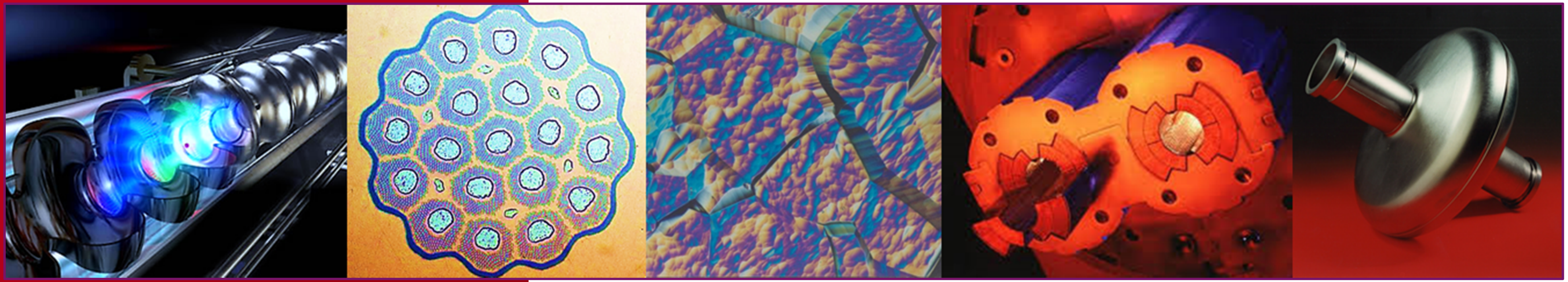
DE LA RECHERCHE À L'INDUSTRIE

MATERIALS FOR SUPERCONDUCTING ACCELERATORS: BEYOND BULK Nb



SRF 2019 Tutorials

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+ some material gathered by A.M. Valante-Feliciano

université PARIS-SACLAY

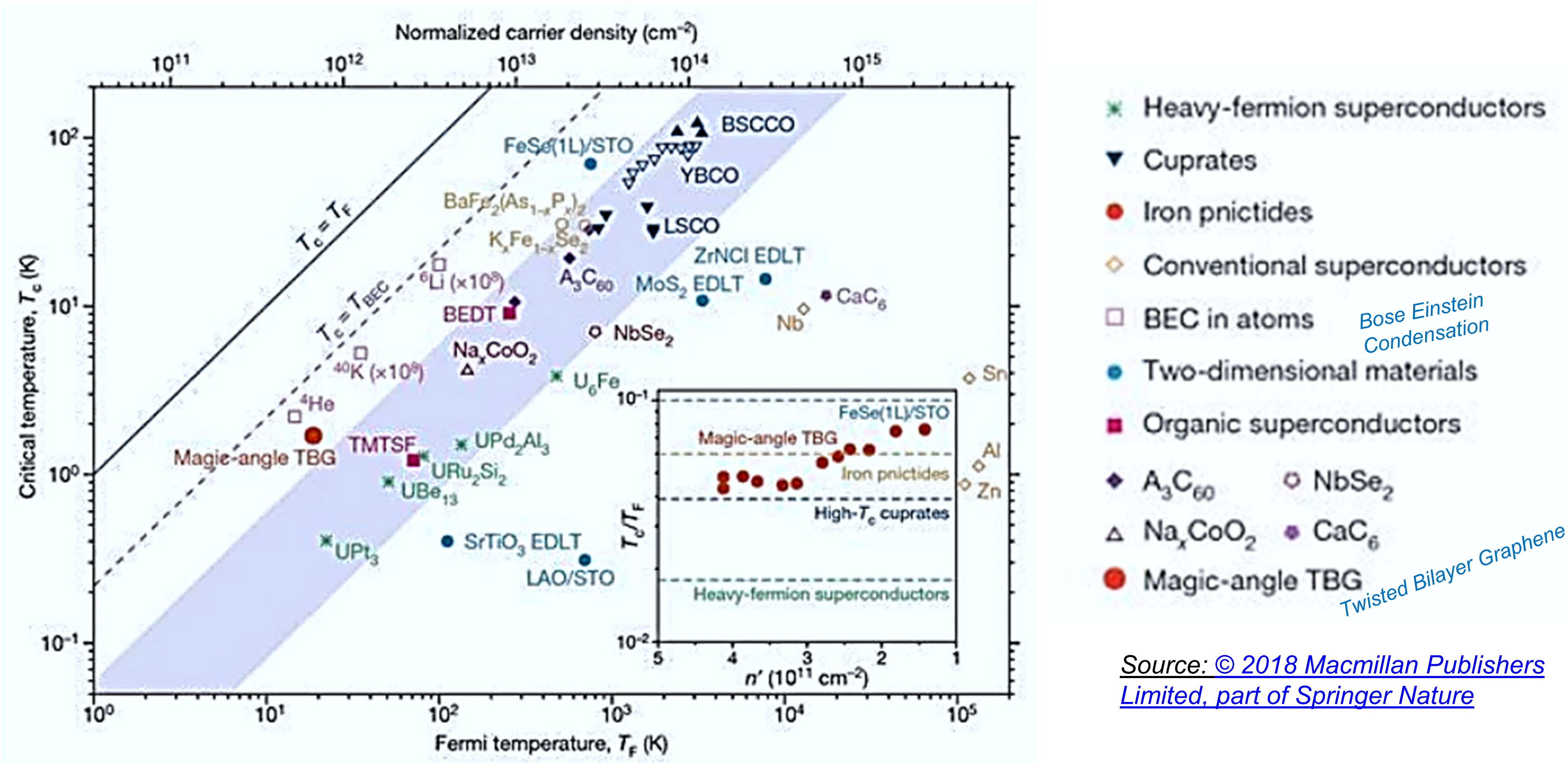
www.cea.fr

Irfu

CHOICE CRITERIA ?

THOUSANDS OF SUPERCONDUCTORS …

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



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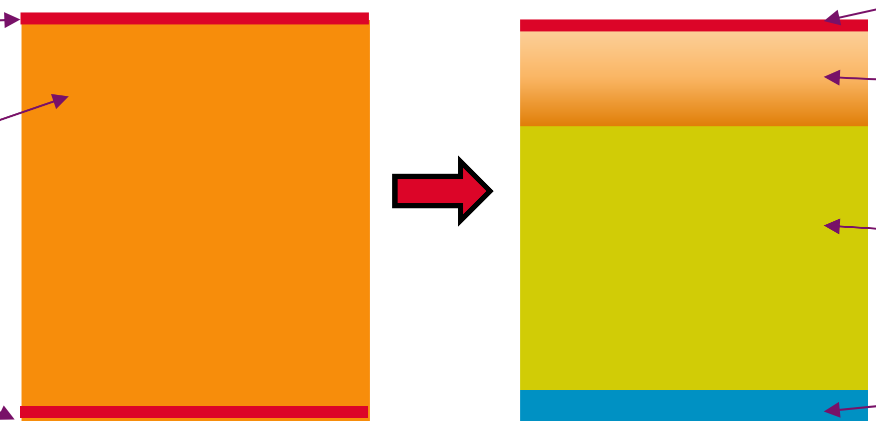
High RRR not required for superconductivity but for thermal stabilization in case of defects

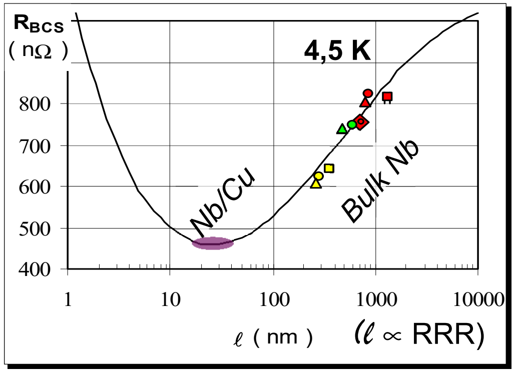


- **"RF" layer optimized for superconductivity:**
  - Low surface resistance (medium m.f.p.)

and/or*

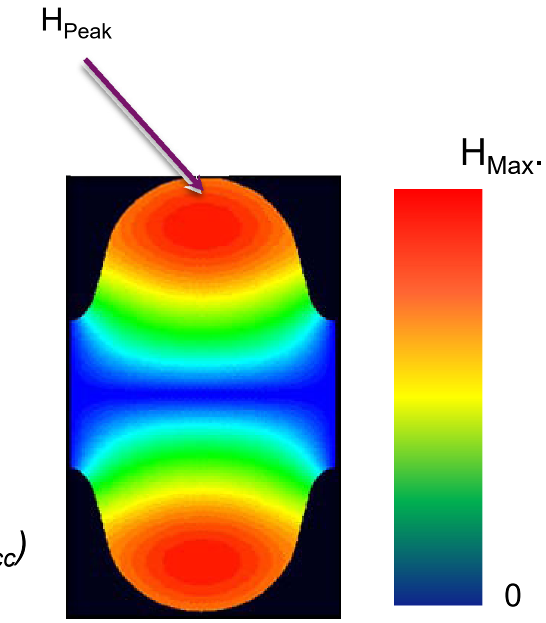
  - High H_P (high H_{C1} or high H_{SH})

**Depends on the application*



Niobium superconducting radiofrequency cavities

- **Performances**
  - $E_{acc} \propto H_{RF}$
  - Q_0 ($\propto$ $1/R_S$) $\propto T_C$ => **Nb_3Sn, MgB_2, NbN…** *(but not YBCO)*
  - Limit = magnetic transition of the SC material @ H_{peak}
- **Superconductivity only needed inside :**
  - Thickness ~10 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)

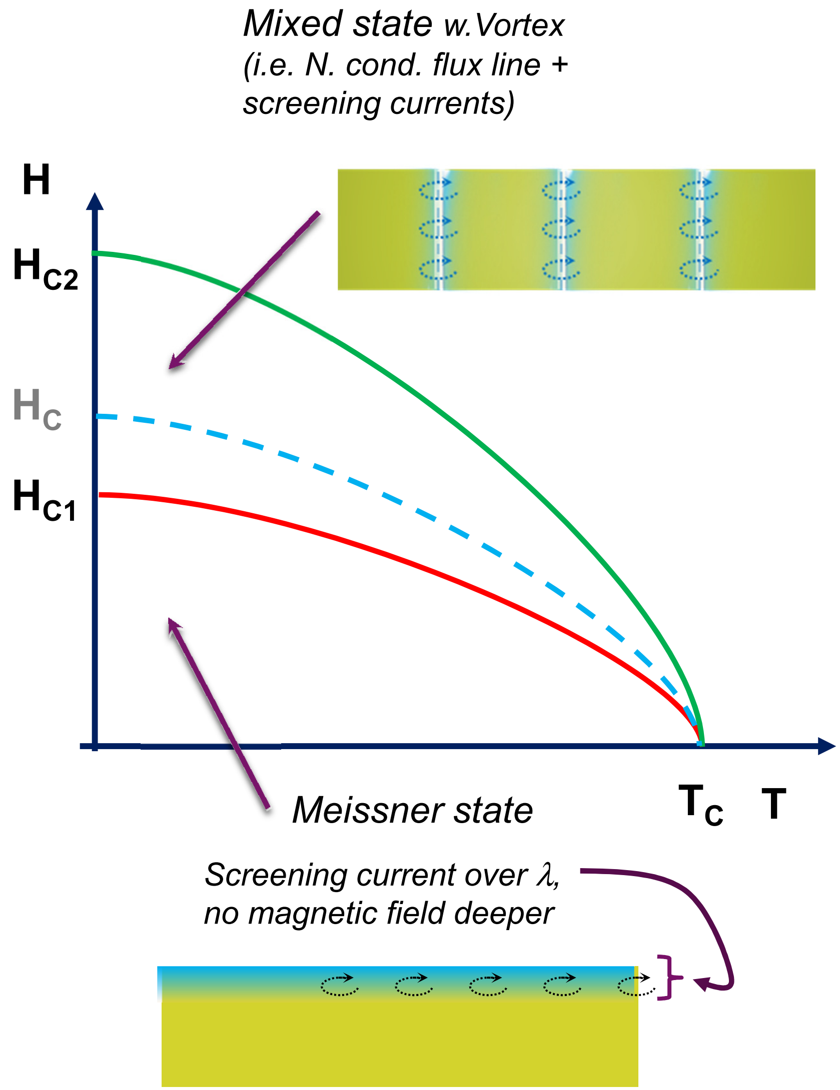
Or

- H_{SH} "Superheating field": Metastable state favored by H // to surface
  - Difficult to get in real life !

