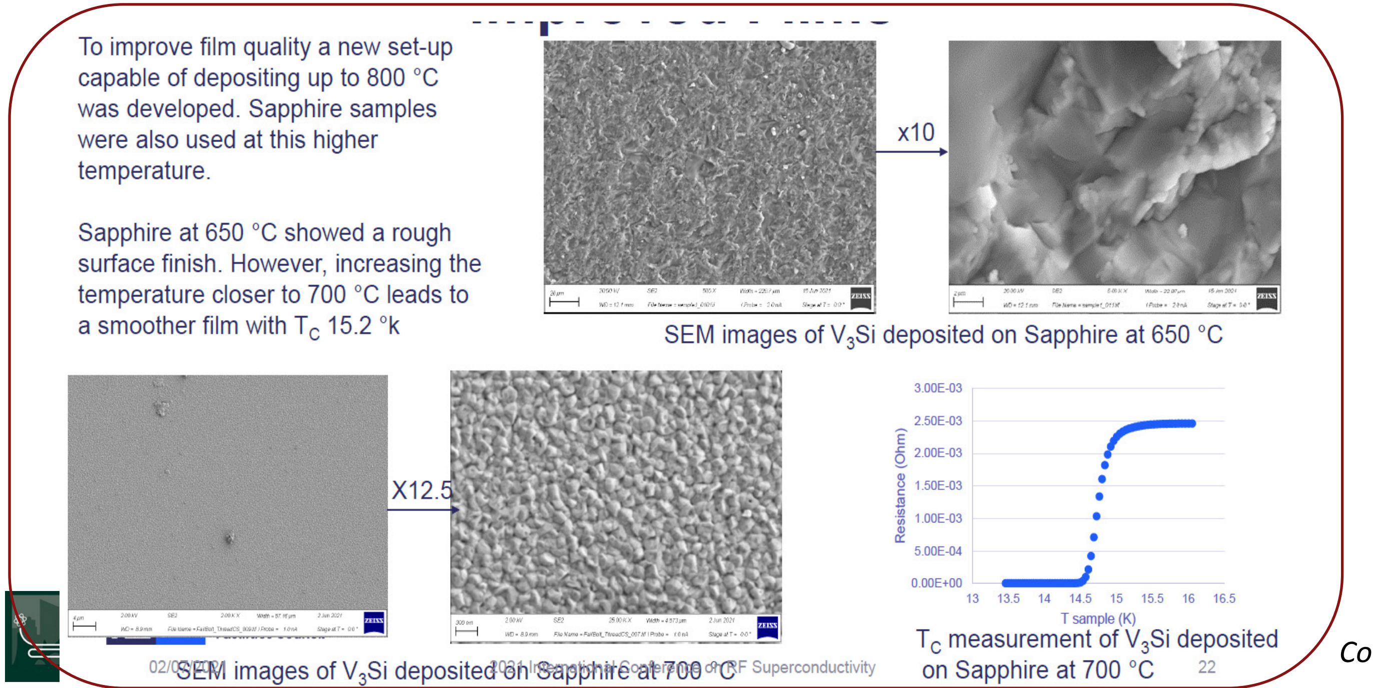




* Diffusion parameters and silane flow rate have been optimized

* Tc ~ 16 K is routinely obtained

* RF measurement on 6 GHz V-cavities will be available soon



To improve film quality a new set-up capable of depositing up to 800 °C was developed. Sapphire samples were also used at this higher temperature.

Sapphire at 650 °C showed a rough surface finish. However, increasing the temperature closer to 700 °C leads to a smoother film with T_C 15.2 °k

SEM images of V_3Si deposited on Sapphire at 650 °C

SEM images of V_3Si deposited on Sapphire at 700 °C

T_C measurement of V_3Si deposited on Sapphire at 700 °C

Mo_3Re thin films by DC magnetron deposition: $Mo_{75}Re_{25}$, $Mo_{60}Re_{40}$

Solid solution , free of bulk and surface inhomogeneities, low intersticials solubility compared to Nb, low κ, high H_{c1} (500G)

Bulk in σ phase, tetragonal low T_c (6K)

but T_c up to 18K reported in literature with bcc structure

S.M. Deambrosis et al., Physica C 441(2006) 108-113

* Deposition on Sapphire, Cu and Nb substrates

*Substrate temperature up to 950⁰ C

*Post-annealing to increase crystallinity and transition sharpness

* Tc = 12K obtained for composition $Mo_{60}Re_{40}$

Higher deposition temperature, longer annealing time

→ Higher Tc

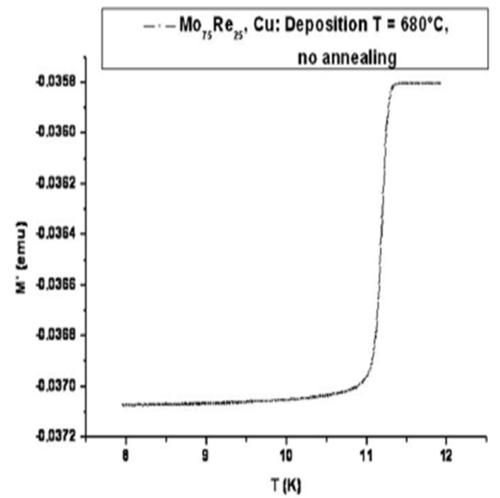
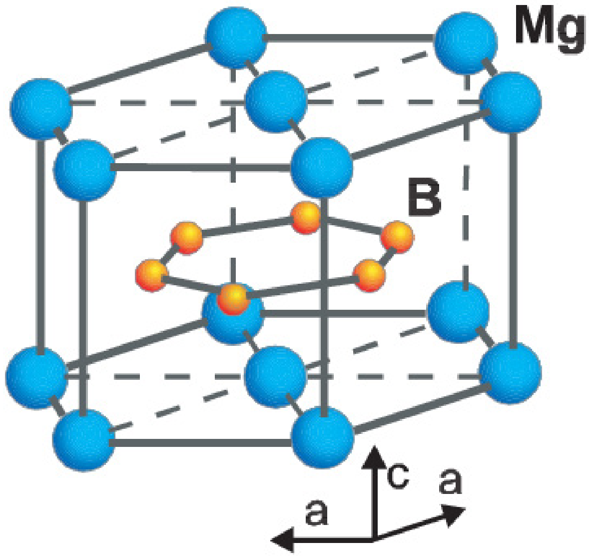


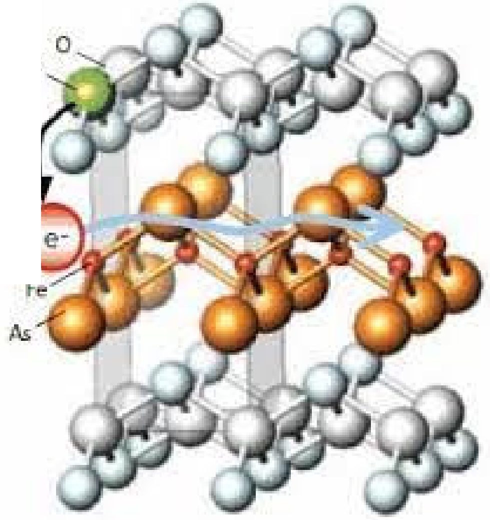
Fig. 4. A $Mo_{75}Re_{25}$ film deposited on Cu transition curve: deposition T = 680 °C, T_c = 11.18, ΔT_c = 0.08 K.

Courtesy R. Valizadeh

2-D SC (Compounds, anisotropic)

- MgB_2
- Cuprates, Pnictides
- Multilayers





MAGNESIUM DIBORIDE (MgB_2)

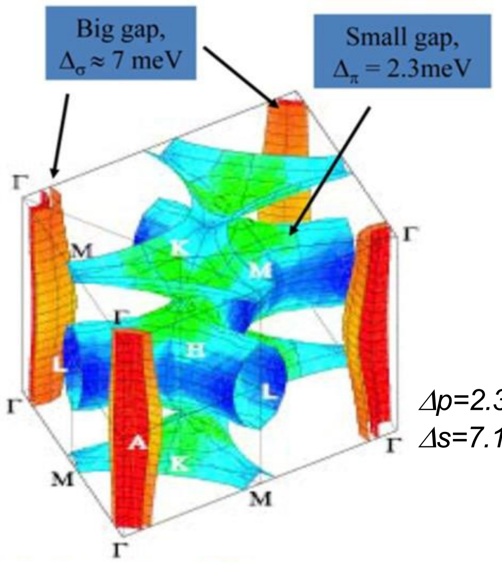
BCS type superconductor

- ❑ **T_C ~40 K, two-gap nature**
- ❑ **Advantages:**
  - ○ Very high T_C *(higher temp operation)*
  - ○ Semimetal, cheap *(fertilizer !)*
  - ○ ξ, ll of high quality* MgB_2 similar to Nb (~50 nm) *(transparency of GB to current flow)*
  - ○ Low ρ_n *(lower R_S)*
- ❑ **Disadvantages:**
  - ○ Orientation issues *(in polycrystalline materials !)*
  - ○ RF dominated by lower gap ☹ !
  - ○ Still better than Nb :

Δ^{Nb}= 1.5 meV < Δ_π^{MgB2}= 2.3 meV < Δ^{Nb3Sn}= 3.1 meV

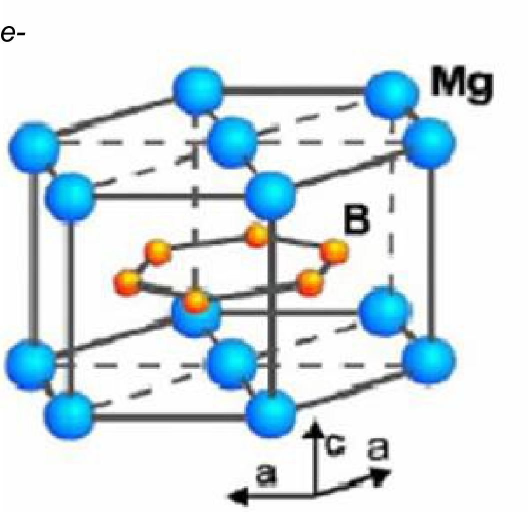
$<\Delta_\sigma^{MgB2}$ = 7.1 meV

  - ○ Sensitive to H_2O *(capping necessary ?)*
  - ○ Thin film routes difficult to achieve



Liu, Mazin and Kortus (2002);
Choi et al, (2002)

Graphite-type boron layers separated by hexagonal close-packed layers of magnesium



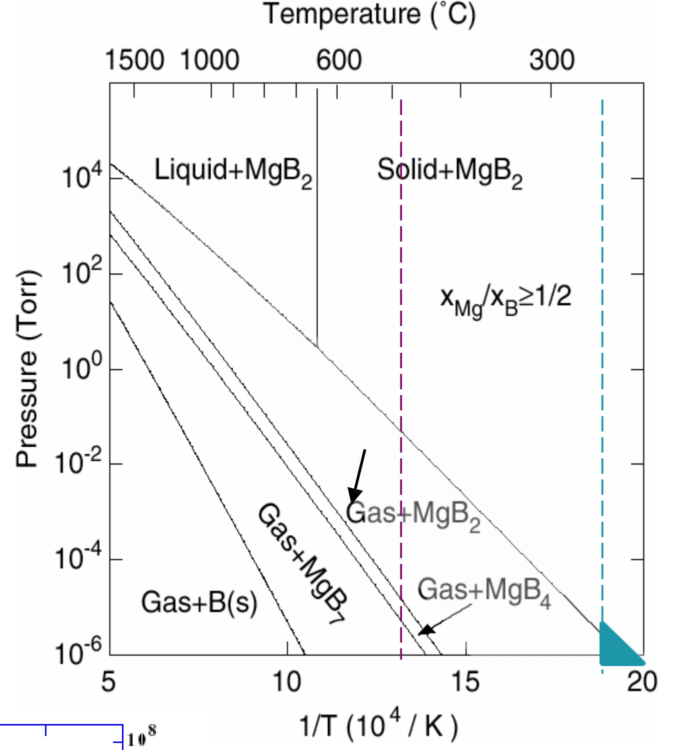
Δp=2.3meV, 2D, in-plane s-orbital
Δs=7.1meV 3D, out-of-plane p-orbitals

A. Floris et al., cond- mat/0408688v1 31 Aug 2004

MAGNESIUM DIBORIDE (MgB_2)

Phase diagram: at low Mg pressure only extremely low deposition temperatures can be used

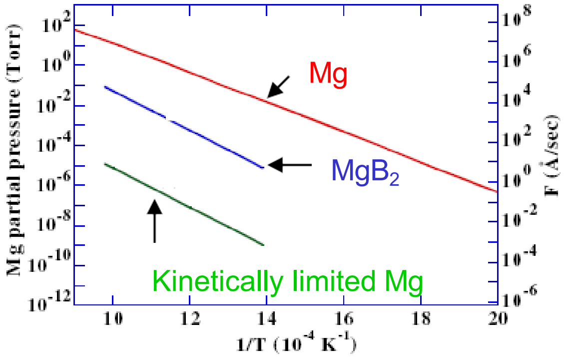
- **Optimal T for epitaxial growth ~ $T_{melt}/2$**
  - For MgB_2 $T_{melt}/2$ = 540°C => P^{Mg} ~11 Torr
  - Too high for UHV deposition techniques (PLD, MBE...)
- **At $P^{Mg} = 10^{-4}$-10^{-6} Torr, and T_{sub} ~ 400°C**
- Compatible with MBE, and other deposition techniques MgB_2 is stable, but no MgB_2 formation:
  - Mg atoms re-evaporate before reacting with B
- **At $P^{Mg} = 10^{-4}$-10^{-6} Torr, and lower T**
  - MgB_2 is stable,
  - If Tsub >250°C, free Mg is lost because the re-evaporation rate is higher than the impinging rate If Tsub < 250°C



Z.-K. Liu et al., APL 78(2001) 3678.

.Growth rate is very slow,
(kinetically limited by available Mg)

evaporation pressure of Mg from MgB_2 < decomposition curve of MgB_2 < Mg vapor pressure

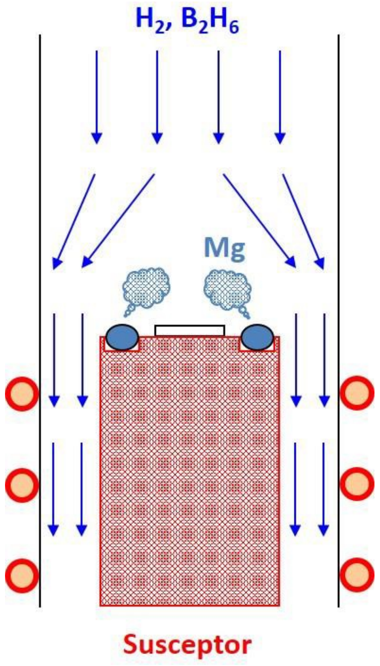


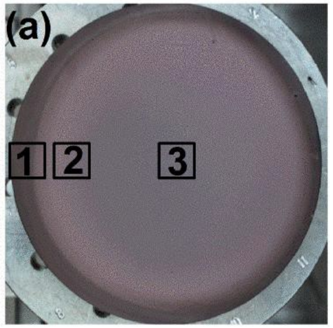
M. Naito and K. Ueda, SUST 17 (2004) R1

MgB_2 – HPCVD ON METAL SUBSTRATES

[X. Xi- TempleUniversity]

HYBRID PHYSICAL CHEMICAL VAPOR DEPOSITION





Polycrystalline MgB_2 films deposited: On stainless steel, Nb, TiN, and other substrates.