Surface resistance:

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

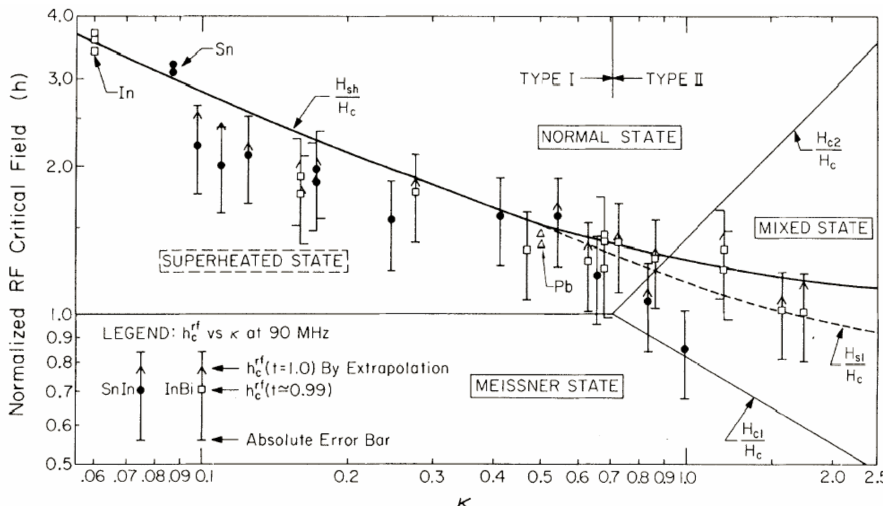
- High Tc is better
- $T \ll T_C$ is better ($e^{-\Delta/kT}$)
- Metallic character in NC state is better (ρ_n)
- Dirty is better than high RRR (ℓ) ? *(e,g, doping, but more complex than that !)*

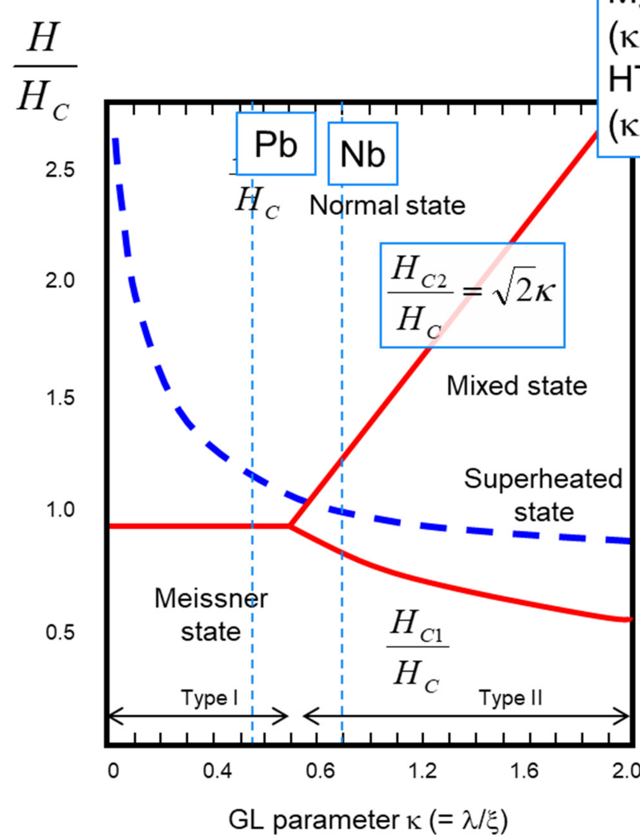


SUPERHEATING FIELD

→ MgB_2, NbTi (κ~40-50)
HTc (κ~60-2000)

- **Metastable Meissner state above H_{C1}**
  - observed close to Tc in DC/AC





- **Physical Origin**
  - normal zone nucleation ~10^{-6} s ?
  - RF ~10^{-9} s *

but in fact

  - 1! vortex penetration ~10^{-13} s **
  - SH state favored by H// surface (BL barrier) ***

H_{SH} ~1,2.H_C pour κ~1
H_{SH} ~0,75.H_C pour κ>>1
(Thermodynamics)

** H. Padamsee, J. Knobloch, and T. Hays, "RF superconductivity for accelerators". 1998: J. Willey & son.*
*** Gurevich, Brandt, Smethna…*
**** C. P. Bean and J. D. Livingston, Phys. Rev. Lett. 12, 14 (1964).*

SUPERCONDUCTORS FOR SRF ?

Material	T_C (K)	ρ_n (μΩcm)	$\mu_0 H_{C1}$ (mT)*	$\mu_0 H_{C2}$ (mT)*	$\mu_0 H_C$ (mT)*	$\mu_0 H_{SH}$ (mT)*	λ (nm)*	ξ (nm)*	Δ (meV)	Type
Pb	7,1		n.a.	n.a.	80		48			I
Nb	**9,22**	**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				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 ?

Surface barrier

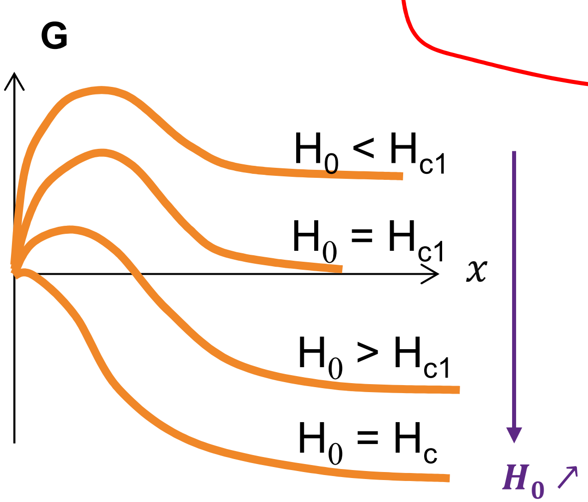
(Bean & Livingston, 1964)

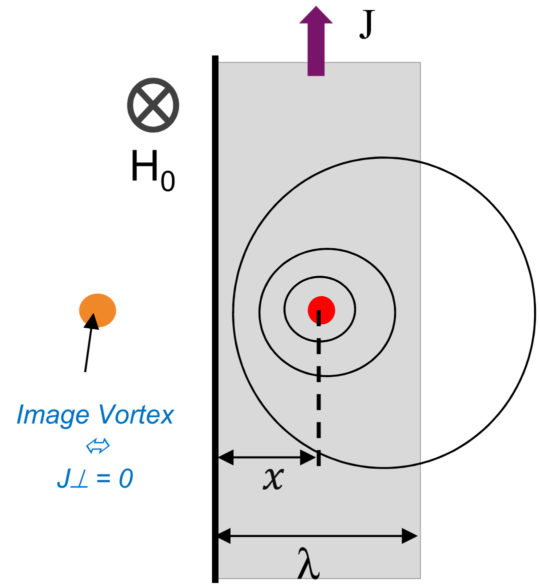
- Boundary condition. ($J_\perp = 0$) ≡ “image” vortices
  - Supercurrent tends to push Vx inside
  - Image antivortex tends to pull it out
- Before entering the material Vx have to cross a surface barrier:
  - Vx thermodynamic Potential :

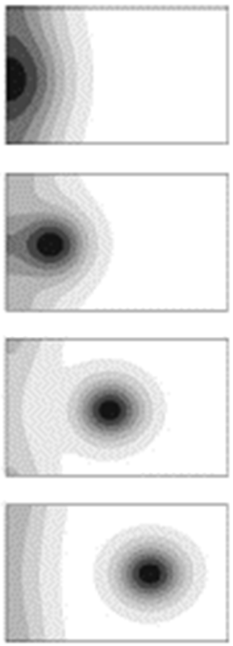
$$G(x) = \phi_0 \left[H_0 e^{-x/\lambda} - H_v(2x) + H_{C1} - H_0 \right]$$

Meissner

Image



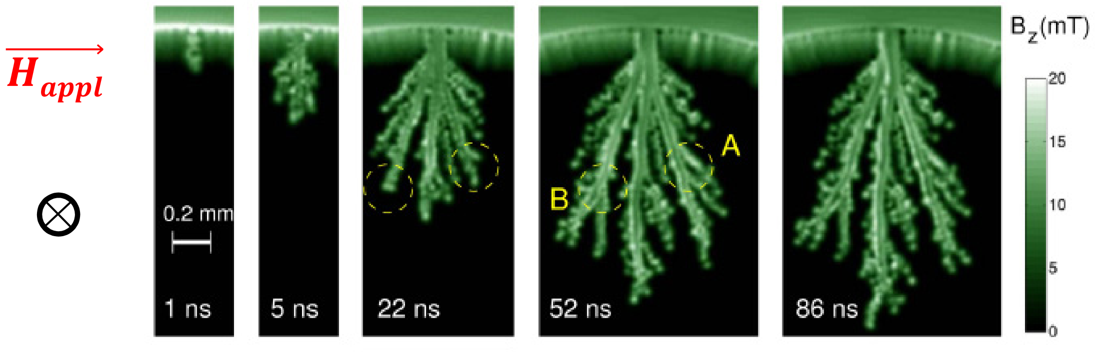




- “Ideal surface”
  - Barrier disappears only at $H_{SH} \sim H_C > H_{C1}$
  - Rationale used to predict SRF limits
- BUT
  - If ∃ localized defect w.: $H_C^{Local} \ll H_C^{bulk}$ (or $T_C^{Local} \ll T_C^{bulk}$) => early penetration of 1 or several Vx there

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

- Avalanche penetration/flux jumps

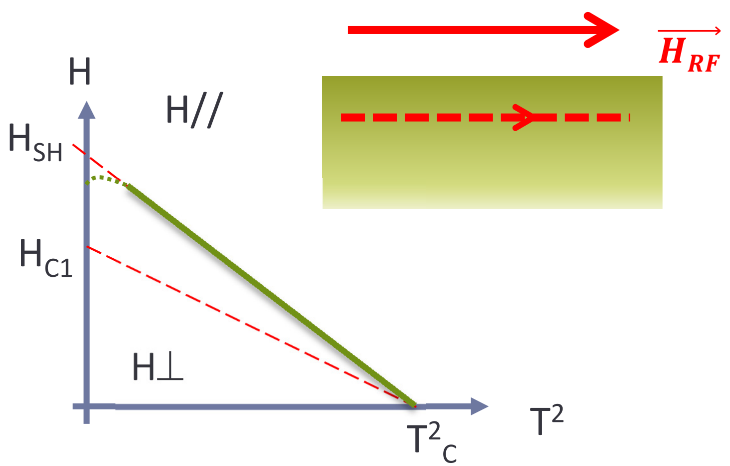


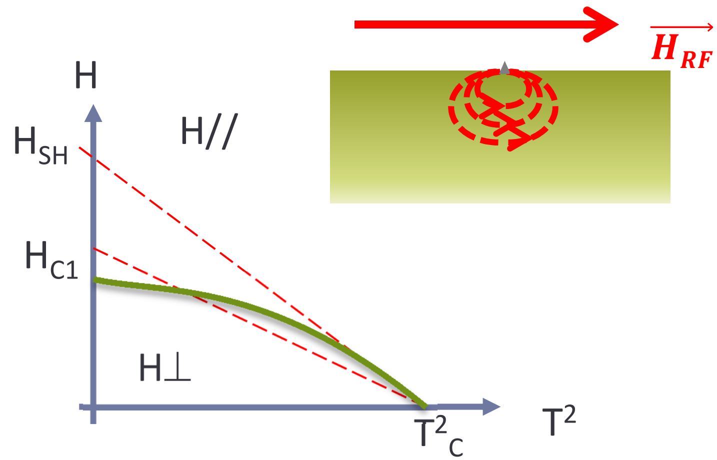
- ~100 µm in 1 ns *(~RF period)*
- Compare with λ *(field penetration depth)*
  - Nb : ~ 40 nm
  - MgB_2 ~ 200 nm
- Avalanche : high RF dissipation

MgB_2: http://www.nature.com/srep/2012/121126/srep00886/full/srep00886.html?message-global=remove&WT.ec_id=SREP-20121127

- 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



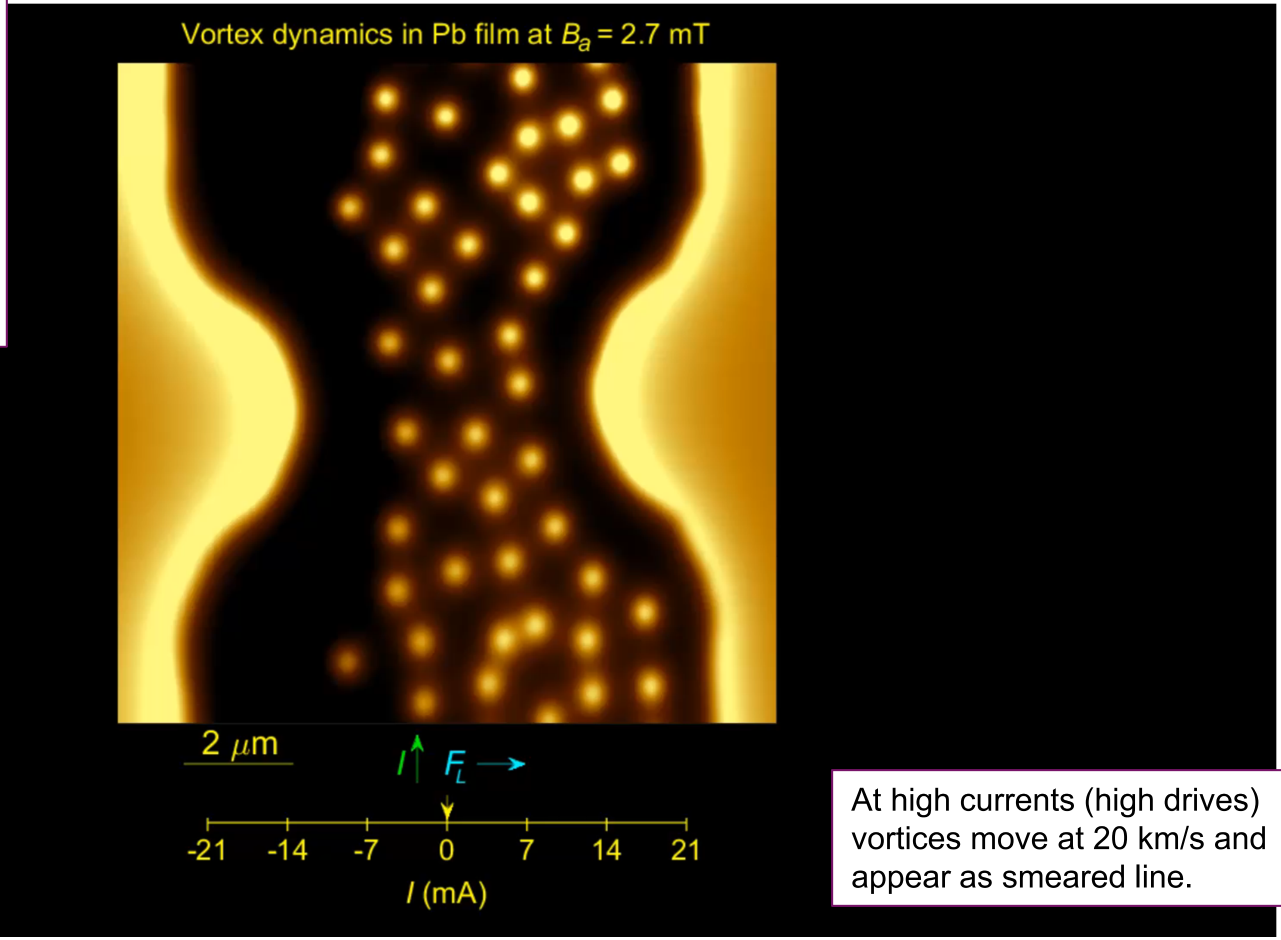


VORTICES AVALANCHES

https://www.eurekalert.org/multimedia/pub/145764.php\

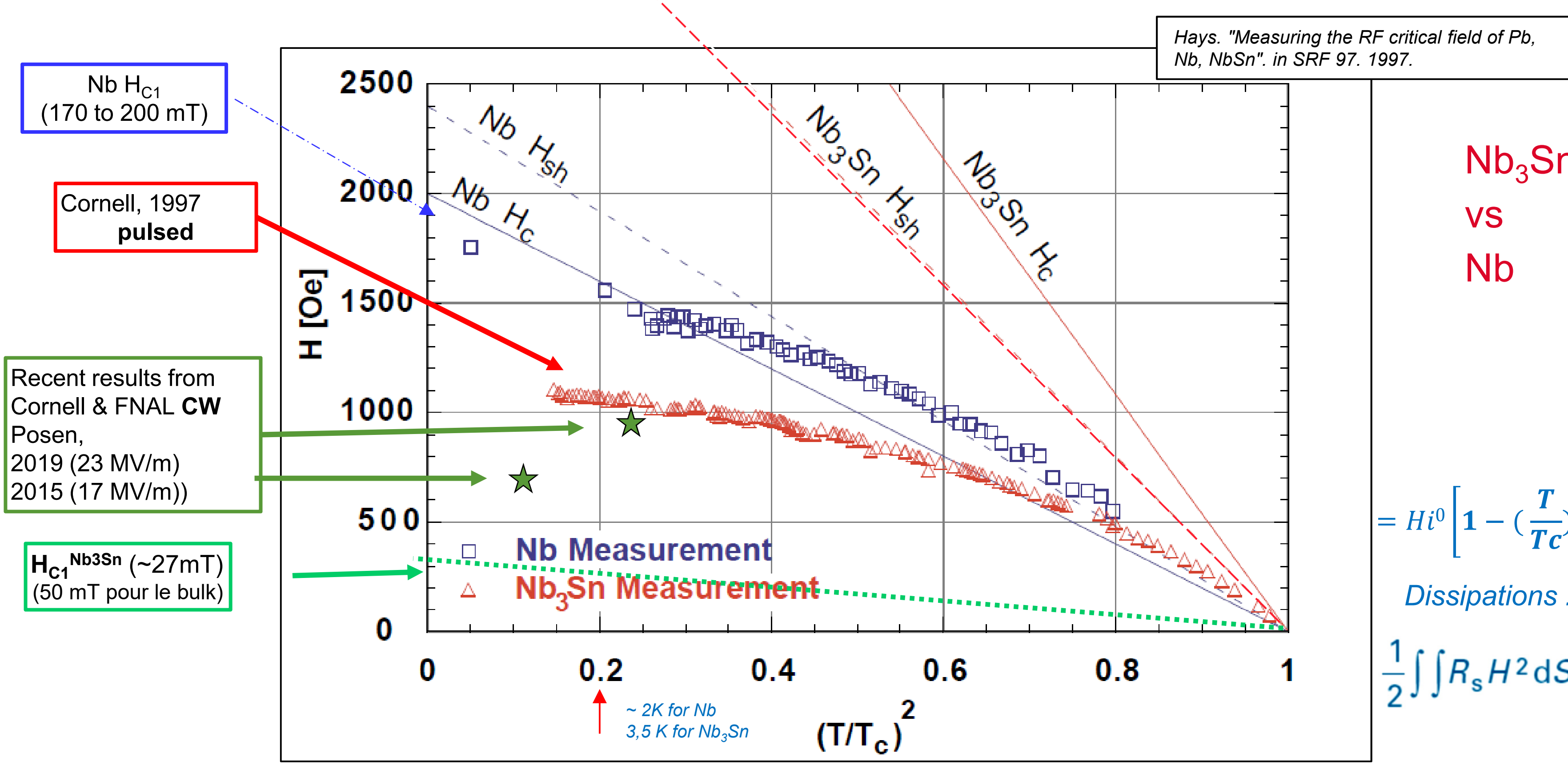
© Dr. Yonathan Anahory
Racah Institute of Physics
The Hebrew University of Jerusalem

- *Lead films*
- *scanning SQUID-on-tip microscopy technique*
- *allows magnetic imaging at magnetic sensitivity and high resolution (~50 nm)*



At high currents (high drives) vortices move at 20 km/s and appear as smeared line.

EFFECTS OF LOCAL DEFECTS



Nb_3Sn vs Nb

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

Dissipations :

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

- **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?)**

CHALLENGES TO FACE ON THE ROUTE TOWARD OTHER SUPERCONDUCTORS: GENERALITIES

GENERAL ISSUES WITH SCs

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

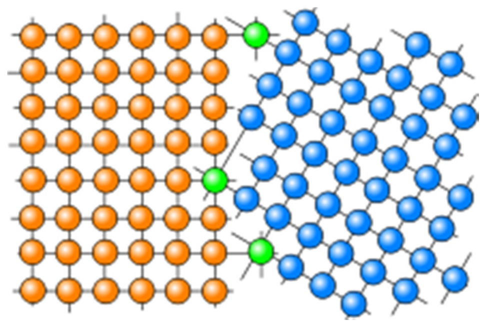
- **Advantages of niobium: pure metal.**
  - Highest T_C of metallic SC, H_{C1}
  - Easy to form
  - Uniform composition, *no phase transition in the domain of interest*
  - Very large ξ: makes it less sensitive to small crystalline defects (e.g. GB)
- **Issues with alloyed, metallic SC compounds (e.g. 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
- **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 .

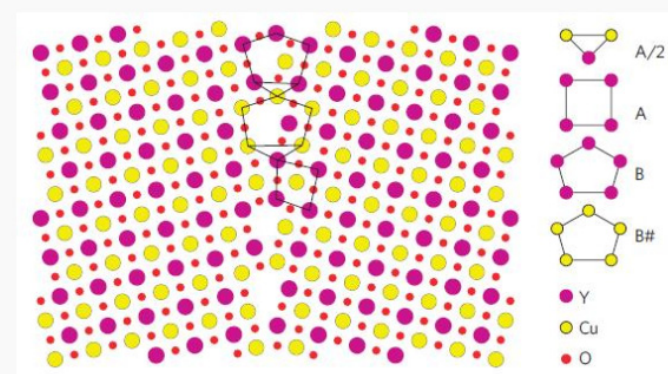
Metallurgy : started ~ 5000 Ys ago

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

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

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

THIN FILMS DEPOSITION

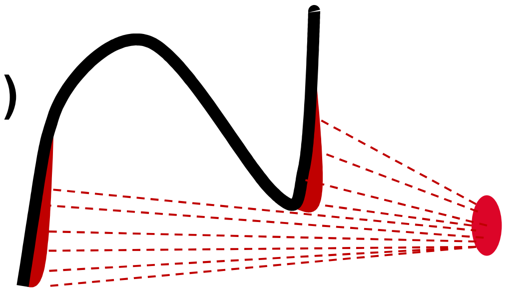
Nb : λ~50 nm => only a few 100s nm of SC necessary (the remaining thickness= mechanical support) **=> Make thin films !**

- **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)*

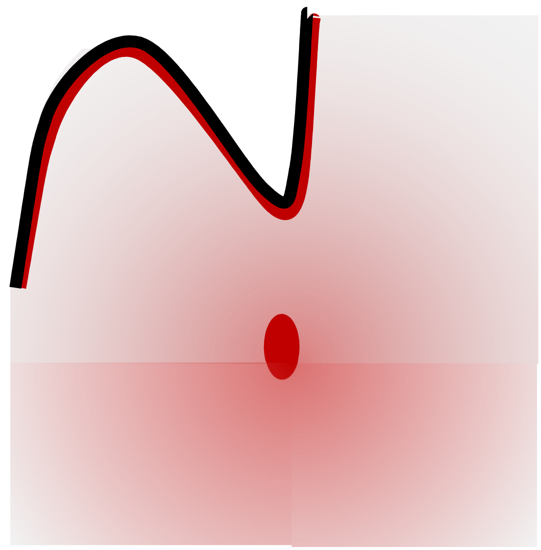
- **Disadvantages**
  - Fabrication and surface preparation of substrate *(at least)* as difficult as for bulk Nb
  - Steep Q_0 reduction often observed by increase of RF field *(sputtered niobium films)*
  - Deposition of innovative materials is very difficult *(large parameters space to be explored)*
  - 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