Flat samples and tubes *(conformational)*

Fitted for SRF apps:

RRR>80

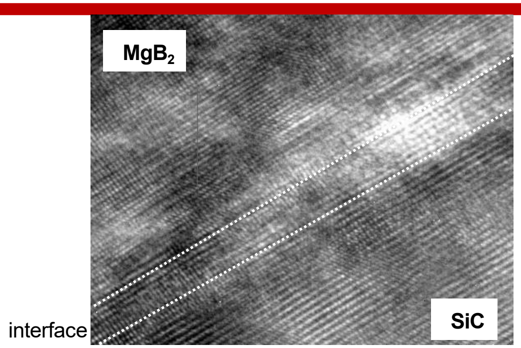
low resistivity (<0.1 μΩ) and long mean free path high Tc ~ 42 K (due to tensile strain),

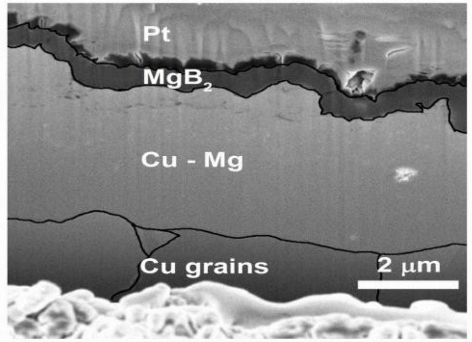
low surface resistance, short penetration depth

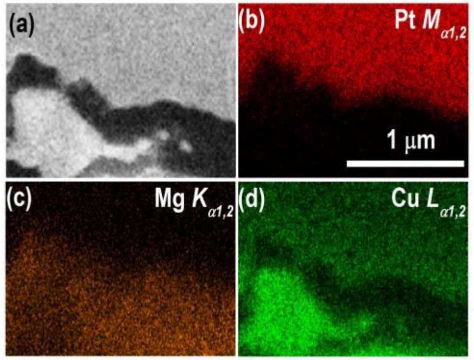
smooth surface (RMS roughness < 10 Å with N_2 addition) good thermal conductivity (free from dendritic magnetic instability)

Keys to high quality MgB_2 thin films: High Mg pressure for thermodynamic stability of MgB_2

- Oxygen-free or reducing environment Clean Mg and B sources
- Preventing formation of spurious phase (e.g.
- Mg-Cu alloy islands on a Cu substrate





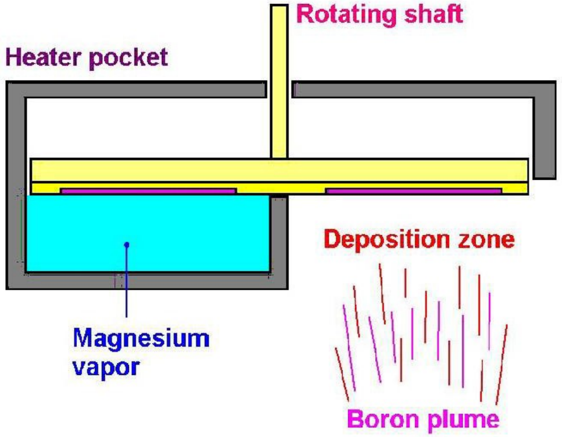


Reactor/reaction designs require complex calculation in thermodynamics and hydrodynamics

MGB$_2$ – OTHER ROUTES

❑ In-situ reactive evaporation @ 550˚C

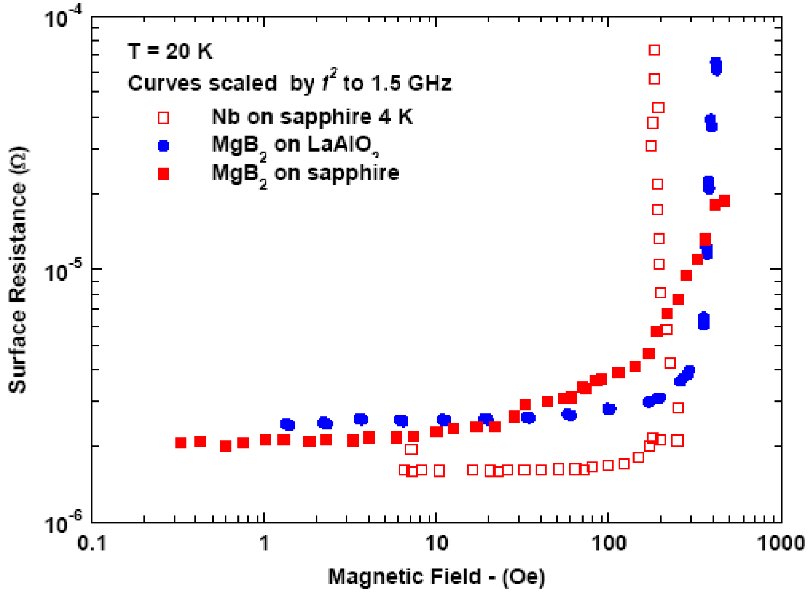
- High quality flat samples
- Difficult to apply to complex geometries



[T. Tajima, LANL]

Superconducting Technologies Inc.

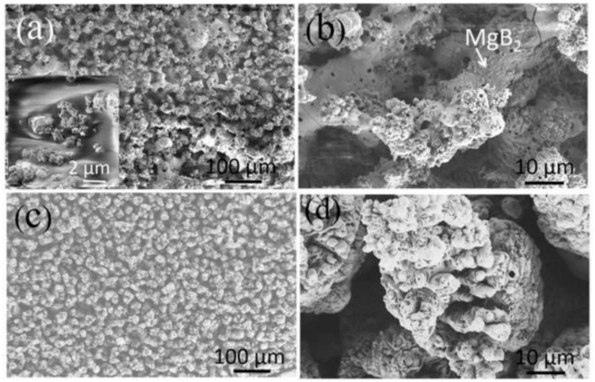
RF measurement @ MIT/Lincoln Lab



❑ Plasma electrolytic oxidation (PEO)

- MgB$_2$ particles in suspension in an electrolyte MgB$_2$ Islands deposited on the surface
- Issues : homogeneity, purity

To be further explored

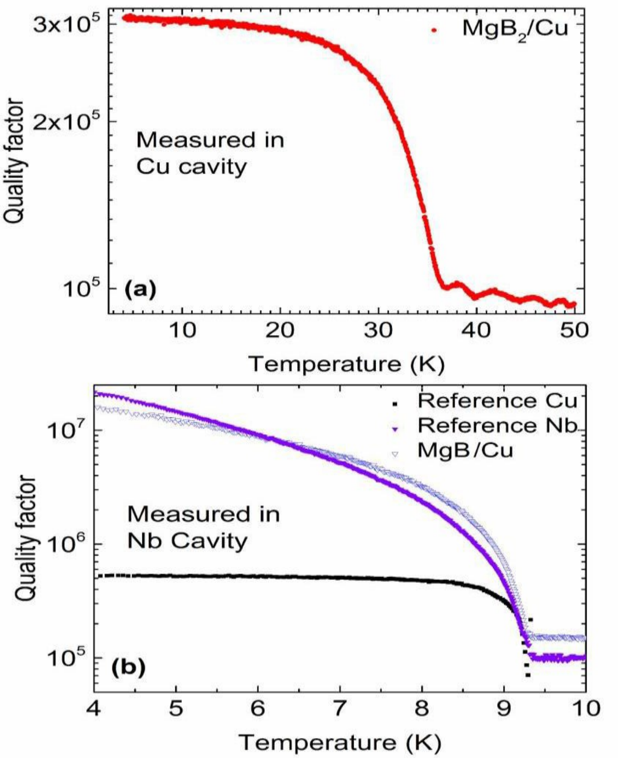


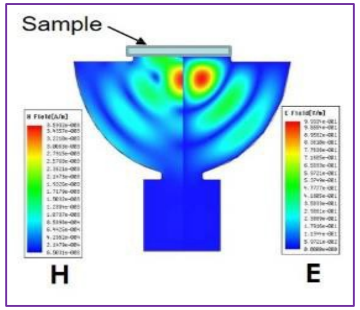
[R. Valizadeh, STFC]

HPCVD MGB$_2$ – RF MEASUREMENTS

❑ 11.4 GHz TE013 cavity @ SLAC

- The MgB$_2$ coatings were also characterized at 11.4GHz at SLAC using a cryogenic RF system.
- The samples showed a Q factor comparable to a Nb reference sample and higher than the Cu reference sample.
- The films showed a Tc of 37 K.

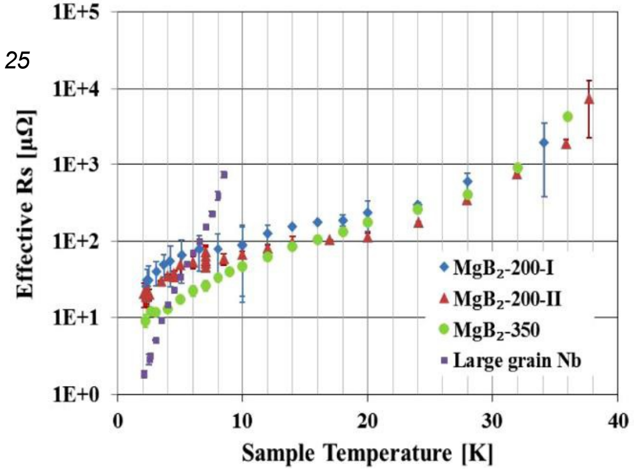




[P. Welander, SLAC]

❑ 7.5 GHz sapphire-loaded TE011 cavity at JLab

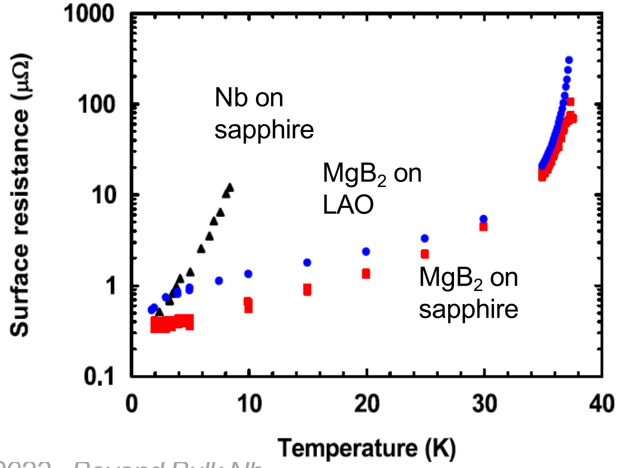
B.P.Xiao et al., SUST 25 (2012) 095006.



❑ Stripline resonator

Scaled to 1,5 Ghz

Lower surface resistance comparable to Nb film.



Oates et al., SUST 23, 034011 (2010)

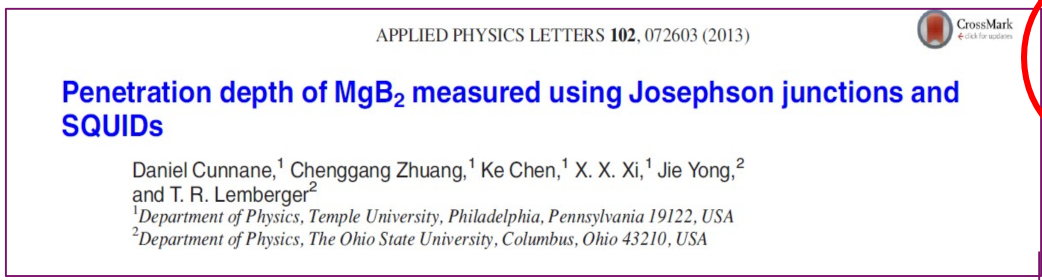
THE IMPORTANCE OF MEAN FREE PATH, MgB_2 EXAMPLE

- Most developments of HT_c are done in view of magnet applications : small ξ high ll by playing with ℓ
- Small x makes the superconductors very sensitive to (usual) crystalline defects (wanted for magnets, not for SRF)
- Typical values found in literature for MgB_2 : λ~100-150 nm ξ~ 5-10 nm
- if $\ell \nearrow$ then:
  - $\xi \nearrow$
  - $\lambda \searrow$
  - $\kappa \searrow \searrow$

ℓ mean free path

$$\frac{1}{\xi} = \frac{1}{\xi_0} + \frac{1}{\ell}$$

$$\lambda = \lambda_L \cdot \left(\frac{\xi_0}{\xi}\right)^{\frac{1}{2}} = \lambda_L \cdot \left(1 + \frac{\xi_0}{\ell}\right)^{\frac{1}{2}}$$



APPLIED PHYSICS LETTERS **102**, 072603 (2013)

CrossMark

Penetration depth of MgB_2 measured using Josephson junctions and SQUIDs

Daniel Cunnane,[1] Chenggang Zhuang,[1] Ke Chen,[1] X. X. Xi,[1] Jie Yong,[2] and T. R. Lemberger[2]

[1]*Department of Physics, Temple University, Philadelphia, Pennsylvania 19122, USA*
[2]*Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA*

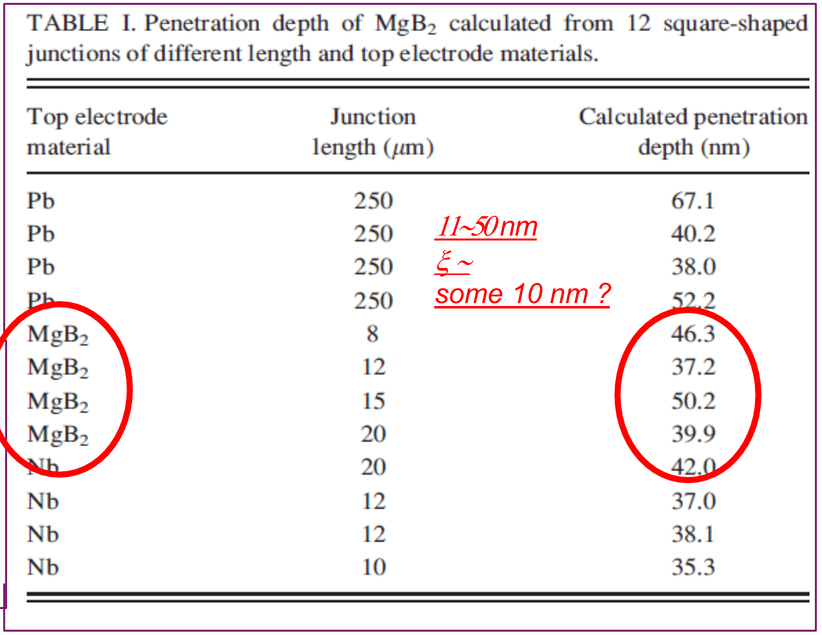


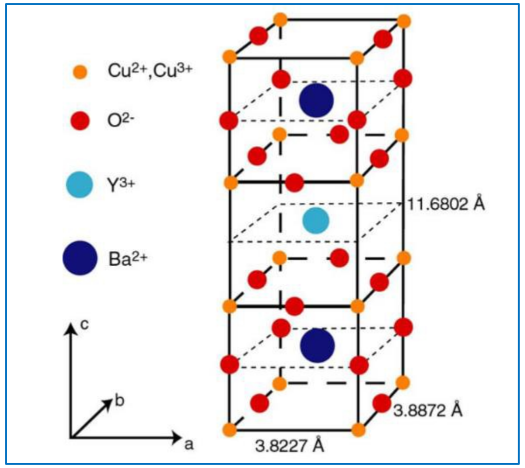
TABLE I. Penetration depth of MgB_2 calculated from 12 square-shaped junctions of different length and top electrode materials.

Top electrode material	Junction length (μm)	Calculated penetration depth (nm)
Pb	250	67.1
Pb	250	40.2
Pb	250	38.0
Pb	250	52.2
MgB_2	8	46.3
MgB_2	12	37.2
MgB_2	15	50.2
MgB_2	20	39.9
Nb	20	42.0
Nb	12	37.0
Nb	12	38.1
Nb	10	35.3

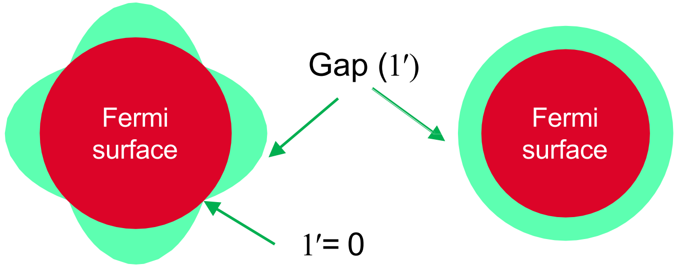
11~50nm
ξ ~
some 10 nm ?

YBCO FAMILY… NOT FOR SRF !

- Mono crystal: Jc maximum for (a,b) planes and minimum when // c axis
  - ξc (~0,03 nm) <<ξa, ξb (~1-2 nm) => “layered material”
- Realistic material : polycrystalline, ceramic, fragile…
  - ξc << disordered area at G.B => grains are decoupled (weak links)
  - => try to introduce preferential orientation (epitaxy): difficult to get on a cavity (but is applied to fabricate tapes for magnets)
- D-symmetry of the gap
  - superconducting gap is also anisotropic
  - = zero at 4 line nodes located at the diagonals of the Brillouin zone
  - 1′= 0 => power law for R_S: R_S α to T^2-T^3
  - For the recall: gaps of conventional SC have s symmetry:
    isotropic and R_S α $e^{-1'/T}$ (BCS resistance)



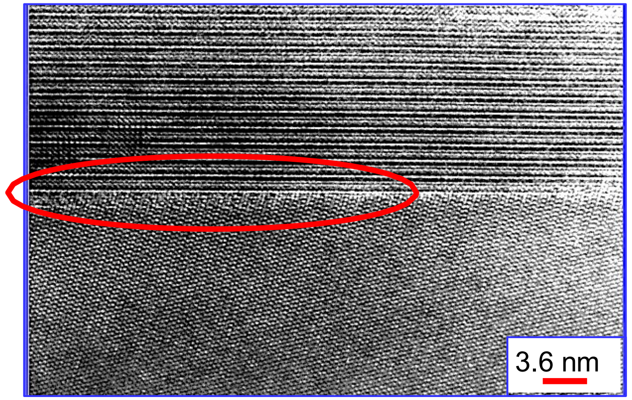
http://mason.gmu.edu/~grobert1/2014syl641.htm



d-wave

s-wave

Crystal structure is also related to Brillouin zones. So the relative orientation of the grains can influence the way Cooper pairs are scattered by defects

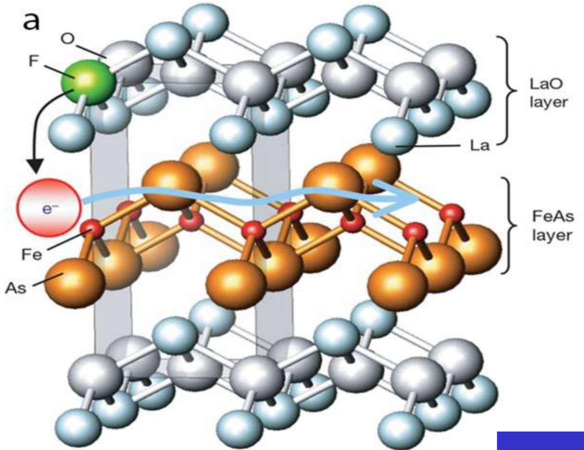


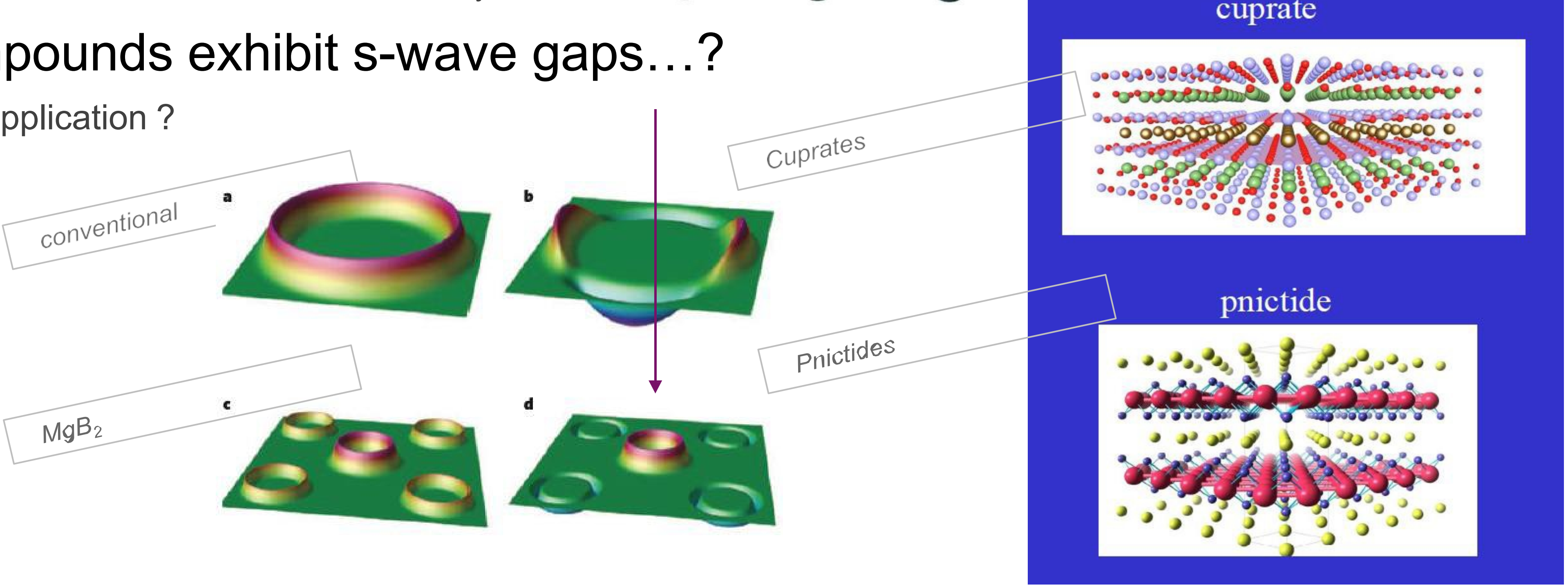
Twin boundary in YBCO

https://areeweb.polito.it/ricerca/superconductivity/melt.htm

PNICTIDE FAMILY… MAYBE YES ?

- ❑ Oxypnictide base: ReOMPn
  - ○ M = Fe, Co, Ni, Pn = As or P
  - ○ Re = La, Nd, Sm, Pr
- ❑ A lot in common with YBCO
  - ○ High T_C (10-55 K up today) Layered structure
  - ○ Brittle material
  - ○ d-wave symmetry observed for some member of the family
- ❑ But most compounds exhibit s-wave gaps…?
  - ○ Opening for SRF application ?





PNICTIDE FAMILY… MAYBE YES ?

☐ A lot in common with YBCO

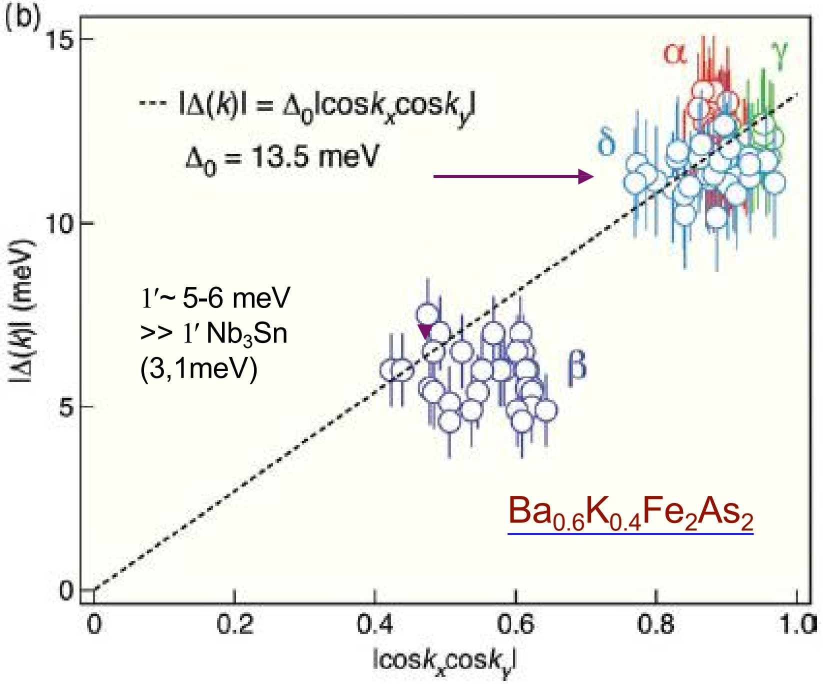
- High T_C (10-55 K up today)
- Layered structure
- Brittle material

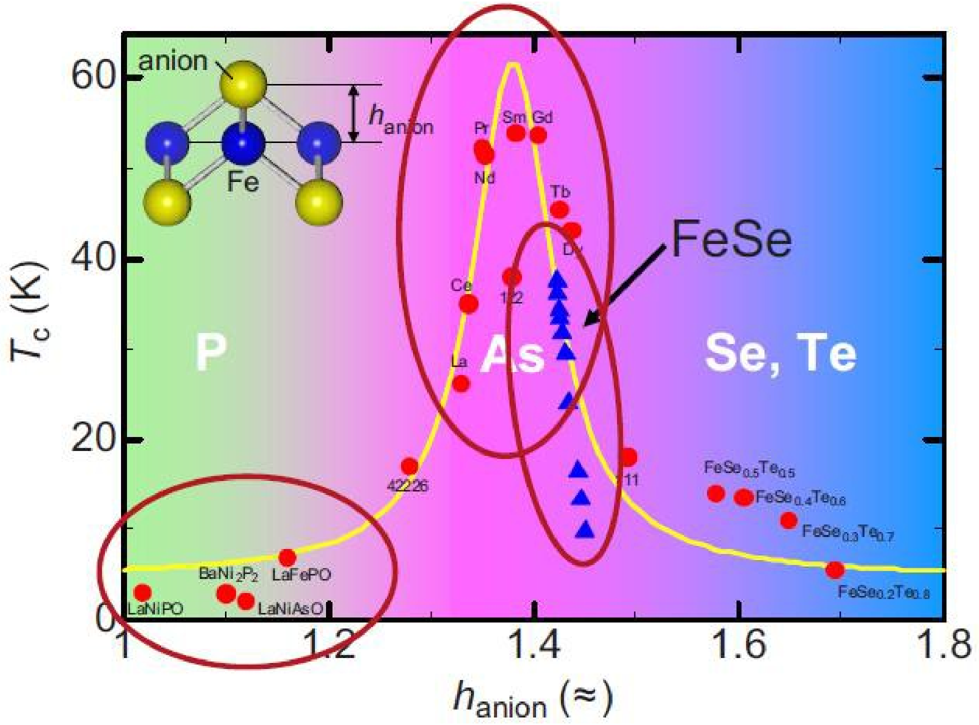
but

- Most compounds exhibit s-wave gaps
- Very sensitive to impurities content (either magnetic or not)

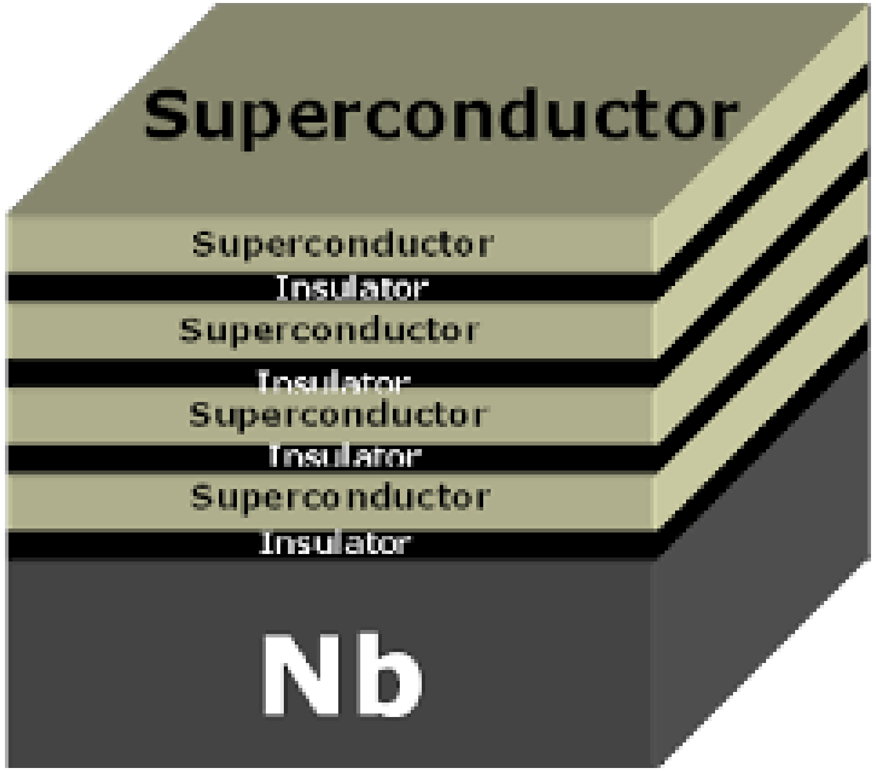
$NaFe_{1-x}Co_xAs$ (x = 0.0175)
= ferromagnetic

$NaFe_{1-x}Co_xAs$ (x=0.045)
= SC





MULTILAYERS

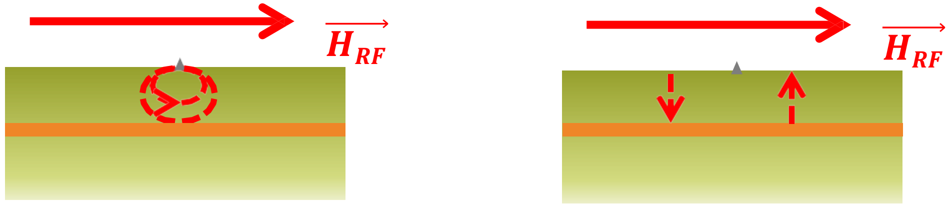


NANOCOMPOSITES MULTILAYERS

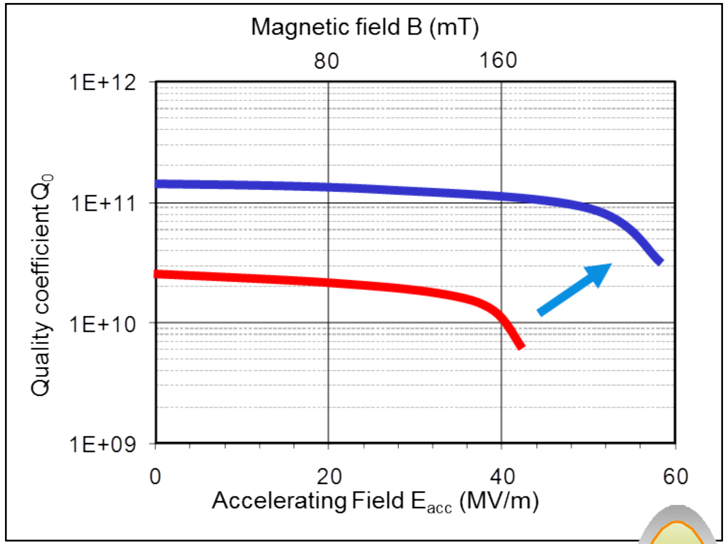
Taking advantage of the high –Tc superconductors with much higher H_c without being penalized by their lower Hc1…

Multilayer coating of SC cavities: alternating SC and insulating layers with $d_{SC} < \lambda$

Higher T_c thin layers provide magnetic screening of the Nb SC cavity (bulk or thick film) without vortex penetration



Structures proposed by A. Gurevich in 2006, SRF tailored



☐ **Dielectric layer**

- ○ Small ⊥ vortex (short -> low dissipation) Quickly coalesce (w. RF)
- ○ Blocks avalanche penetration

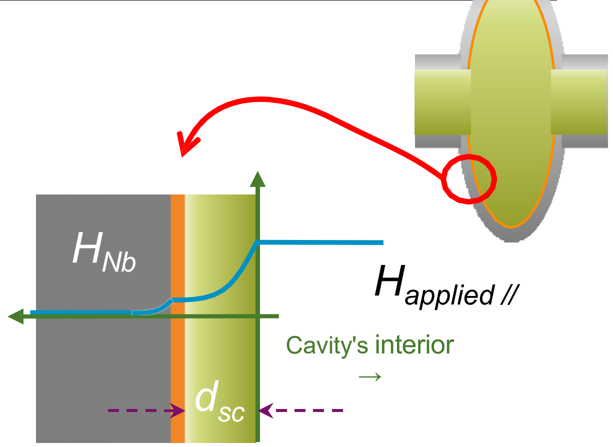
=> **Multilayer** concept for RF application