THIN FILMS (…)

Films: Many techniques, not possible mention all

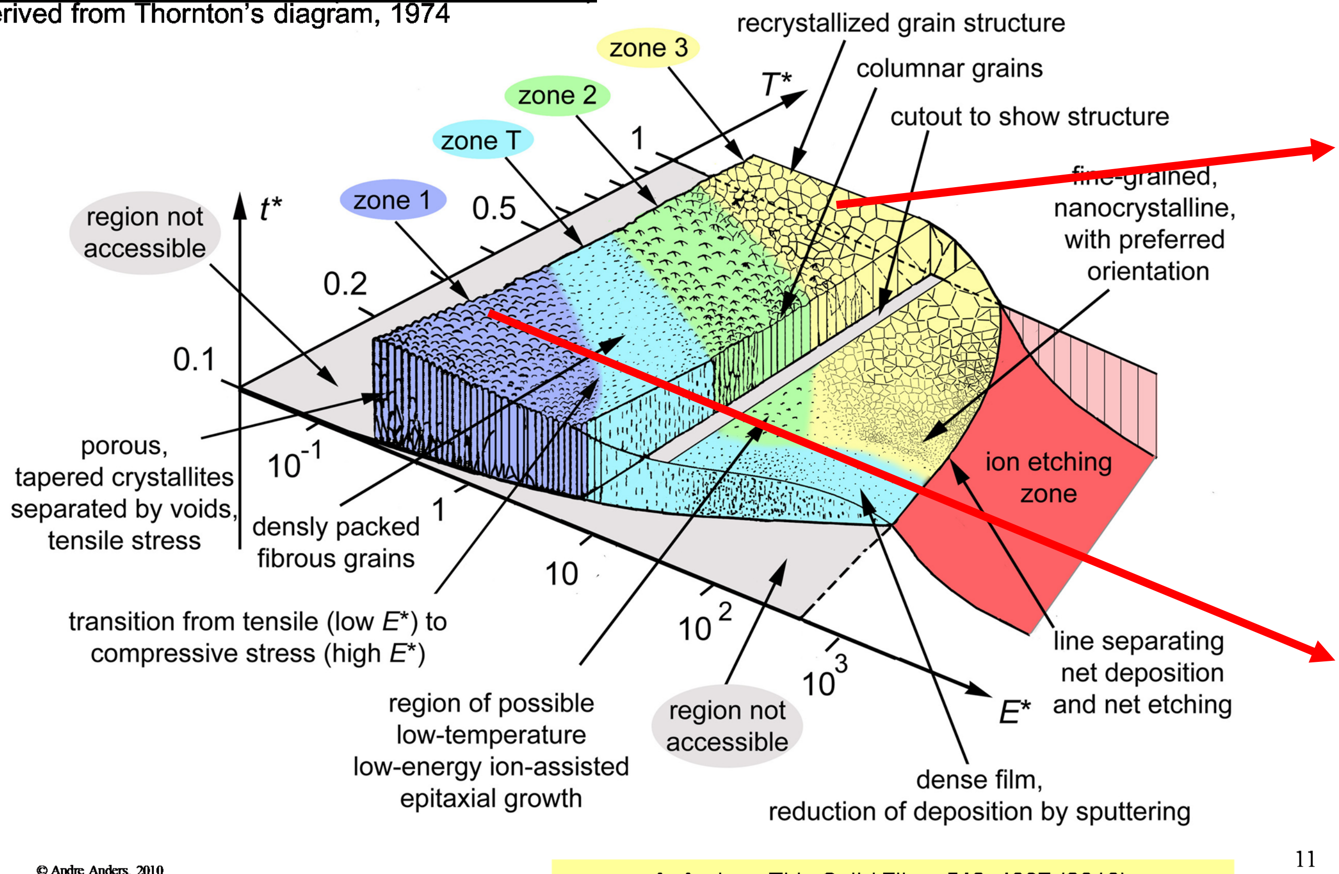
There are two categories of films

- **Films which are intrinsically films**
  - Thin, small grains, under stress
  - Problems: defects & microstructure, impurities, surface state
  - Examples: magnetron sputtered Nb films on oxidized copper

- **The general trend is to move towards films which are bulk-like**
  - Dense, large grain material
  - Examples:
    - high-energy deposition techniques
    - annealed films
    - Nb Cu-clad cavities (hydroformed cavities from bimetallic Nb (2.5 mm), Cu (0.5-1 mm) tube)

SEARCH FOR BETTER STRUCTURE

Structure zone model (from A. Anders)
derived from Thornton's diagram, 1974



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

Unfortunately, more "bulk-like" Nb Films gave disappointing RF results. Not understood yet

THIN FILMS CHALLENGES: DEPENDS ON THE STRATEGY

Optimizing structure/composition of the films on samples

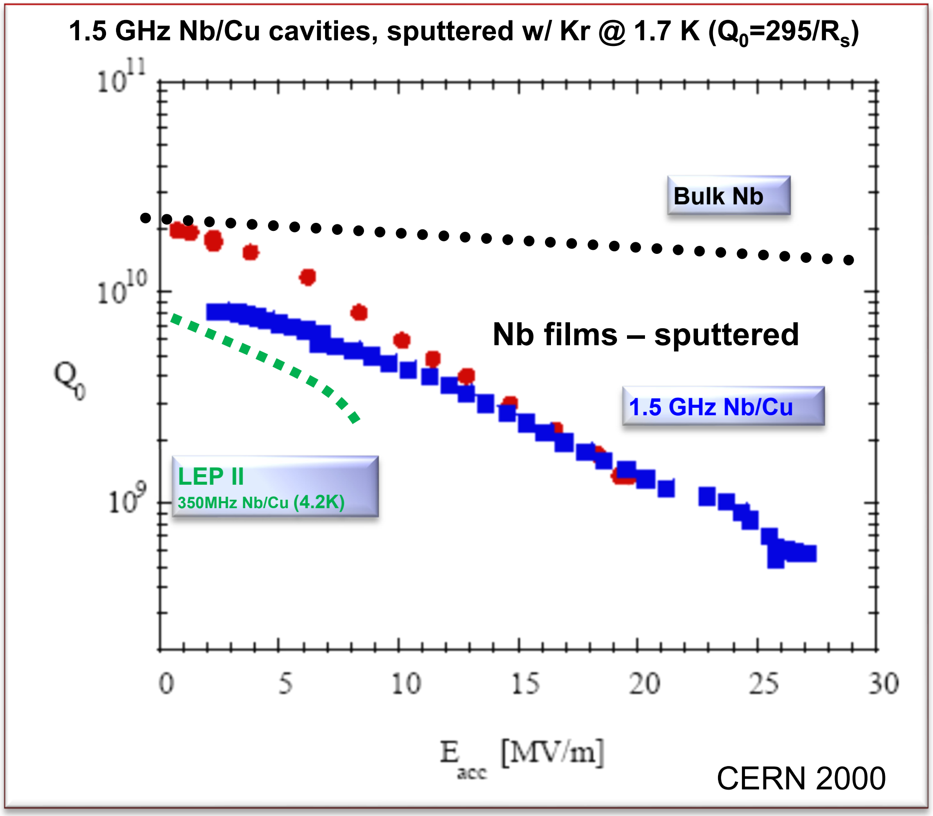
- **Advantages**
  - Structure /composition can be optimized with conventional techniques
  - Ideal structure and composition can be achieved on model sample (guide for deposition of cavities)
  - Cost
- **Disadvantages**
  - RF performances cannot be directly measured
  - **Specific measurement tools need to be developed** (sample cavity, magnetometer…)
  - Ultimately a cavity deposition set-up will be needed, but with a known aimed composition & structure

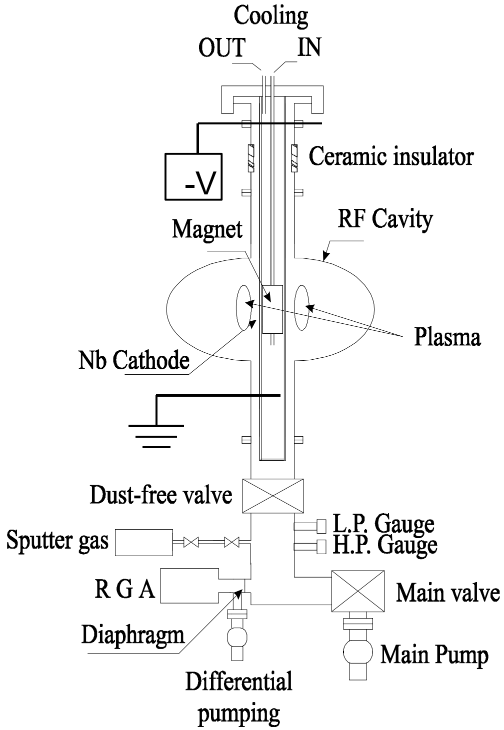
Optimizing deposition inside cavities

- **Advantages**
  - RF testing easy and gives direct performance
  - Work is done only once, direct cavity production
- **Disadvantages**
  - Very heavy and lengthy, many parameters
  - Need to develop a specific cavity deposition set-up
  - **Difficult to optimize set-up and films together**
  - Optimization of the structure/composition of the film is difficult without structure/ composition info

Nb/ Cu:
example of the issues
when dealing with thin fims

- The only Nb films deployed in accelerators were made by magnetron or diode sputtering (CERN).
  - Reached relatively low surface fields => Eacc ~ 5 MV/m.
  - Exponential slope in Rs and Q0



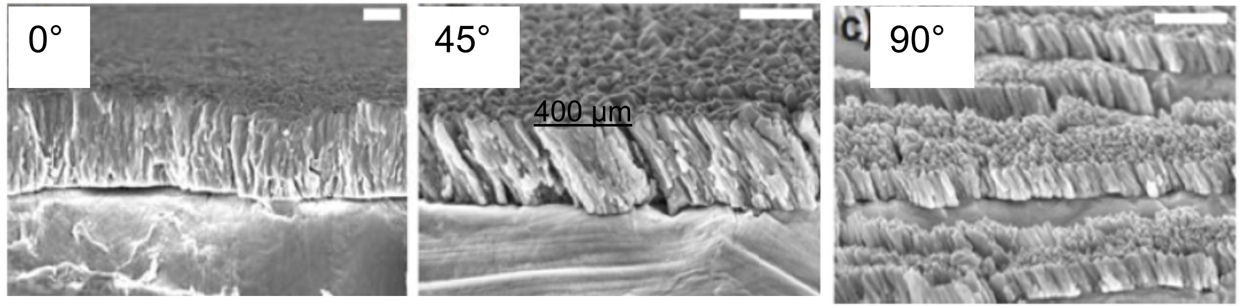


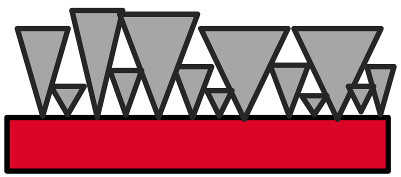
- Possible origin of the slope
  - Depinning of trapped flux
  - Low H_{C1}
  - Early vortex penetration due to roughness