☐ **Nanometric S/I/S/I/ layers deposited on Nb**

- ○ SC nanometric layers (≤ 100 nm) => $H_{C1}\uparrow$ => Vortex enter at higher field
- ○ Nb surface screening => allows high magnetic field inside the cavity => higher E_{acc}

SC w. high T_C than Nb (e.g. NbN): $R_S^{NbN} \approx \frac{1}{10} R_S^{Nb}$

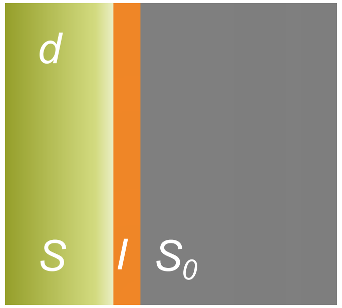
=> $Q_0^{multi} >> Q_0^{Nb}$



S-I-S

FIRST APPROACH: TRILAYERS

- **Meissner state stable if:**
  - Screening current @ both SC surface is < depairing current
  - $J(0) < J_d = H_s/\lambda$ and $J(d) < J_{d0} = H_{s0}/\lambda_0$
  - If d is small, $H_{SH}{}^S$ is high, but most of the field reach S_0
  - If d is thicker, $H_{SH}{}^S$ is lower, but screening is more effective
- **an optimum thickness and a maximum screening field!!!**

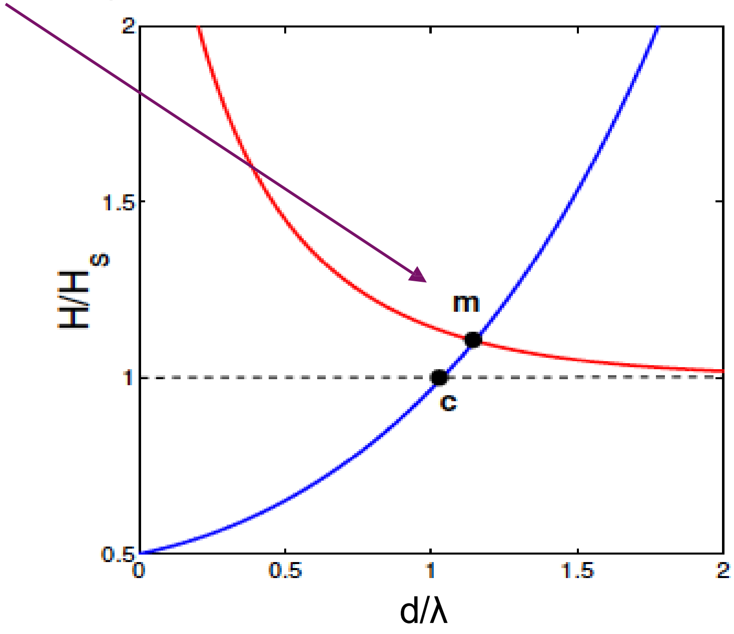


$$\frac{(e^{2d/\lambda} - k)H}{e^{2d/\lambda} + k} \le H_s, \qquad \frac{H(1+k)e^{d/\lambda}}{e^{2d/\lambda} + k} \le H_{s0}$$

$$\boxed{d_m = \lambda \ln(\mu + \sqrt{\mu^2 + k}), \qquad \mu = \frac{H_s\lambda}{(\lambda + \lambda_0)H_{s0}}}$$

$$\boxed{H_m = \left[H_s^2 + \left(1 - \frac{\lambda_0^2}{\lambda^2}\right)H_{s0}^2\right]^{1/2}}$$

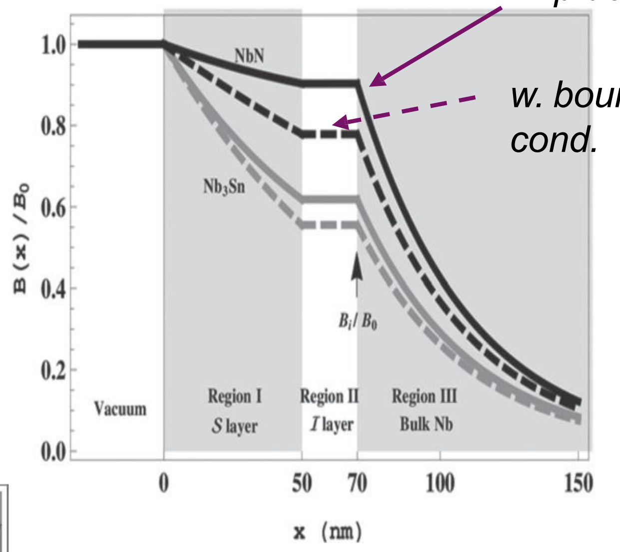
Maximum screening field H_m at the optimum S thickness $d^S = d_m$



SIS OPTIMIZATION: IMPORTANCE OF MODELS

- **First approach: trilayers**
  - Boundary conditions implemented *(including effect of an insulating layer. finite thickness))*
  - H_{SH} determined initially in London approx., further improved w. quasiclassical theory *(valid @$T \ll T_C$)*
  - Initially assume "perfect conditions"
  - *(bulk values, field // to surface)*

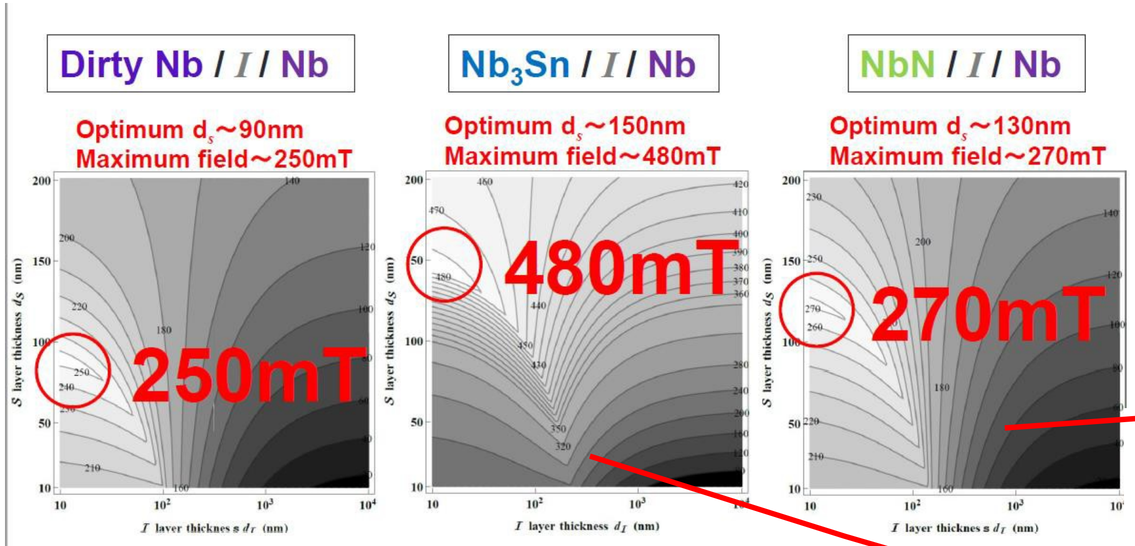
A. Gurevich, T. Kubo



Exp decay

w. boundary cond.

← Quasiclassical Approach, Can be further improved…



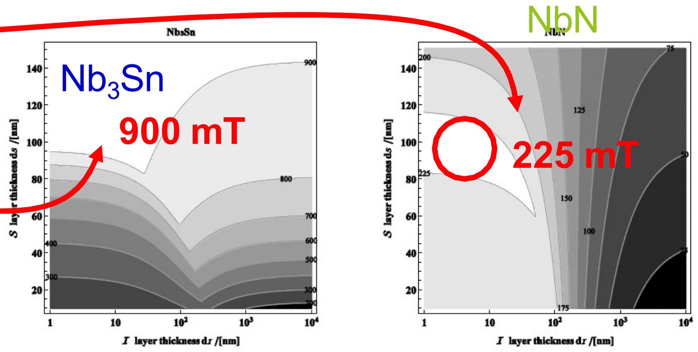
Optimum d_s~90nm
Maximum field~250mT

Optimum d_s~150nm
Maximum field~480mT

Optimum d_s~130nm
Maximum field~270mT

[Kubo 2013-17]

Previous calculation w. London theory only: not realistic →

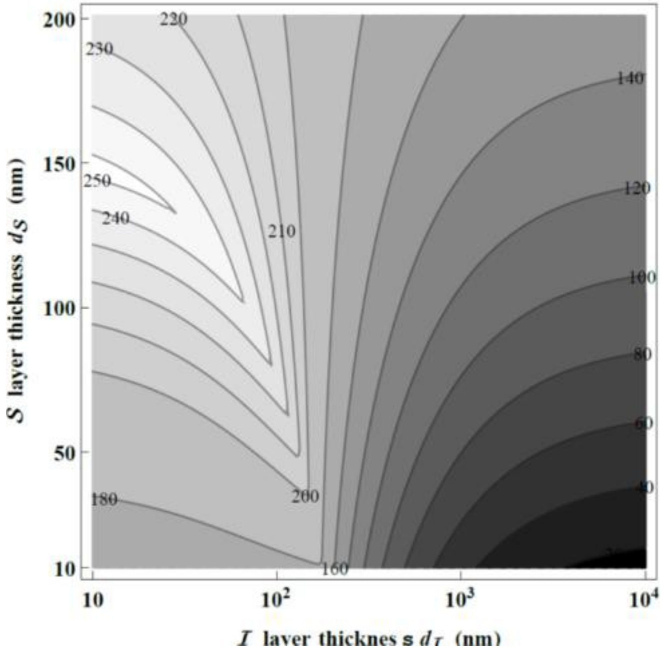


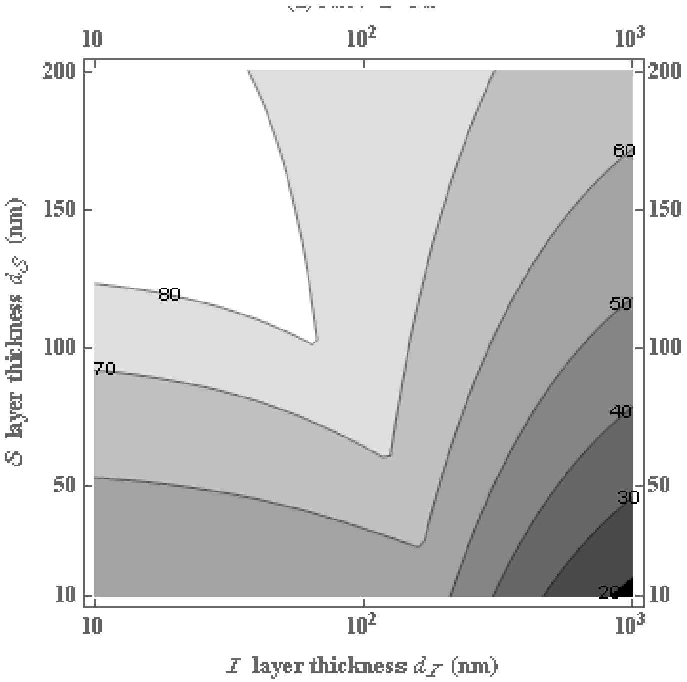
TRILAYER OPTIMIZATION (…)

A. Gurevich, T. Kubo

- **Go for realistic condition**
  - Layers present defects, non-negligible surface roughness, non-uniform thickness.
  - → H_{SH}^{S} suppressed due to of the local screening current enhancement.
  - Introducing material suppression factor η =f(defect size and aspect ratio, ξ^{S})
  - η ~ 0.85 for typical electropolished Nb surface)
  - H_{SH}^{SIS} and optimal S layer thickness dm^{S} can be determined w. surface topographical data

Ideal Nb substrate with B_{C1}=170 mT





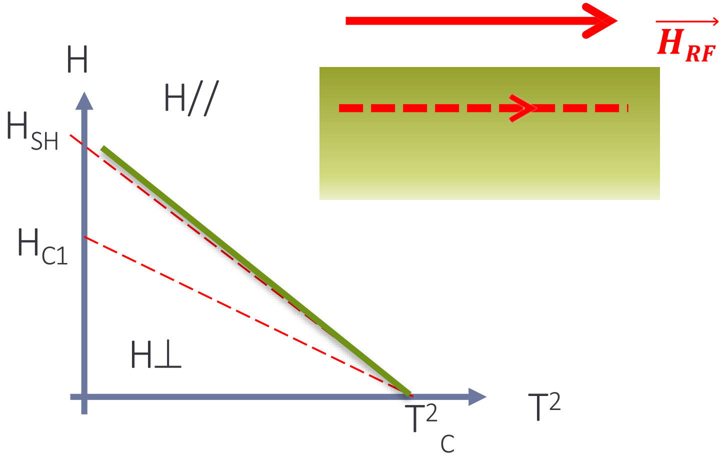
Nb with defects, with B_{C1}=50 mT*

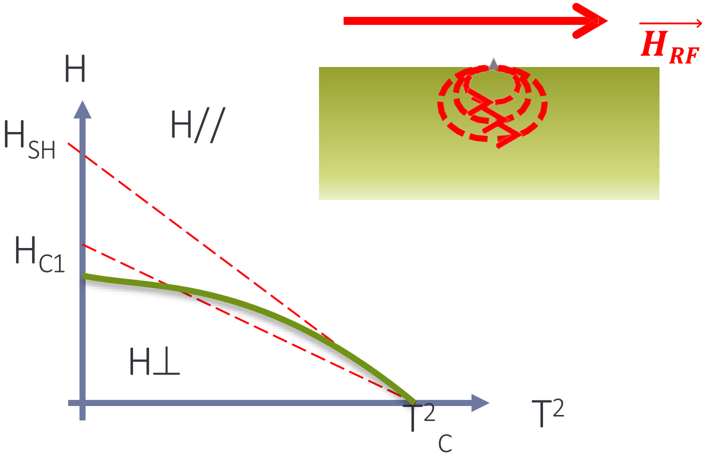
** e.g. morphologic defects that allow earlier vortex penetration*

See exp proof later on

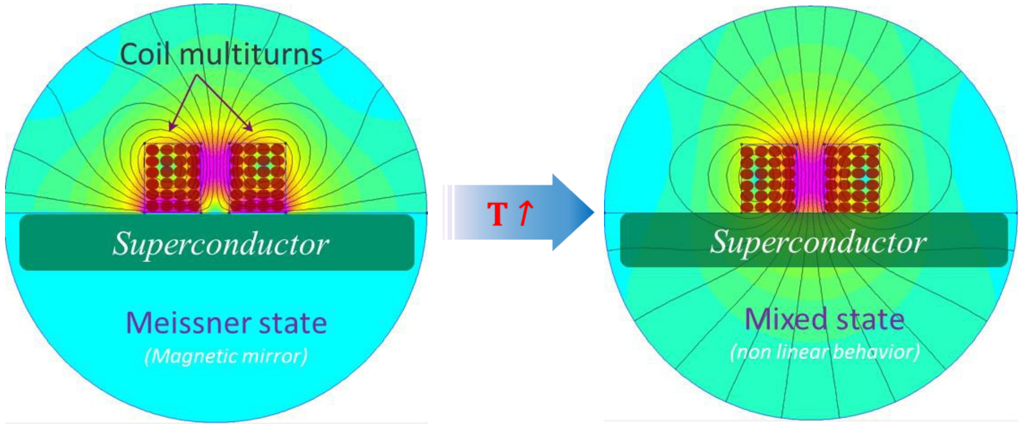
WHAT IS THE LIMIT ($H_{fp}/H_{C1}/H_{SH}$) ?