Magn. Sput. Nb

- Line of sight issues => porosities

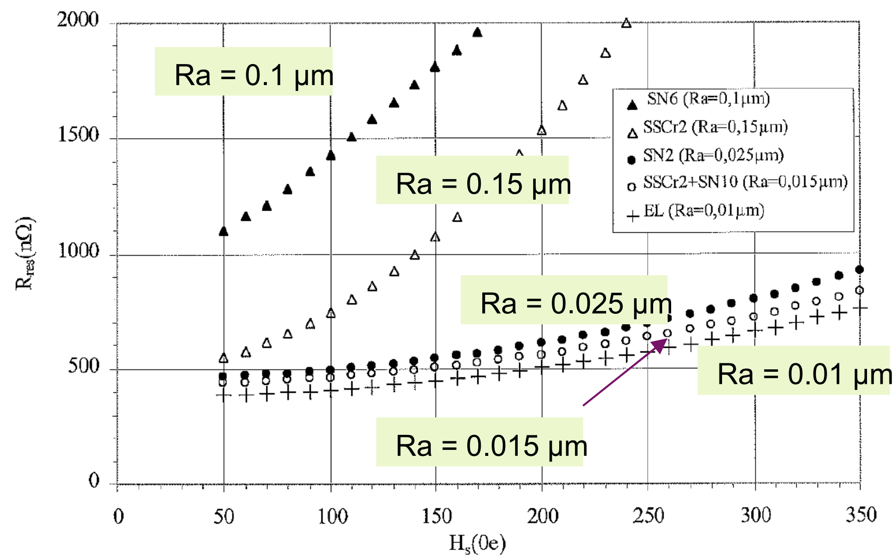
[G. Rozas]





Inverted pyramid crystalline growth

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



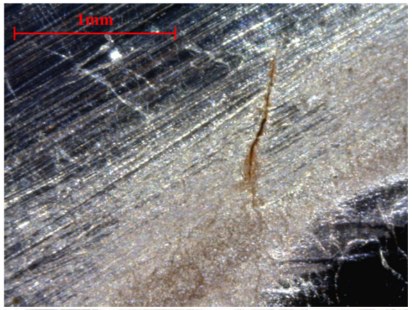
[M. Ribeaudeau, PhD]

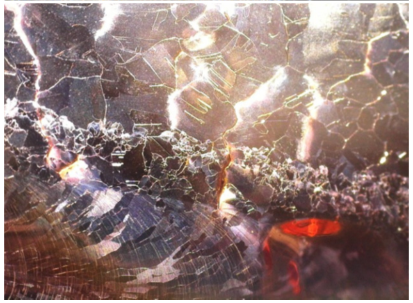
- Internal stress
  - Advantage: higher Tc *(up to a certain impurity concentration)*
  - Disadvantage: adhesion issues *(peeling)*
- High impurities content
  - Nb = getter material *(nearly as good as Ti => high interstitial content)*
  - Carrier gas incorporation *(Ar)*

SUBSTRATE ISSUES

- Cu and Nb not miscible (especially in presence of O)
  - Advantage: low interdiffusion
  - Disadvantage: adhesion issues (peeling)
- Best results are not always where expected:

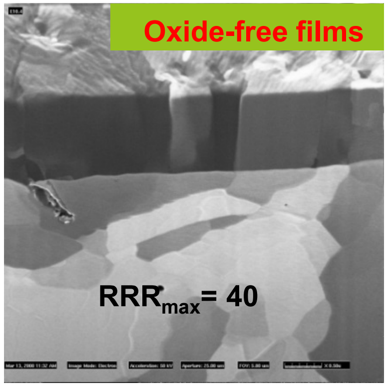
Bulk like films did not perform better ! *(but recent change…?)*





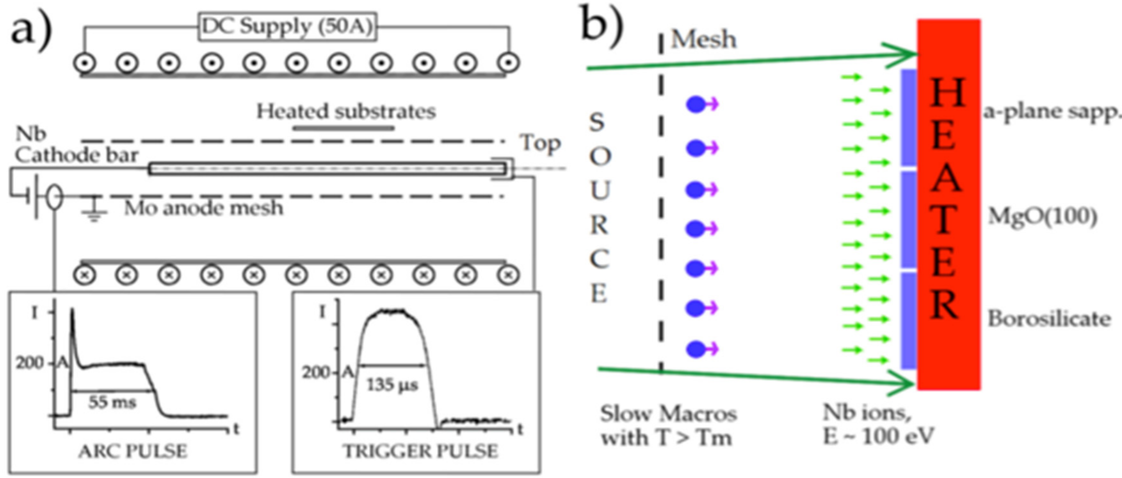
[data from CERN + AM Valente-Feliciano]

	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



COAXIAL ENERGETIC DEPOSITION (CED)

Substrate	RRR
Single crystal insulator	
MgO (100)	176
MgO (110)	424
MgO (111)	197
a-Al_2O_3	488
c-Al_2O_3	247
Cu large grains	289
Record	585



Cathodic arc plasma.

Nb films grown by Jlab and AASC Almeda Applied Science Corporation.

[Ch. Reece; Jlab]

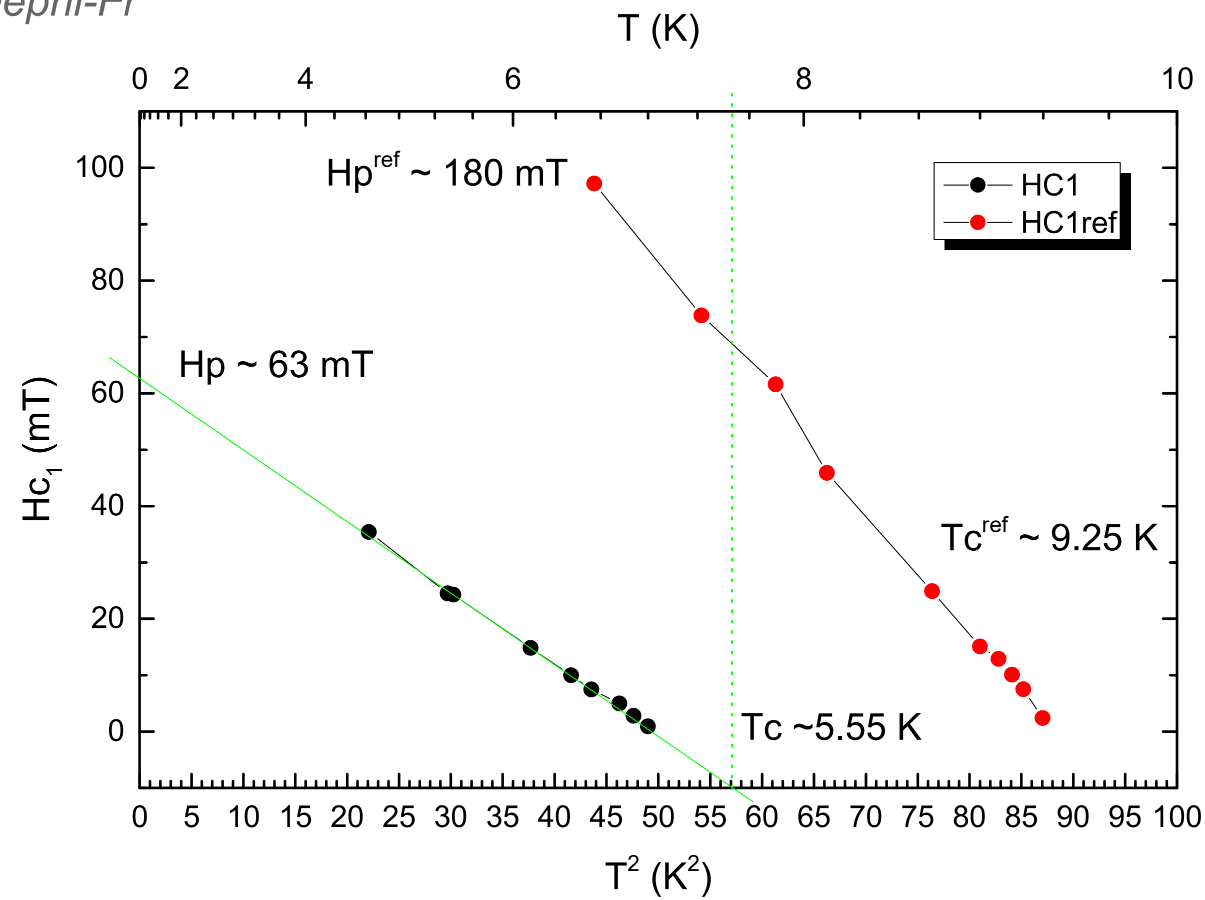
- Ions Energy 60-120 eV
- Arc source is scalable for large scale cavity coatings
- UHV and clean walls important

- Bulk like RRR values
- Here again, cavities performances disappointing

Coaxial Energetic Deposition (CED^{TM})

Thin films

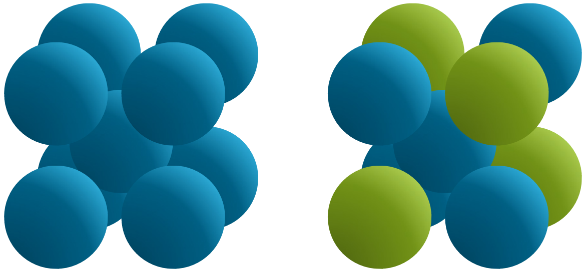
- Thin films : lower H_{C1}, higher H_{C2} / bulk values (because of high λ and low ℓ)
- *HPIMS sample from Dephi-Fr*



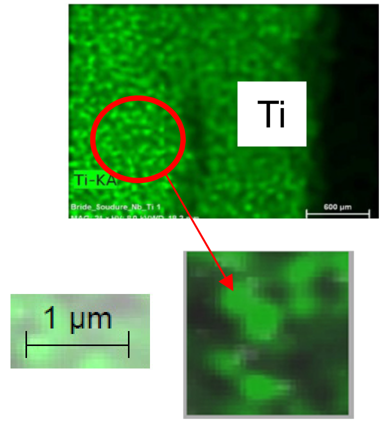
CURRENT SUPERCONDUCTORS:

- **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)

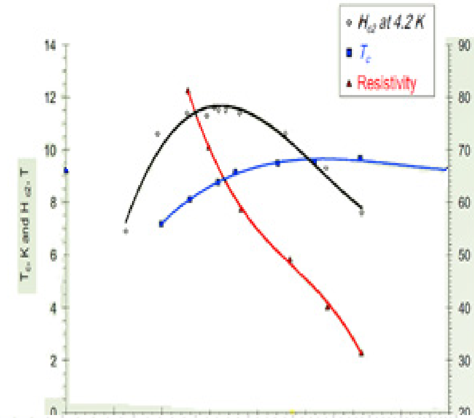
A2 SC ALLOYS: e.g. NbTi

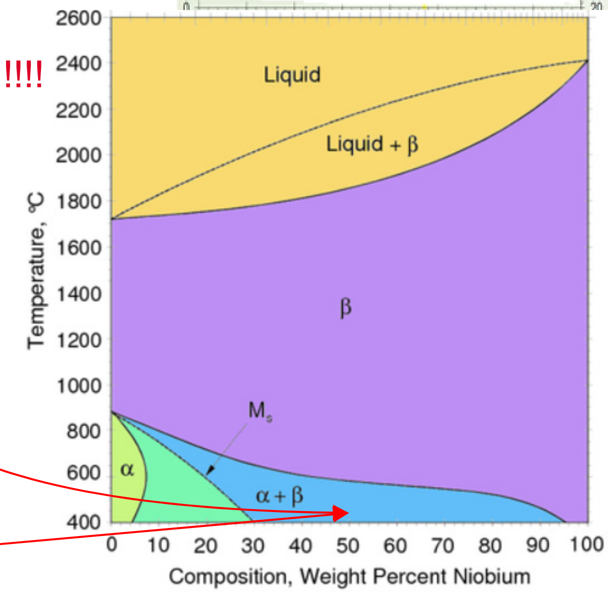


BCC pure metal and solid solution alloy



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





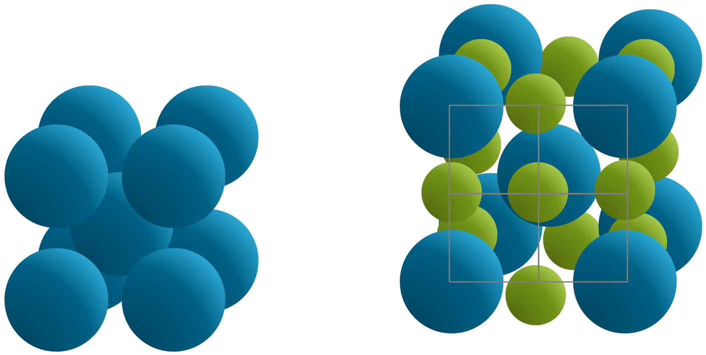
- NbTi widely used in coils
- Available alloys range around 45-55 % Ti
- Ti is not fully miscible inside Nb (Ti precipitates ∃ at low T when [Ti] > 5 W%)