- Real world cavities behavior is dominated by a few number of defects
- It is very important to measure the penetration field of samples in realistic conditions



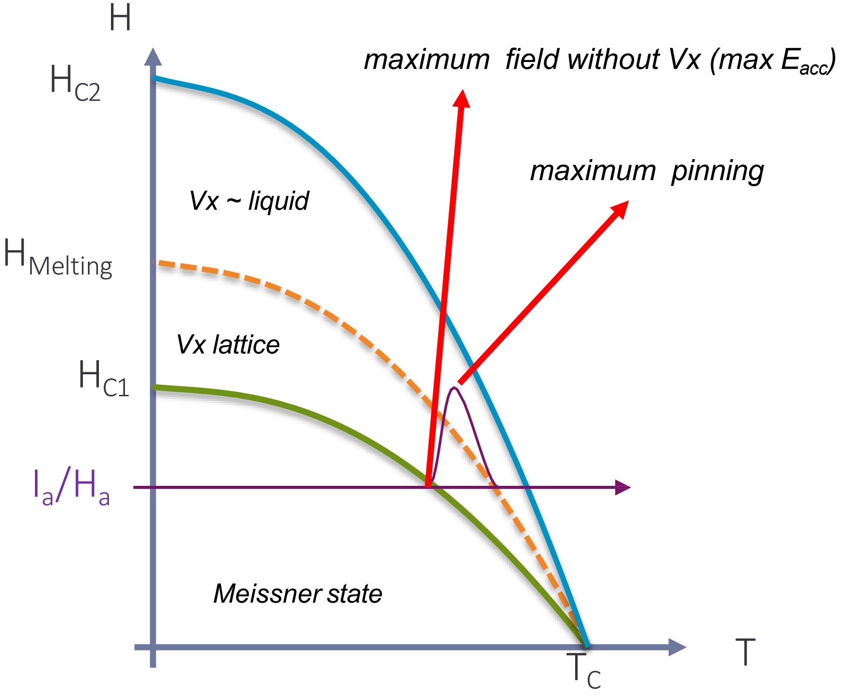


- Local magnetometry
  - ~ Same geometry as cavities
  - No shape/edge effect (vs DC/ Squid magnetometry)
  - No demagnetization effect
  - Measures actual penetration field wherever it is $H_{fp}/H_{C1}/H_{SH}$



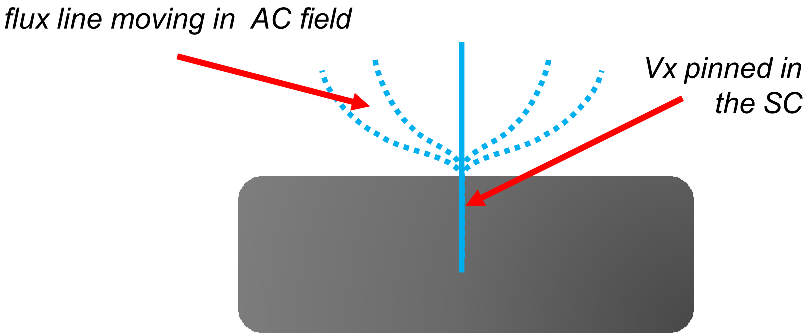
EXPERIMENTAL DETAILS

3^{rd} Harmonic Setup for H_{FP} measurement



Low frequency ≡ DC :

- 0 < H_a< H_{C1} => R=O, Meissner state state
- H_{C1} < H_0 < H_M=>Vx are trapped, R=O, Campbell regime
- H_M< H_a< H_{C2} =>Vx are moving liquid like, R≠O, Flux flow regime
- Third harmonic signal arise from flux line tension (affects the e- inside the Cu coil),
- It does not depend on dissipation inside Nb, BUT depends on #
- of Vx trapped there (and length).



Nb – INSULATOR – NbN MODEL

NbN coating by Magnetron Sputtering

- **NbN single layers series**
  - NbN SL / “thick” Nb layer
    - Magnetron sputtered
    - MgO as dielectric layer
  - Far from perfect…

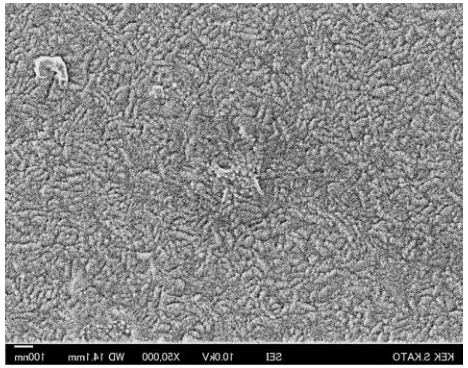
Nb (nm)	MgO (nm) Calc(actual)	NbN (nm) Calc(actual)	T_C (K)
250†	14	0	8.9
250†	14	25	15.5
500	10 (10.3)	50 (65)	15*
500	10 (8.4)	75 (72)	14.1*
500	10 (9.8)	100 (94)	14*
500	10	125	14.3*
500	10 (6.7)	150 (132)	15.9*
500	10 (10.4)	200 (164)	15*

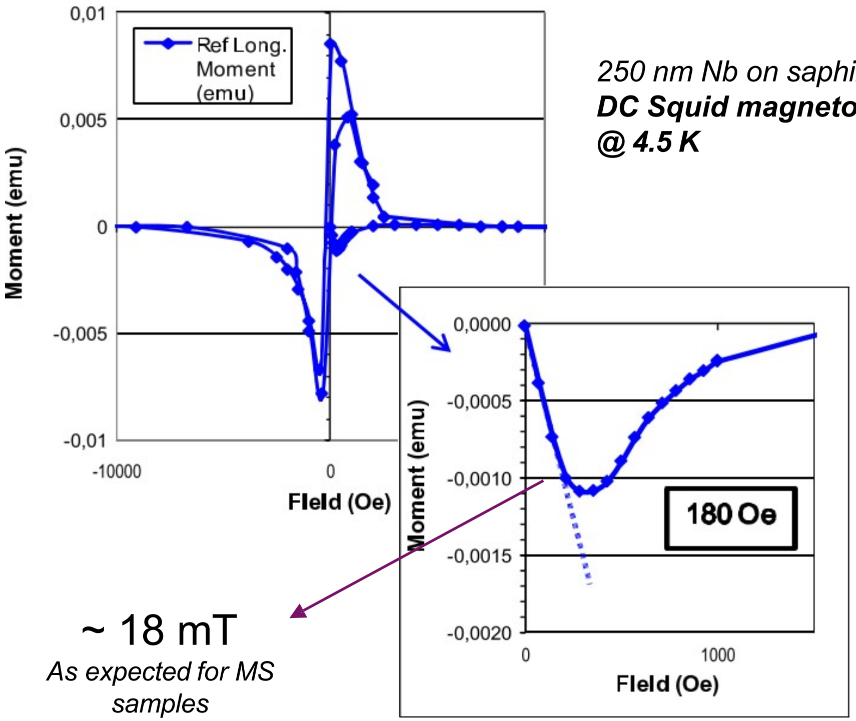
† Not same batch, deposited on the same conditions, but substrate = sapphire
*As determined with magnetometry, see below.

SPUTTERED MATERIALS…

Typical defects…

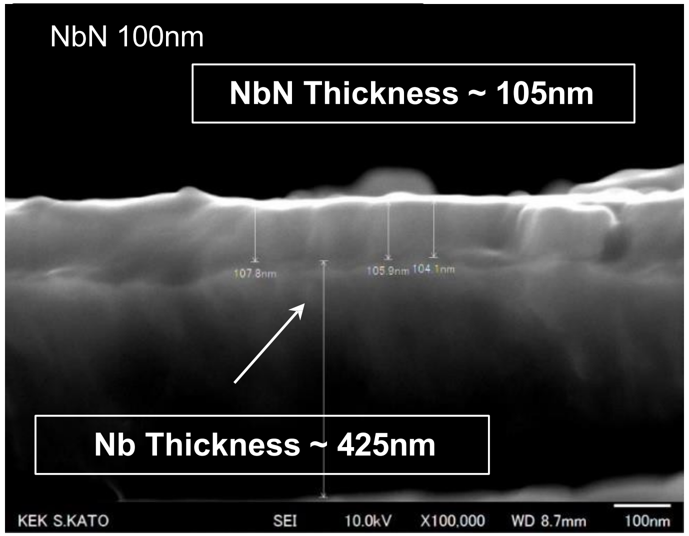
- Low H_{C1}
- Thickness ≠ uniform
- …

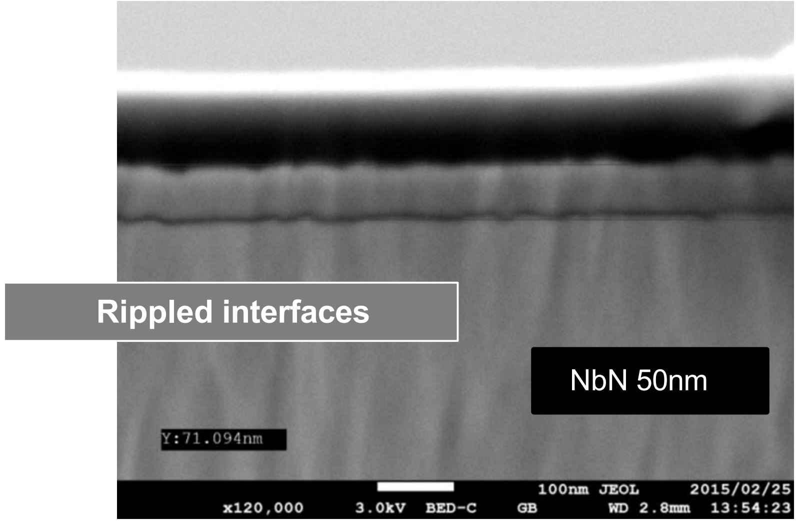




250 nm Nb on saphire
DC Squid magnetometry @ 4.5 K

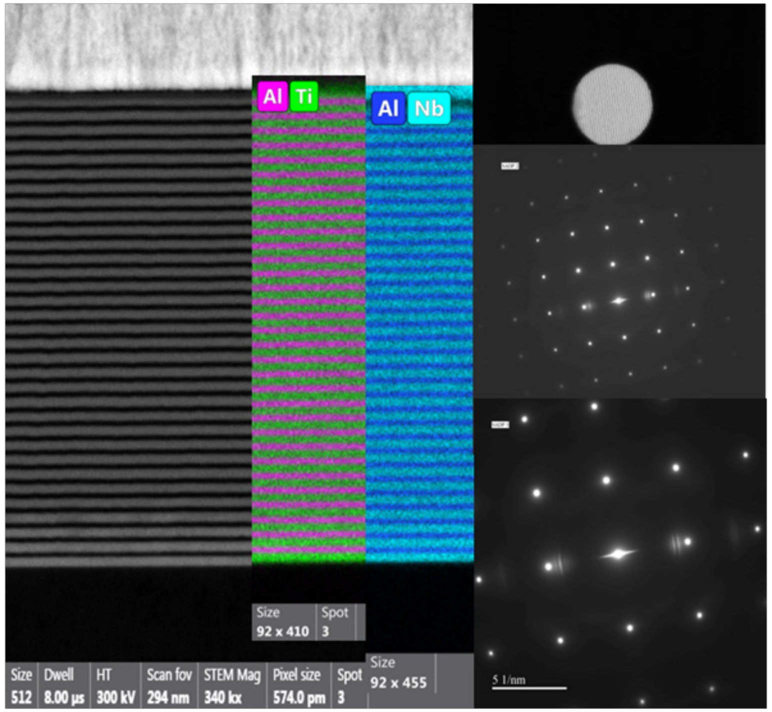
~ 18 mT
As expected for MS samples





BUT with careful methods:

32 x (NbTiN/AlN)/NbTiN/MgO

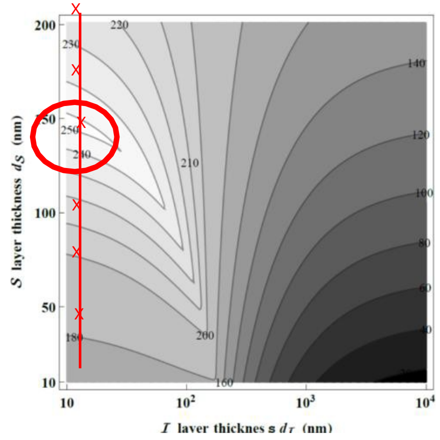


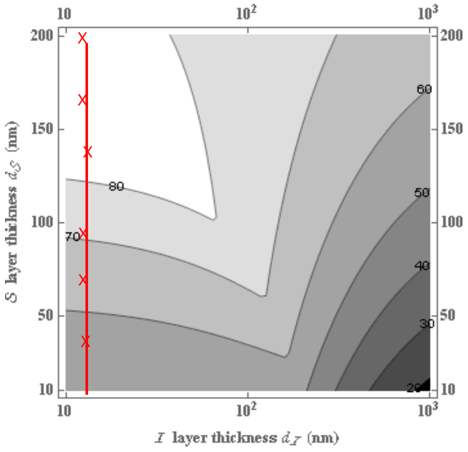
A-M Valente-Feliciano

COMPARISON WITH THEORY

Theoritical predictions from T. Kubo (KEK)

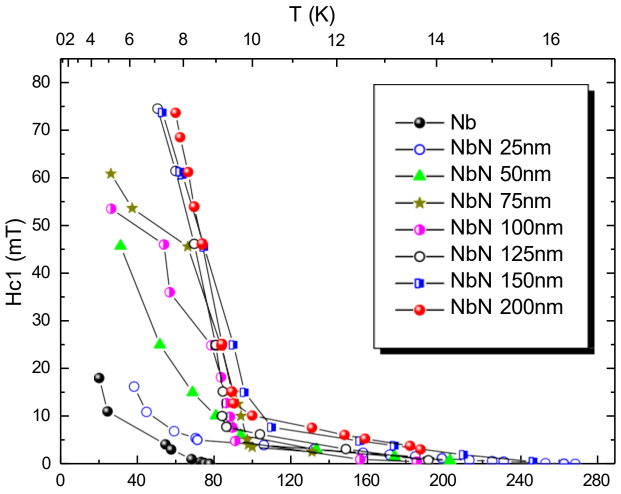
Ideal Nb substrate with B_{C1}=170 mT





Nb with defects, with B_{C1}=50 mT*

** e.g. morphologic defects that allow earlier vortex penetration See SST paper cited earlier*

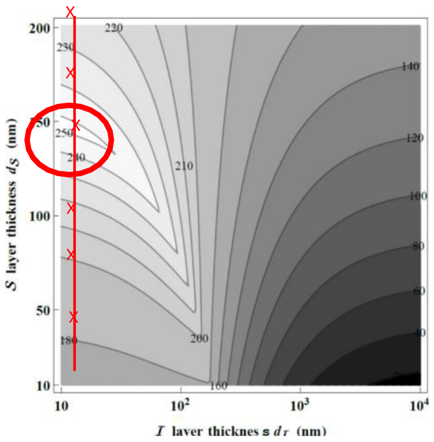


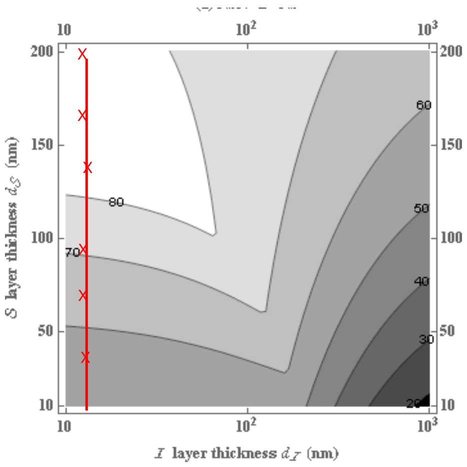
- ❑ The enhancement of the field penetration increases with thickness of NbN
- ❑ It reaches a saturation at thicknesses > 100 nm

COMPARISON WITH THEORY

Theoritical predictions from T. Kubo (KEK)

Ideal Nb substrate with B_{C1}=170 mT





Nb with defects, with B_{C1}=50 mT*

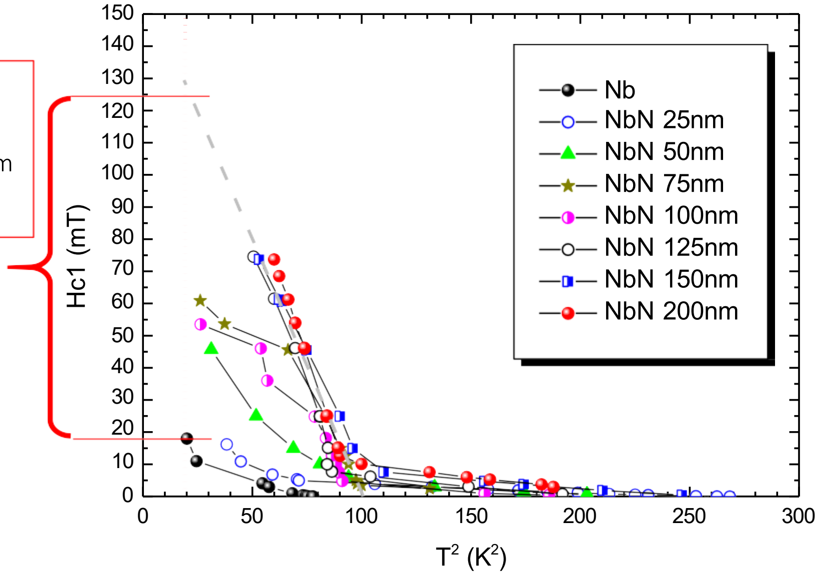
** e.g. morphologic defects that allow earlier vortex penetration See SST paper cited earlier*

@ 4.5 K

~ + 110 mT?

~25-30 MV/m

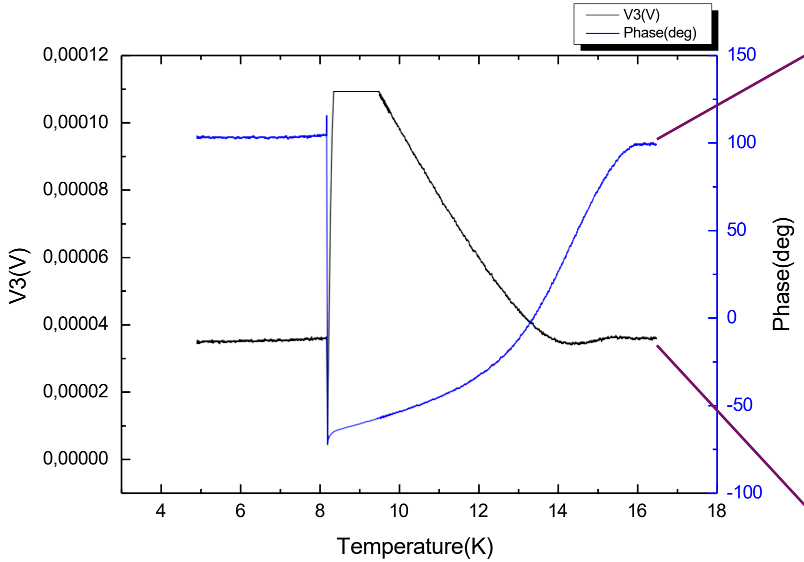
ILC shape

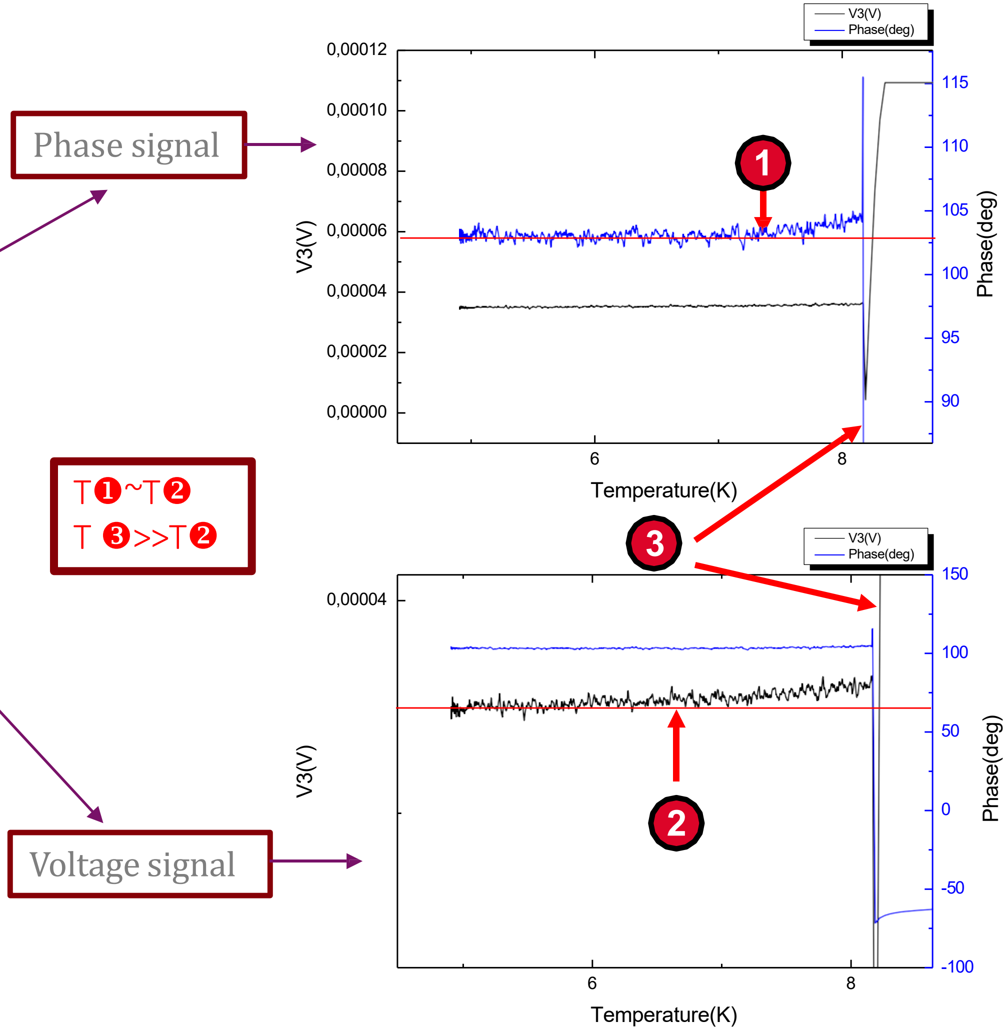


- ❑ The enhancement of the field penetration increases with thickness of NbN
- ❑ It reaches a saturation at thicknesses > 100 nm

CLOSEUP OF 3rd HARMONIC SIGNAL

- For a given H_{appl}, we observe 3 ≠ transition temperatures

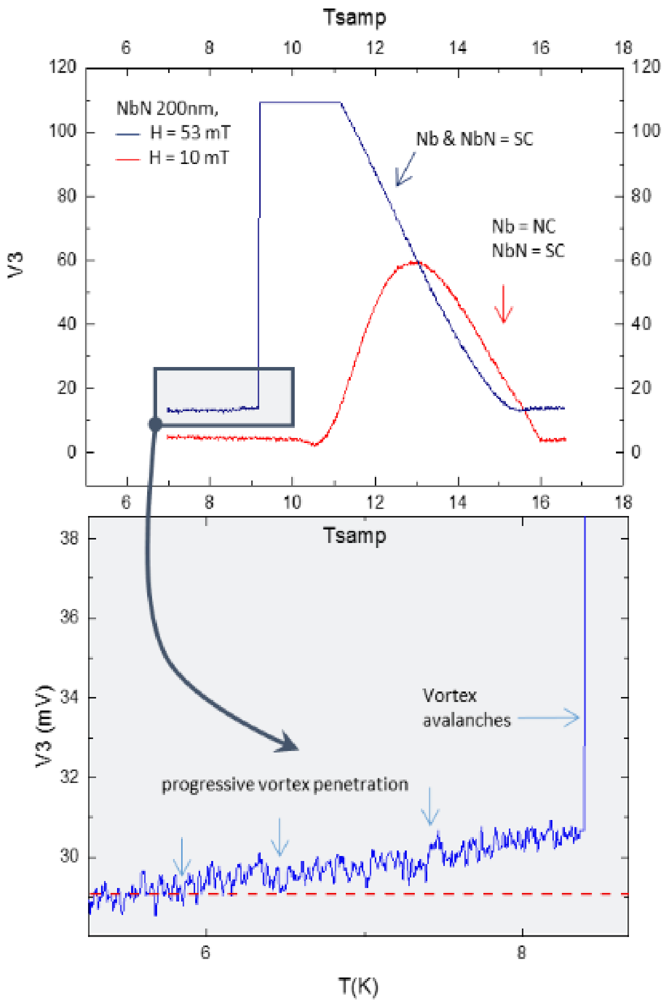


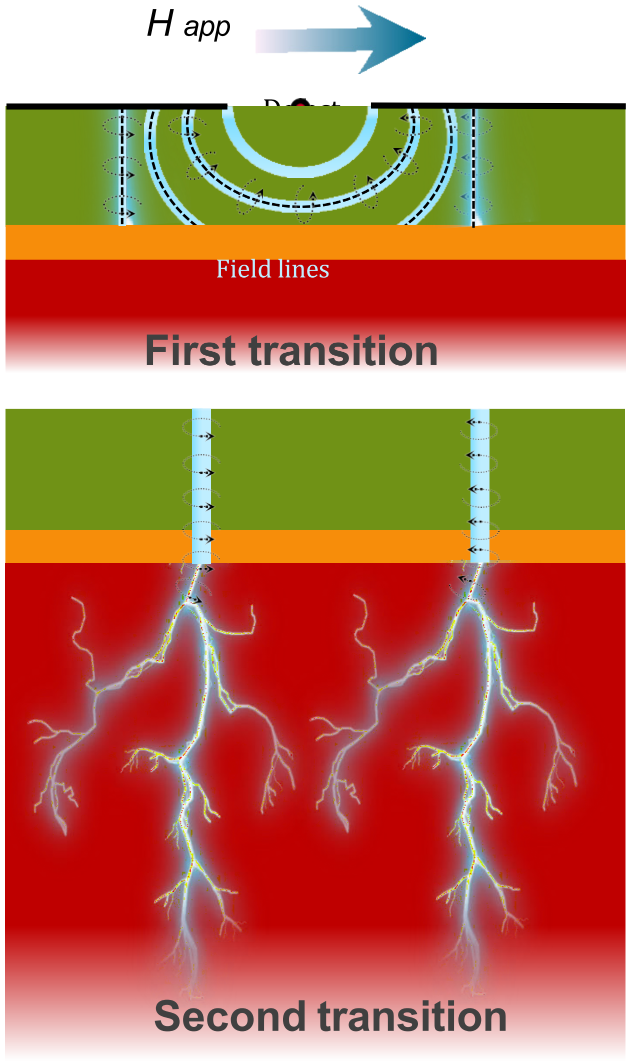


- T❶~T❷: within noise level
- T ❸>>T❷: dramatic transition

ROLE OF THE DIELECTRIC LAYER !

- Why do we have two transitions ?





● Thin SC layer NbN
● Insulator MgO
● Thick SC layer Nb

H // surface => surface barrier[†]

A defect locally weakens the surface barrier

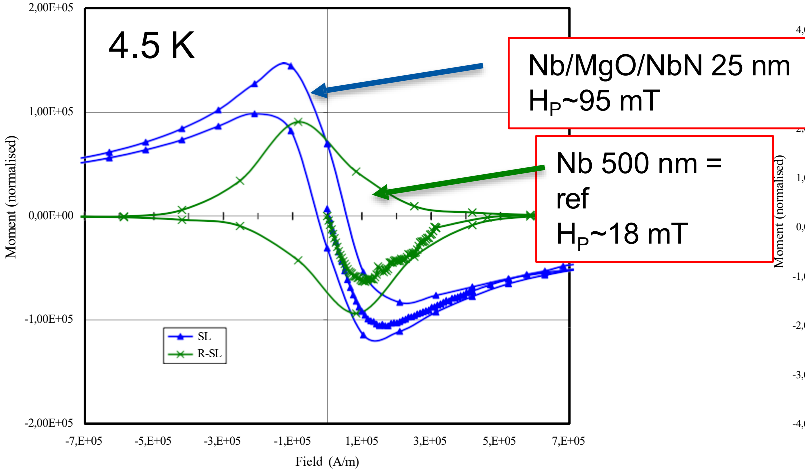
1st transition, vortex blocked by the insulator ~100 nm => low dissipation.

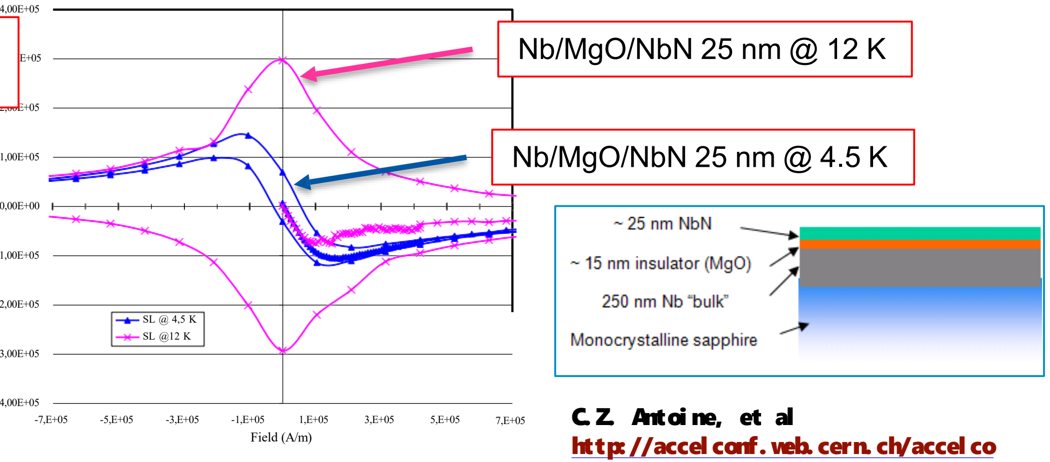
2nd transition, propagation of vortex avalanches (~100 µm) => high dissipation.

Dielectric layer = efficient protection !!!

[†] *B. Bean and J. D. Livingston, Phys. Rev. Lett. 12, 14 (1964).*

SIS : IRREVERSIBILITY => NO VORTEX PINNING <= NO VX ENTRY ?