  => 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 κ

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

A1 SC COMPOUNDS: e.g. NbN



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

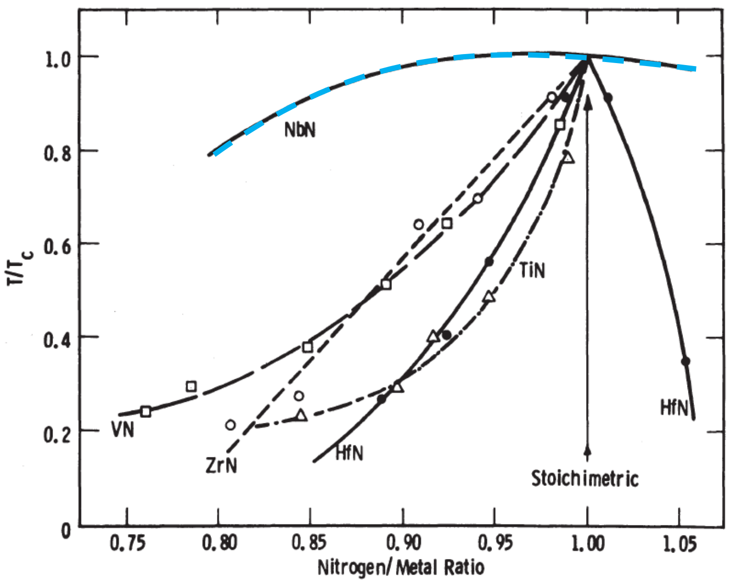


Fig. 20 Critical temperature versus nitrogen-to-metal ratio for various B1-structure nitrides of the transition metals (data assembled by Hulm and Blaugher).

- 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)

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		

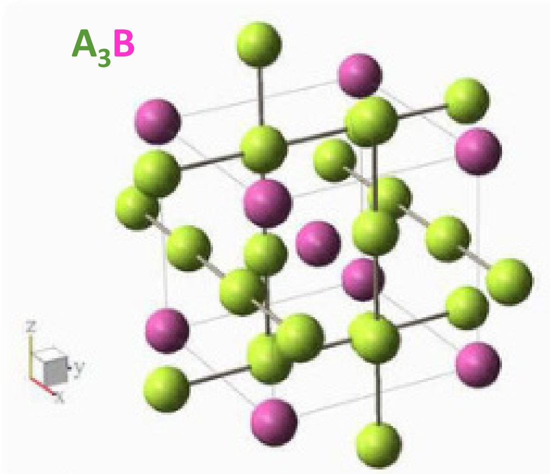
[after Due-Hugues]

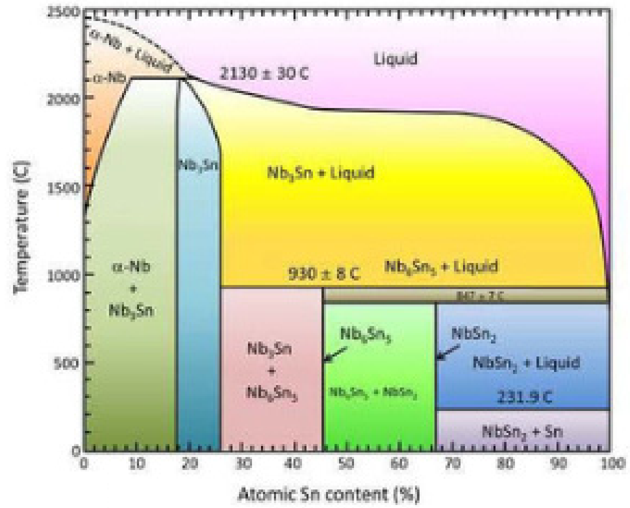
- **Extreme brittleness !!!**
  - cannot be formed
  - thin/thick film route only !

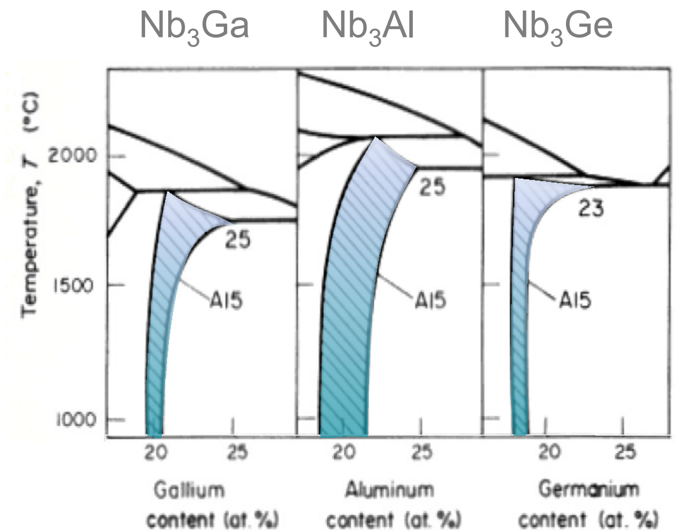
nm *µm*

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

A15 COMPOUNDS : NARROW DOMAIN OF SC

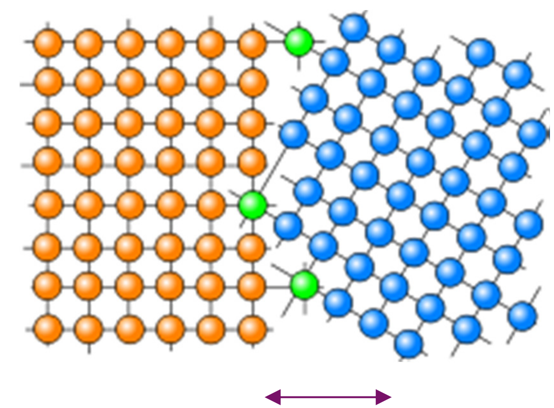






B *atoms occupy corners and center of BCC structure*

A *atoms form orthogonal chains bisecting the faces of the BCC unit cell.*
Linear Chain Integrity is crucial for Tc (long-range order required)



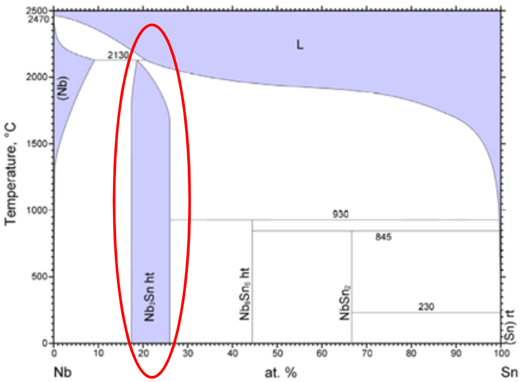
Compare with ξ

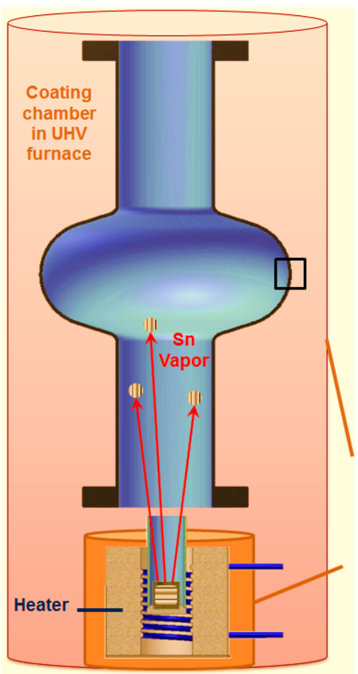
- **Narrow range of concentration for the SC phase:**
  - Highest T_C area is even narrower
  - Difficult to get uniform SC phase everywhere*
  - Special issues at grain boundaries: “intrinsic” local deviation of stoichiometry*
  - In Nb_3Sn wires : GB exhibit degraded SC => weak links, pinning centers

Nb_3Sn

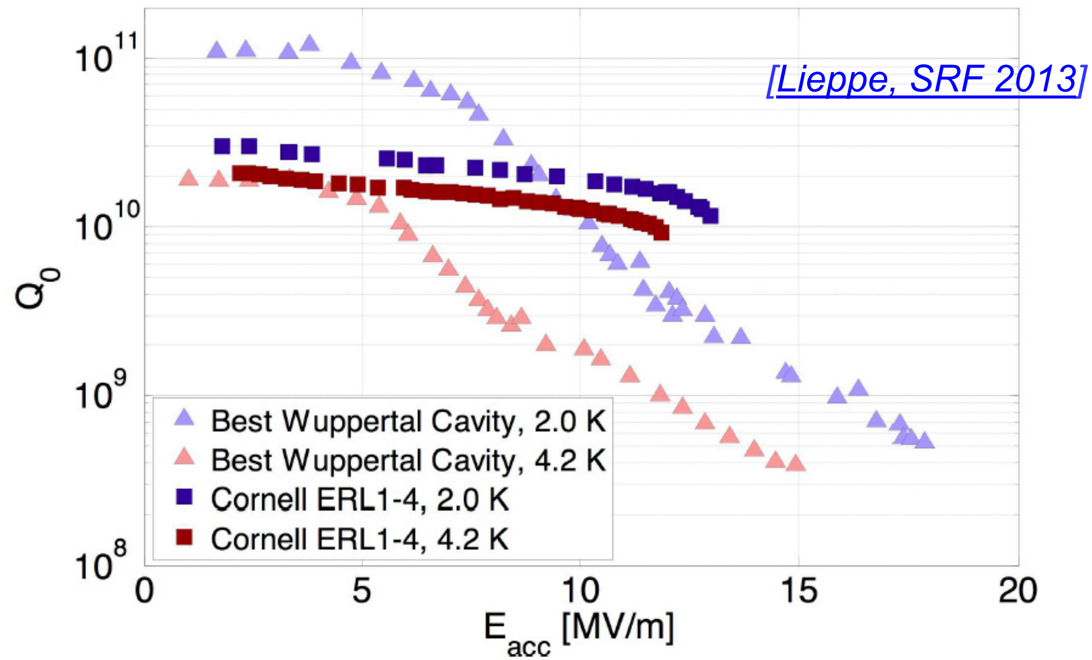
Special interest for SRF since the 1980's

Nb_3Sn ON Nb (thermal way)