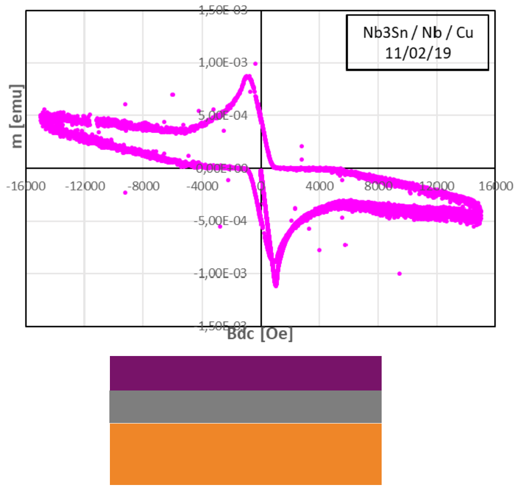


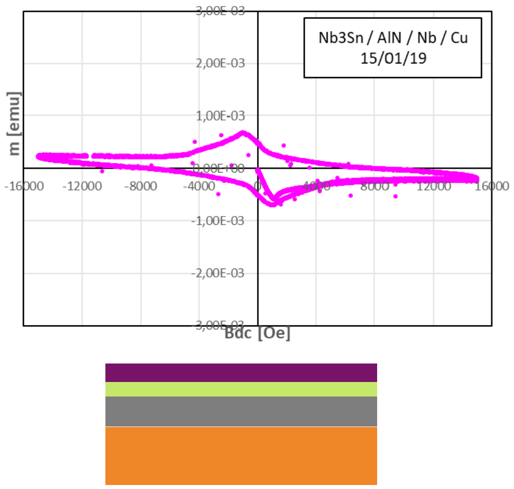


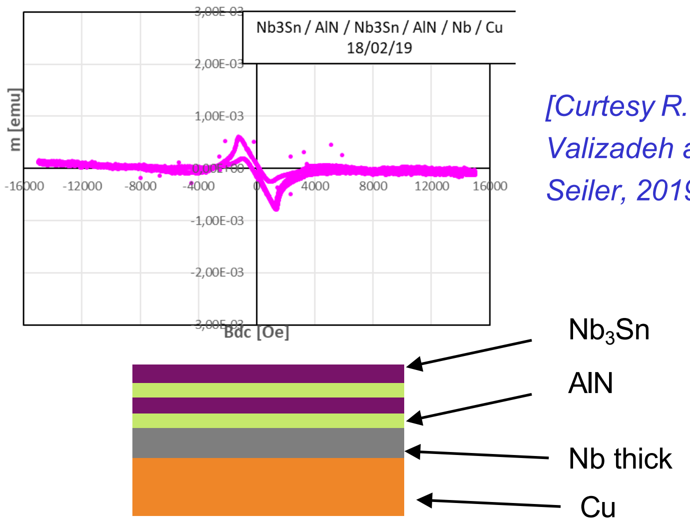
H // sample plane; longitudinal moment

C.Z. Antoine, et al
http://accelconf.web.cern.ch/accelconf/SRF2009/papers/tuppo070.pdf

Each individual layer : ∃ defects, but combination: seems protected







[Curtesy R. Valizadeh and E. Seiler, 2019]

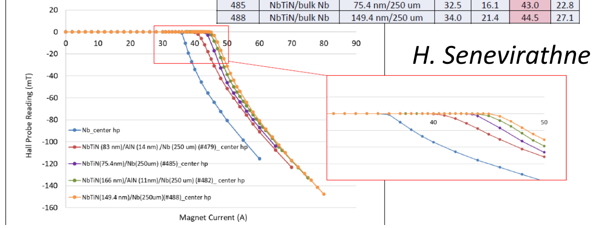
SIS : an intrinsically safe structure ?

SIS Multilayered Structures based on NbTiN

Measurement on NbTiN SIS structures on 1” & 2” Nb substrates

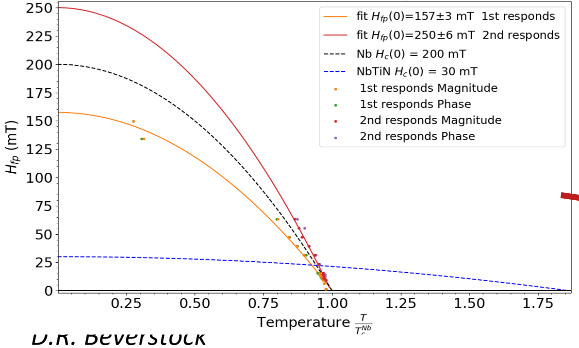
Center Probe at 2.00 K

Sample #	Sample	Thickness	Current at first full penetration (A)			
			At the center			
			4.35 K	%	2.00 K	%
3	Nb	250 um	28.0	-	35.0	-
479	NbTiN/AlN/bulk Nb	83nm/14 nm/250 um	30.0	7.1	39.5	12.8
482	NbTiN/AlN/bulk Nb	166 nm/11 nm/250 um	33.5	19.6	43.5	24.3
485	NbTiN/bulk Nb	75.4 nm/250 um	32.5	16.1	43.0	22.8
488	NbTiN/bulk Nb	149.4 nm/250 um	34.0	21.4	44.5	27.1



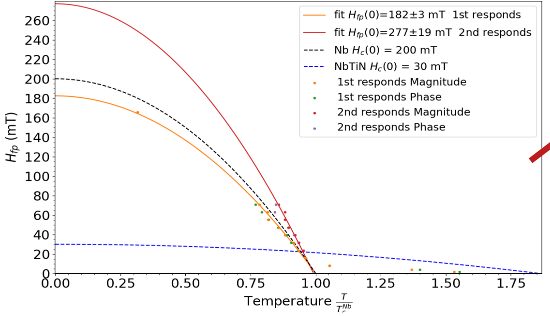
H. Senevirathne

Reactive DCMS NbTiN (80±5nm) with AlN (23.6±2nm) on MP + EP Nb
Fitted with $H_{fp}(T) = H_{fp}(0)\left(1 - \left(\frac{T}{T_c}\right)^2\right)$

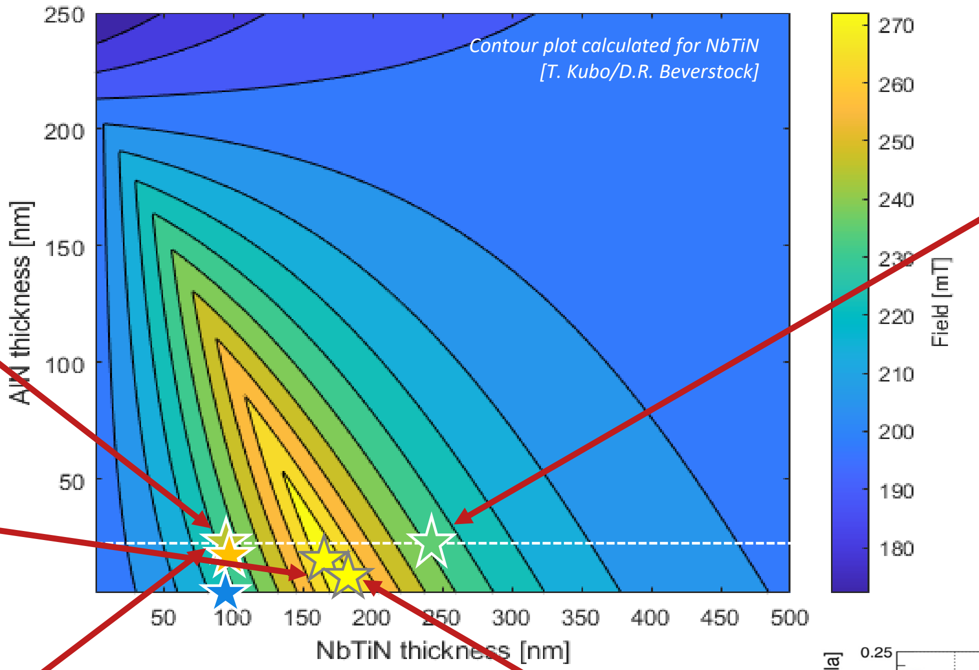


D.R. Beverstock

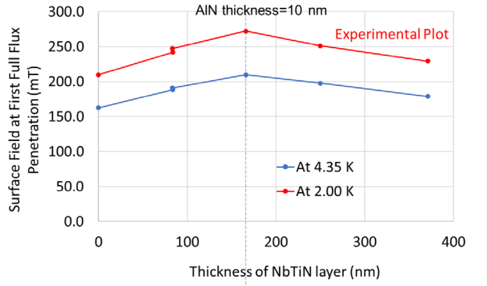
Reactive DCMS NbTiN 183 nm with AlN 10.6 nm on MP+EP Nb
Fitted with $H_{fp}(T) = H_{fp}(0)\left(1 - \left(\frac{T}{T_c}\right)^2\right)$



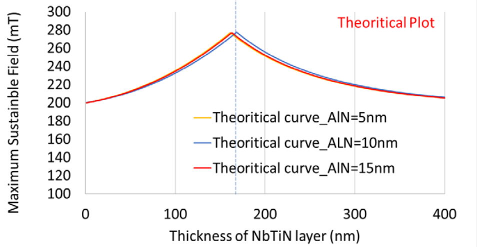
Penetration depth = 240 nm, Coherence length=3.5 nm

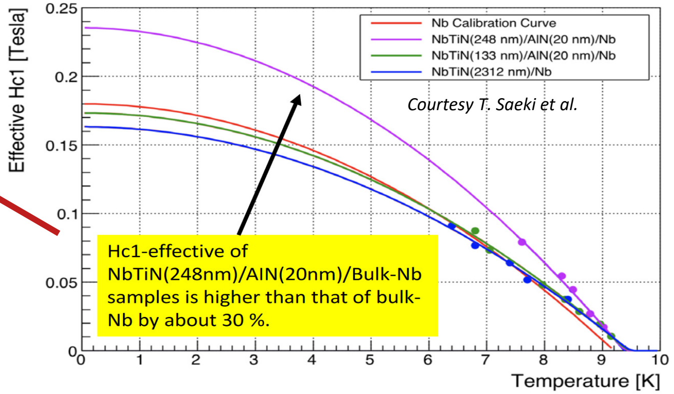


Contour plot calculated for NbTiN [T. Kubo/D.R. Beverstock]



Penetration depth=240 nm, Coherence Length=3.5
AlN thickness=10 nm





Courtesy T. Saeki et al.

Hc1-effective of NbTiN(248nm)/AlN(20nm)/Bulk-Nb samples is higher than that of bulk-Nb by about 30 %.

- ☐ *Deposited SIS structures fit the theoretical model*
- ☐ *3rd harmonic measurements show field enhancement up to 20-60% compared to base bulk Nb .*
- ☐ *Effect most sensitive to coherence length ξ*

KEK
OLD DOMINION UNIVERSITY
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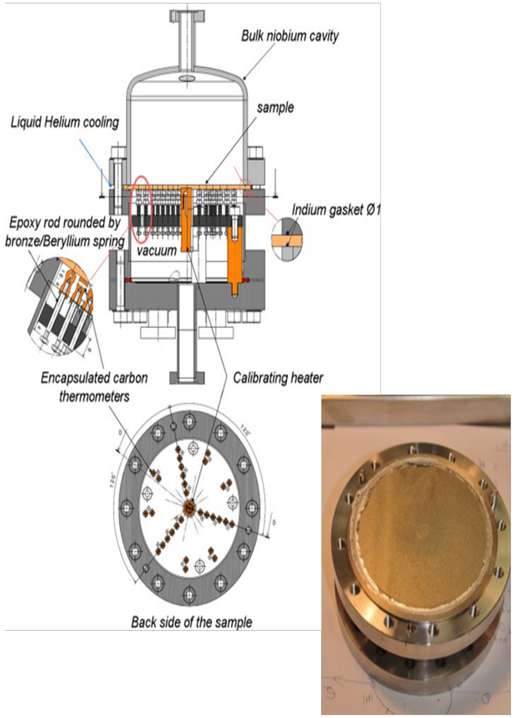
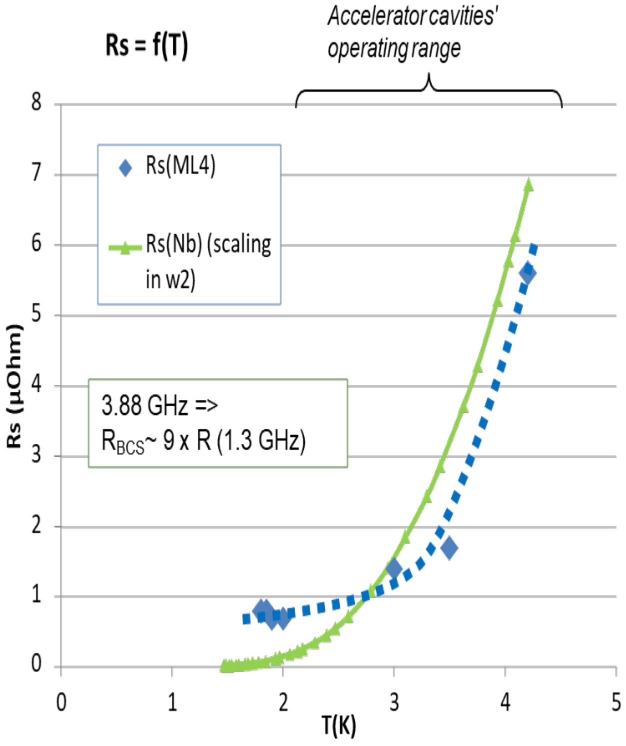
SRF 2023 GRAND RAPIDS

Jefferson Lab

1st RF TESTS

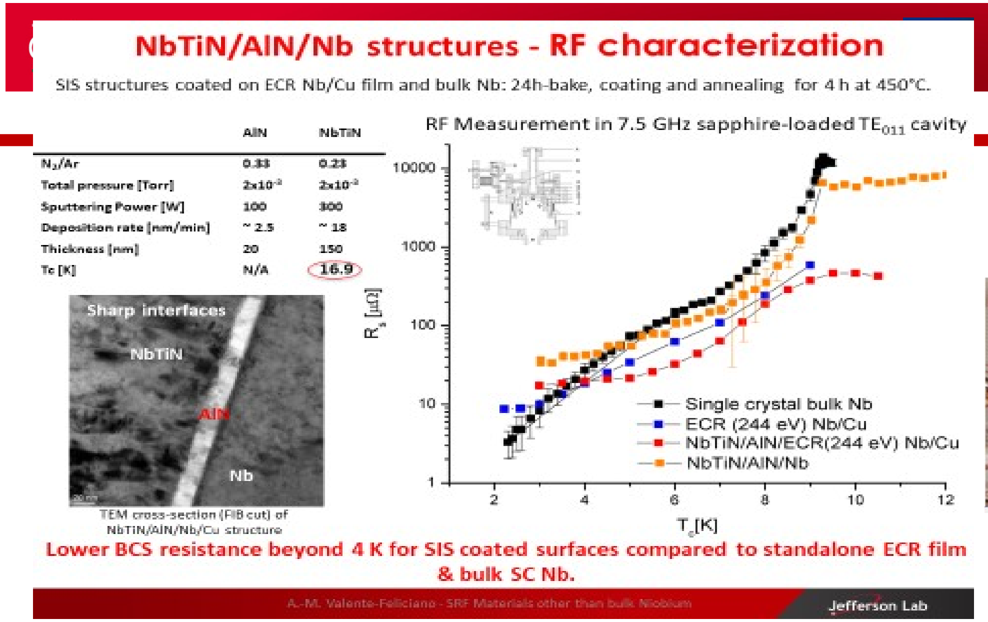
1st TEST RF @ 3.88 GHZ (4x 25nm NbN LAYERS)





3.88 GHz => R_{BCS}~ 9 x R (1.3 GHz)

- Comparison is done with a high performance 1.3 GHz Nb cavity (scaling in ω^2)
- Indium gasket presents some defects measured with thermometric map => extra RF losses
- Residual resistance comes from NbN + bulk Nb substrate + indium gasket. Further investigations needed.



NbTiN/AlN/Nb structures - RF characterization

SIS structures coated on ECR Nb/Cu film and bulk Nb: 24h-bake, coating and annealing for 4 h at 450°C.

	AlN	NbTiN
N_2/Ar	0.33	0.23
Total pressure [Torr]	2×10^{-3}	2×10^{-3}
Sputtering Power [W]	100	300
Deposition rate [nm/min]	~ 2.5	~ 18
Thickness [nm]	20	150
Tc [K]	N/A	16.9

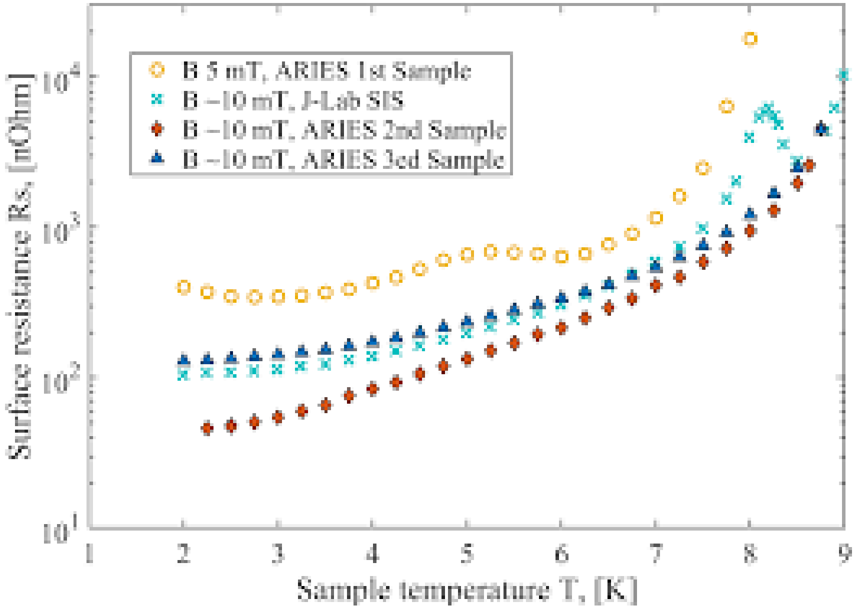
TEM cross-section (FIB cut) of NbTiN/AlN/Nb/Cu structure

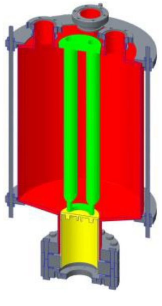
RF Measurement in 7.5 GHz sapphire-loaded TE_{011} cavity

Lower BCS resistance beyond 4 K for SIS coated surfaces compared to standalone ECR film & bulk SC Nb.