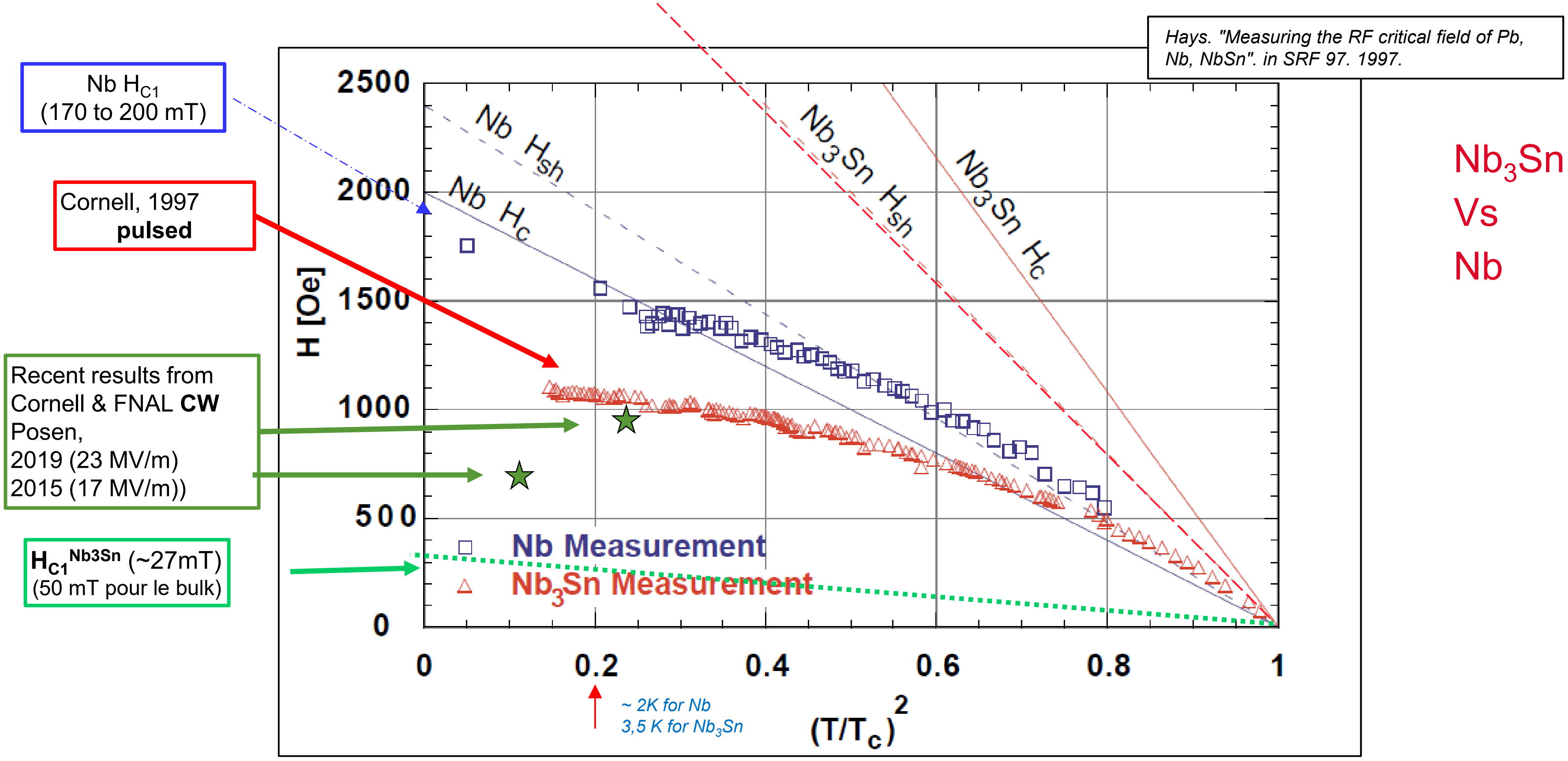


Pioneer work: Wuppertal, Cornell



- @ 4,2 K: Q_0 x 20 compare to Nb, @ 2K ~ the same
- Limited in E_{acc} , best results today ~17 MV/m
- Important developments: FNAL, JLAB, CERN, PKU….

EFFECTS OF LOCAL DEFECTS



Nb_3Sn
Vs
Nb

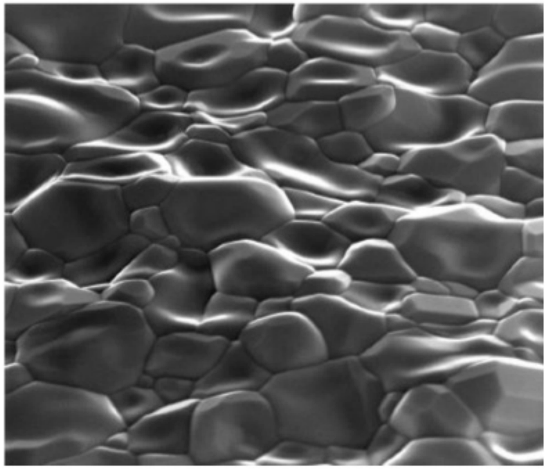
=> We have to reduce defect density **(yes but which ones?)**

Nb_3Sn : NON UNIFORM LAYER

Candidates of Q-slope and quenching in Nb_3Sn

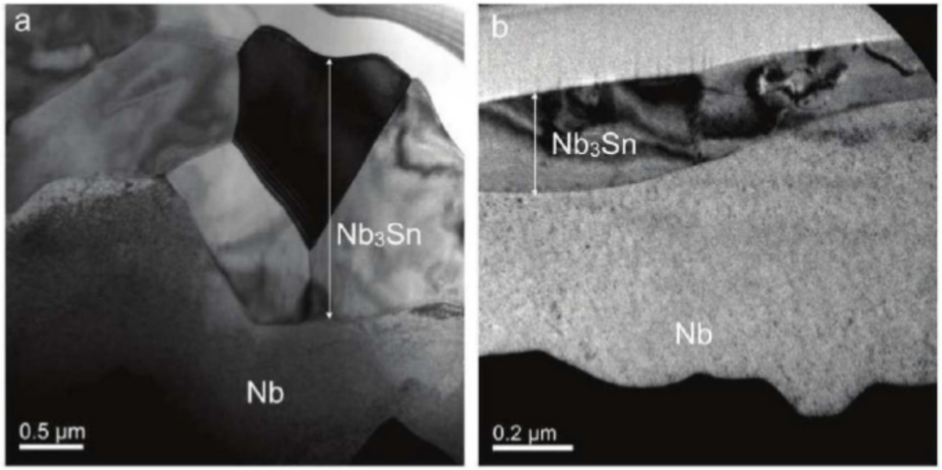
Jaeyel Lee ttc Milano meeting 2018

1. Surface roughness



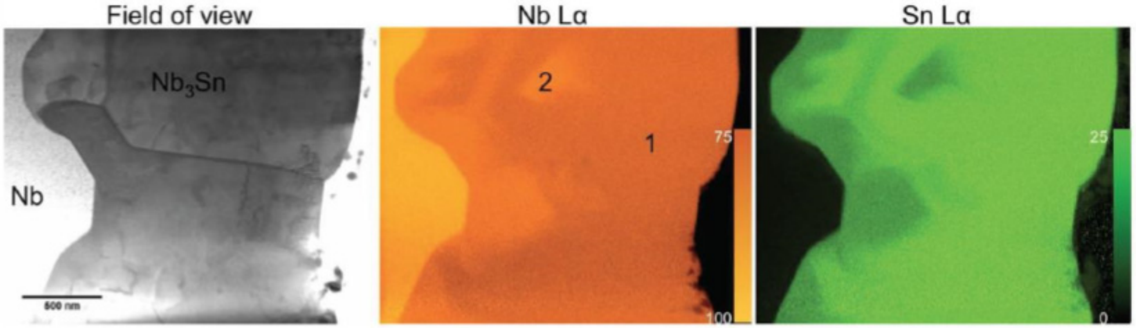
S Posen, PhD thesis, Cornell University (2015)

2. Thin regions



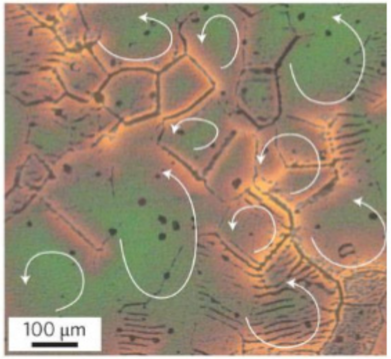
Y Trenikhina et al 2018 Supercond. Sci. Technol. 31 015004

3. Composition variation (Sn-deficient region)



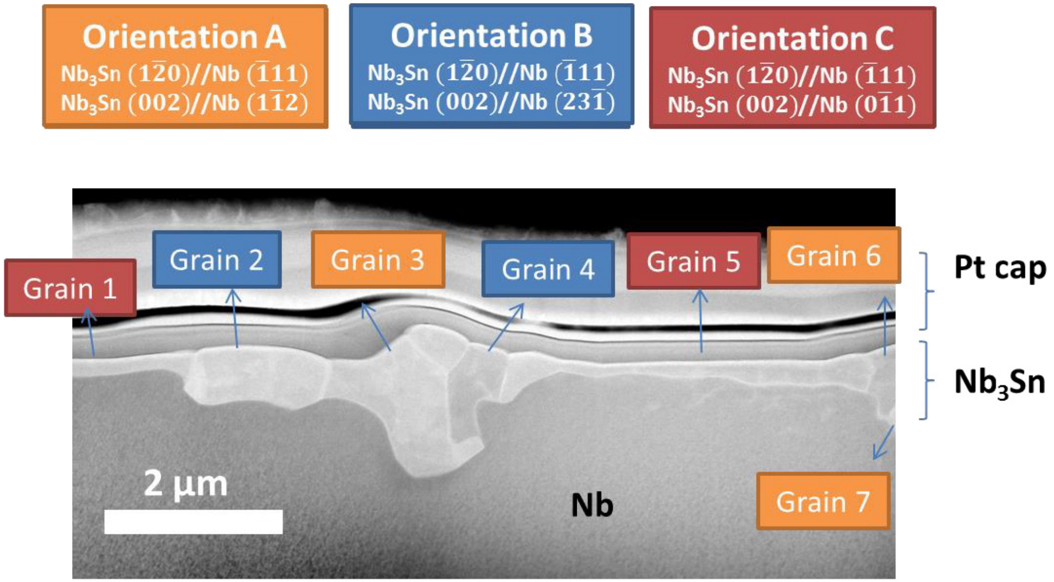
C Becker et al, APL 106, 082602 (2015)