A.-M. Valente-Feliciano - SRF Materials other than bulk Niobium

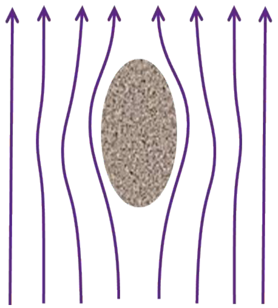
Jefferson Lab



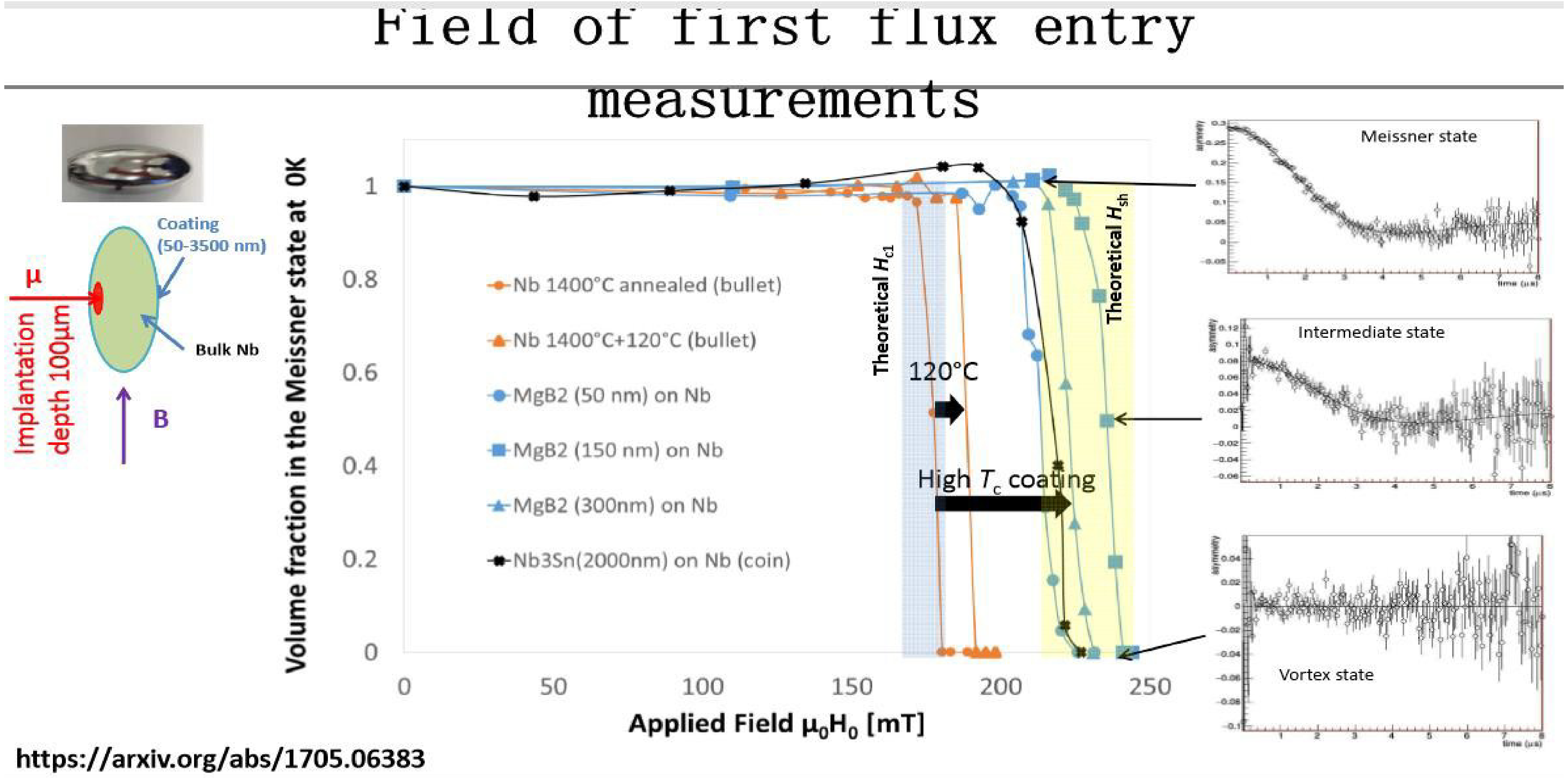


ML WITHOUT DIELECTRIC INTERLAYER

μ-SR



[Junginger, SRF 2017]



Field of first flux entry measurements

https://arxiv.org/abs/1705.06383

The SS boundary provides an additional barrier to prevent penetration of vortices. It would not be as robust as the I layer of the SIS structure, but it also contributes to pushing up the onset of vortex penetration.

[Kubo, SST]

Wrapping Up…

WHAT IS A GOOD THIN FILM SUPERCONDUCTOR ?

- ☐ **A compromise between:**
  - ❖ High superconducting/RF performance (High Tc, High superheating field)
  - ❖ Easy fabrication process,
    - ≡ high reproducibility at “industrial scale”
    - Easy process to go from 1-cell to multi-cells or complex shapes
    - Easy process to adapt to various frequencies
  - ❖ Tunability
    - Beware of brittle materials !
  - ❖ Low sensitivity to trapped flux upon cooling down
    - Few crystalline defects or a structure not too sensitive to them (e.g. SIS)
- ☐ **Thin films on copper = route to help cost savings**
  - ❖ Cheaper manufacturing
  - ❖ Higher operation temperature
  - ❖ Higher gradients : lower capital costs

COST SAVINGS beyond bulk Nb : Construction & Operations

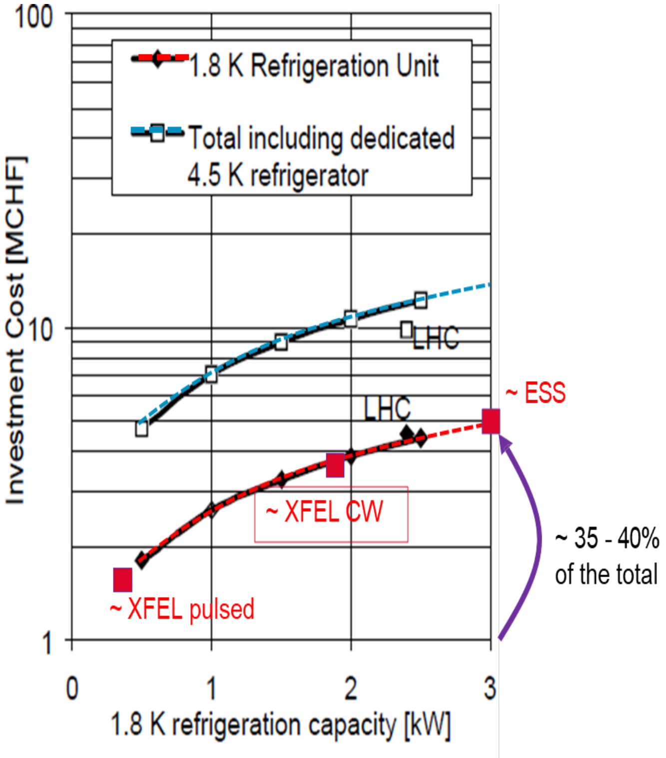
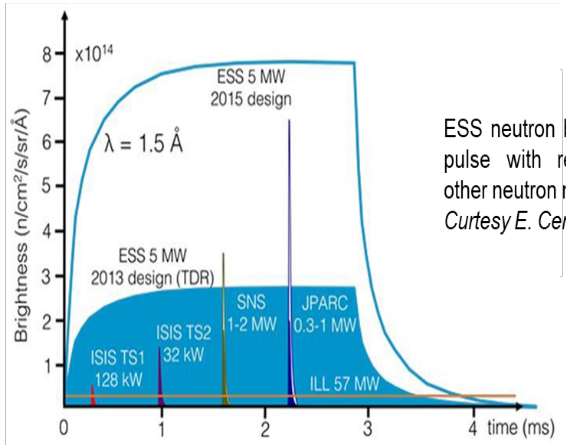


Figure 9. Investment cost of 1.8 K refrigeration

Curtesy P. Lebrun

Courtesy C. Antoine, IPAC 2023

- **LHC project report 317** (S. Claudet, Ph. Gayet, Ph. Lebrun, L. Tavian and U. Wagner, "Economics of large helium cryogenic systems: experience from recent projects at CERN")
- **4.5 K instead of 2 K: investment decreased by~35-40 % !!!**
  - e.g. ESS cryogenic total cost ~40 M€
  - ~ 15 M€ savings ?



ESS neutron brightness pulse with respect to other neutron machines
Curtesy E. Cenni

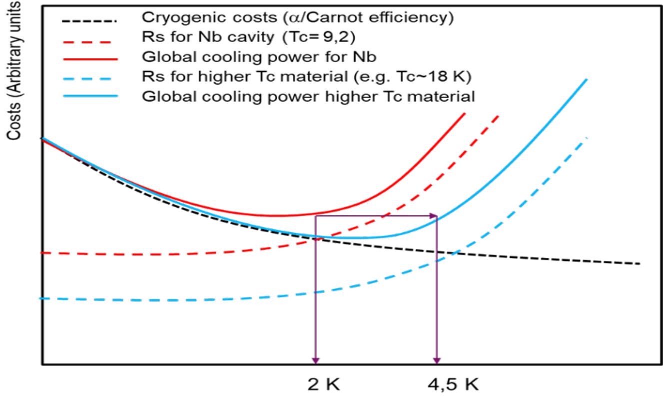
- **Carnot efficiency η_C** *(thermodynamics)*
- **Refrigerator efficiency η_{Th}** *(real life compared to physics)*

$$\eta_c = \frac{T_c}{T_h - T_c} \approx \begin{cases} 1/70 \text{ for } T_h = 300\text{ K}, T_c = 4.2\text{K} \\ 1/150 \text{ for } T_h = 300\text{ K}, T_c = 2\text{K} \end{cases}$$

$$\eta_{th} = \begin{cases} 25 - 30\% \text{ at } T = 4.2\text{K} \\ 15 - 20\% \text{ at } T = 2\text{K} \end{cases}$$

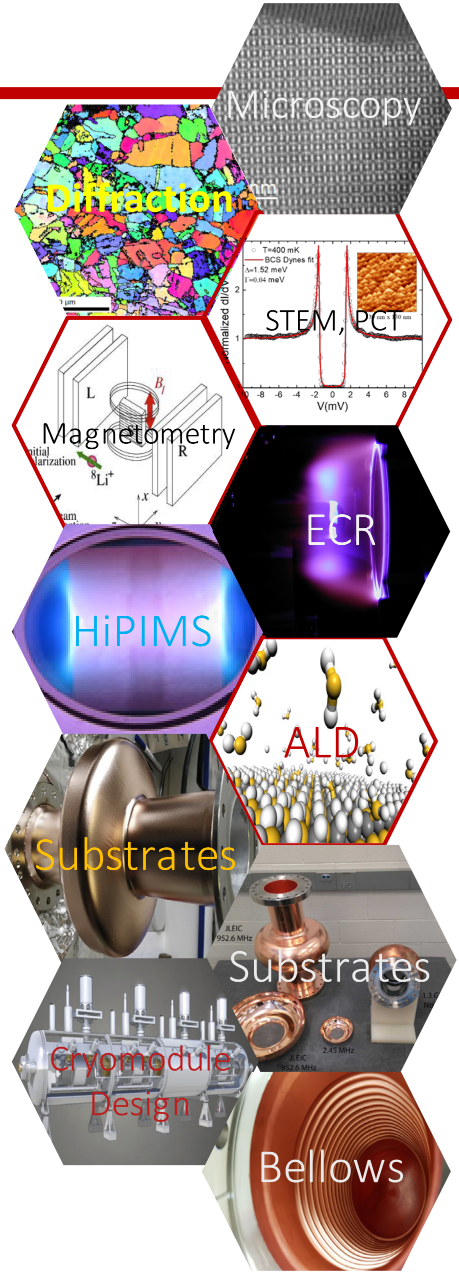
  - To remove 1W @ 80K: **~20W** @ 300K is needed
  - To remove 1W @ 4.2K: **~250W** @ 300K is needed
  - To remove 1W @ 2K: **~750W** @ 300K is needed
- **RF surface resistance**

$$R_S = R_0 + \frac{A\omega^2}{T} e^{-BTc/T}$$



- **Higher Tc materials:**
  - Same cooling power @ 4.5 K instead of 2K
  - Or: lower cooling power at 2 K
- **4.5 K instead of 2 K: plug power divided /3 !!!**
  - Less risks of He pollution
  - Easier maintenance…

Path Forward



- **Theoretical and material studies** to gain in-depth understanding of the fundamental limitations of thin film superconductors under radio-frequency fields
- **Advanced coating technology** for Nb/Cu and alternative materials, Nb_3Sn, V_3Si, NbTiN …
  - Energetic condensation (electron cyclotron resonance (ECR), HiPIMS, kick positive pulse…)
  - Atomic Layer Deposition (ALD)
  - Hybrid deposition techniques
- **Cavity deposition techniques for development of superconductor-insulator-superconductor (SIS) nanometric layers** to further enhance the performance of bulk Nb and Nb/Cu
- **Improved cavity fabrication & preparation techniques**
  - electroforming, spinning, hydroforming, electro-hydro forming, 3D additive manufacturing
  - environmentally friendly electropolishing, diamond cutting, nano-polishing, plasma etching …)
- **Cryomodule design** optimization
- Improvement of **accelerator ancillaries** with advanced deposition techniques
  - HiPIMS Cu coated bellows, power couplers…

TAKE HOME MESSAGE

- Superconducting cavities are dominated by their surface quality (Niobium AND other SC !)
- Niobium is close to its ultimate limits, but can be surface engineered (doping)
- H_{SH} difficult to reach in real “accelerator cavities” (low T, large scale cavity fabrication, surface defects,…)
- Renewed activity on bulk-like Nb films (cost issues) and high H_{SH} SC e.g. Nb_3Sn or NbTiN (higher performances)
- SIS structures seem to be a promising way to go toward realistic complex materials (+ Nb cavity upgrade)
- Look for higher Q_0, not only E_{acc} !
- **A TECHNOLOGICAL REVOLUTION FOR SRF CAVITIES IS WITHIN REACH!**

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- Aknowledgement

Inspiration and material from earlier lectures from:

Prof. V. Palmieri, INFN, Dr. C. Antoine, CEA Saclay; Prof. A. Gurevich, ODU; …

- Next TFSRF Workshop (11th)

September 2024

In PARIS Area, France

Acknowledgement

Jefferson Lab

Old Dominion University

College of William & Mary 1693

University of Maryland 1856

Fermilab

North Carolina State University

Cornell University Founded A.D. 1865

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INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

AMES NATIONAL LABORATORY

PAUL SCHERRER INSTITUT PSI

TECHNISCHE UNIVERSITÄT DARMSTADT

Chinese Academy of Sciences

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

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