4. Grain boundary

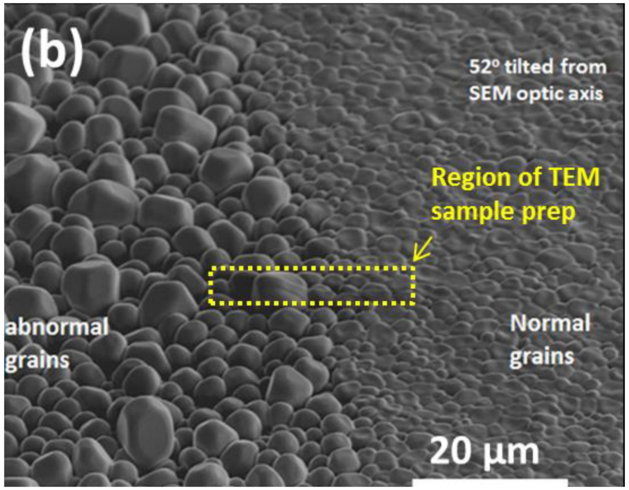


A. Gurevich, Nature Materials 10, 255–259 (2011)

Nb_3Sn : SUBSTRATES ISSUE

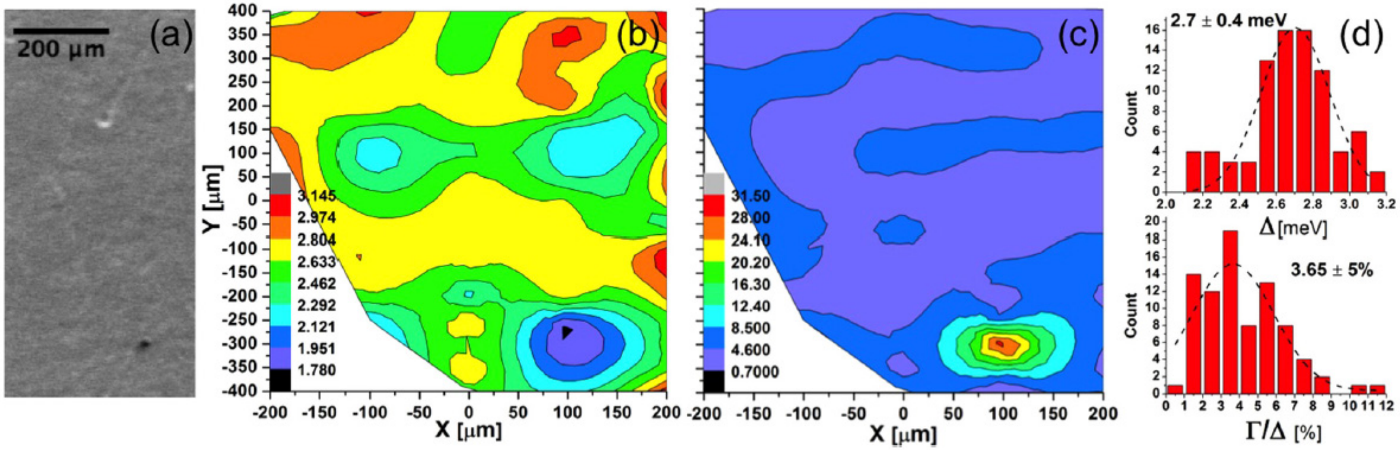


https://export.arxiv.org/ftp/arxiv/papers/1807/1807.03898.pdf



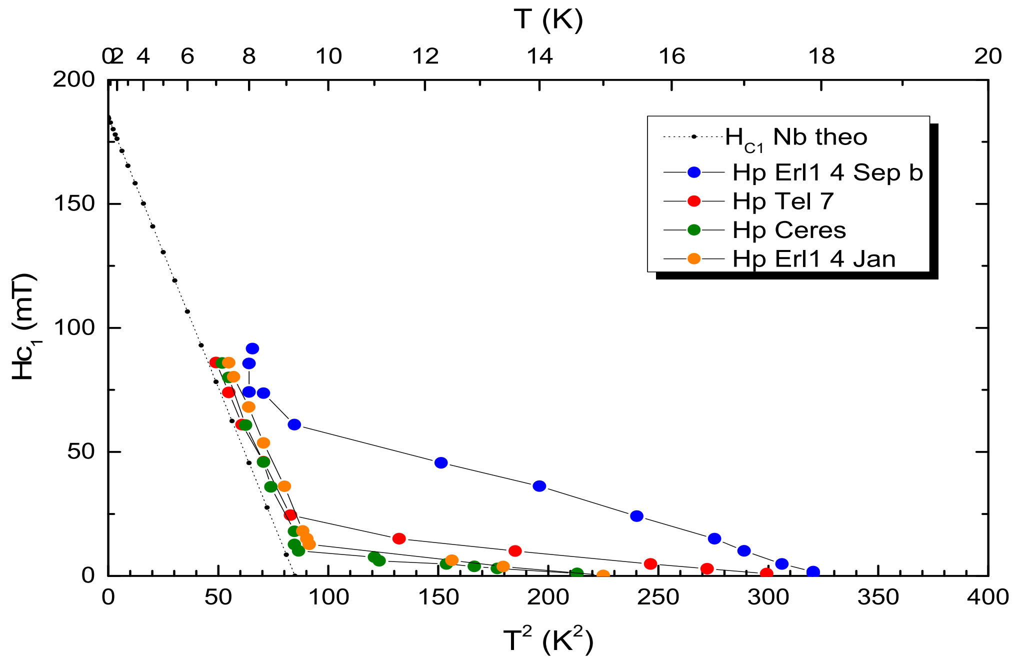
- **Nb_3S film grows in epitaxy**
  - Regions with poor lattice mismatch grow slower
  - Thinner regions tend to be depleted in Sn => lower T_C, early transition
  - Can be partially mitigated with interlayer *(e.g. anodization of Nb)*
- **Complex materials:**
  - Real difficult to master
  - Very sensitive to defects

L. M.: WHAT ELSE CAN BE MEASURED



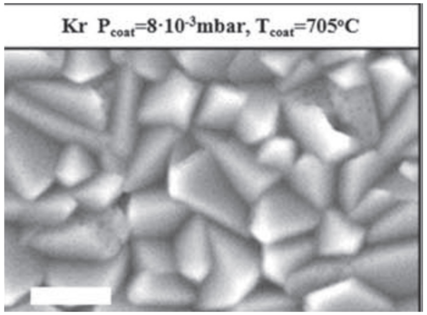
Nb_3Sn series

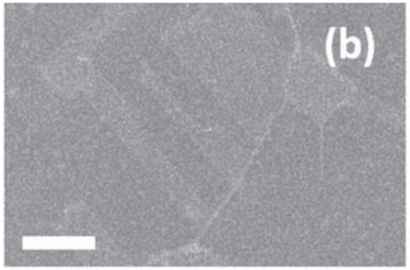
- Along with cavity results and PCT *[T. Proslier]*
- *Magnetometry follows the trends observed on RF tests*



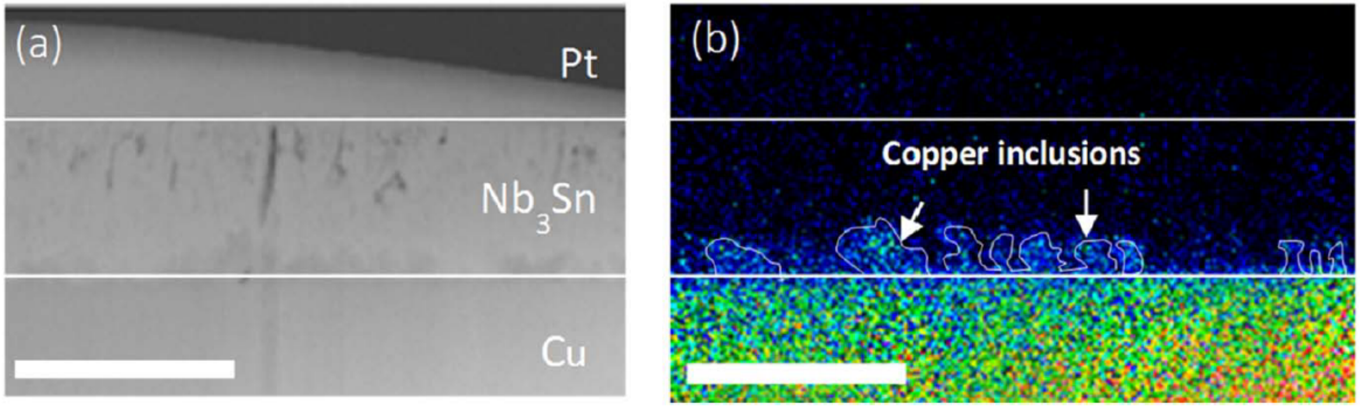
OTHER APPROACHES

- **Sputtered Nb_3S films on copper**
  - Activities at Cern and Jlab
  - 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*



OTHER APPROACHES

Electrochemical deposition + diffusion through copper

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

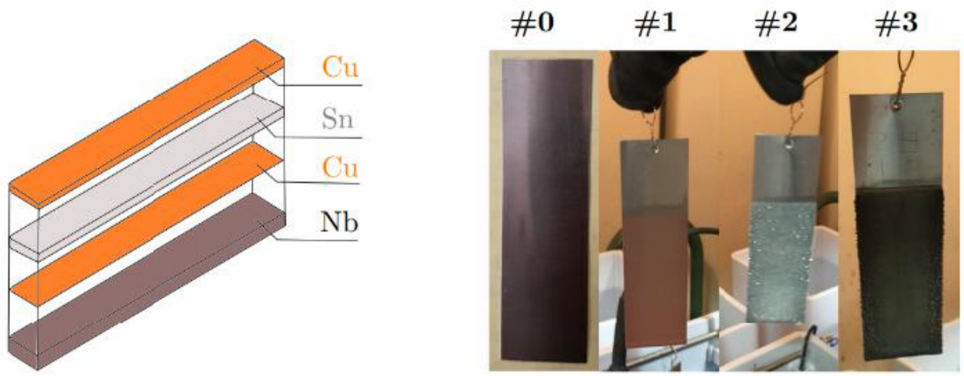
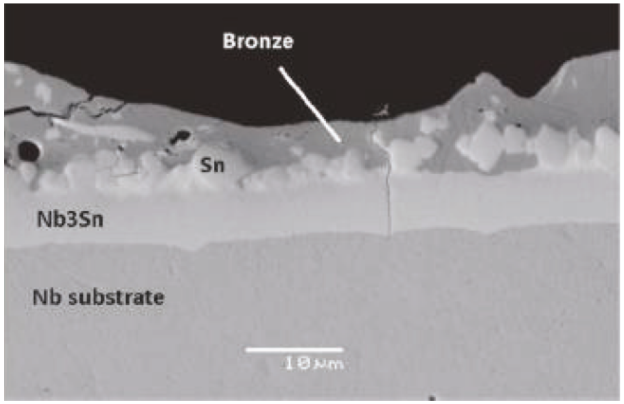


Fig. 3: Sequence of deposited layers (left), and pictures of sample at each deposition step (right).



- 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.

2-D SC (Compounds, anisotropic)

- MgB_2
- Cuprates, Pnictides
- Multilayers

MAGNESIUM DIBORIDE (MgB_2)

BCS type superconductor

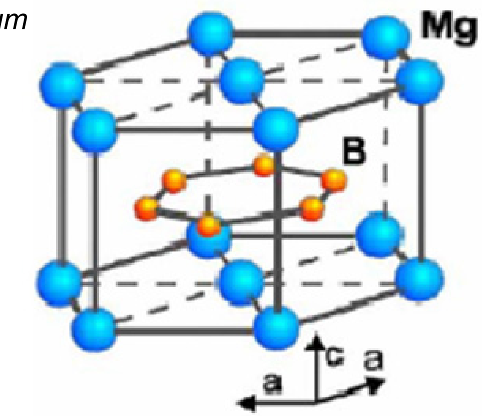
- **T_C ~40 K, two-gap nature**
- **Advantages:**
  - Very high T_C *(higher temp operation)*
  - Semimetal, cheap *(fertilizer !)*
  - ξ, λ of high quality* MgB_2 similar to Nb (~50 nm) *(transparency of GB to current flow)*
  - Low ρ_n *(lower R_S)*
- **Disadvantages:**
  - Orientation issues *(in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

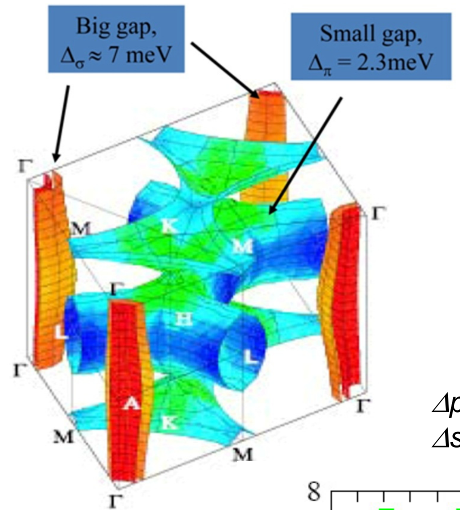
Δ^{Nb}= 1.5 meV < Δ_π^{MgB2}= 2.3 meV < Δ^{Nb3Sn}= 3.1 meV <Δ_σ^{MgB2}= 7.1 meV

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

* *wire quality MgB_2: ξ ~1-3 nm, λ ~250 nm (by playing on m.f.p.: crystal structure, grain size, impurities…)*

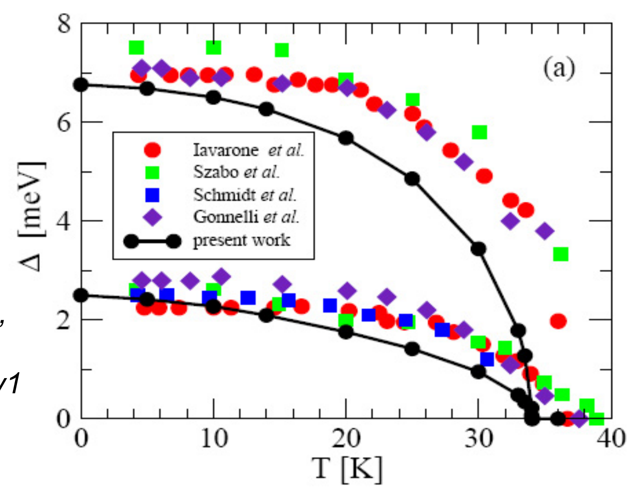
Graphite-type boron layers separated by hexagonal close-packed layers of magnesium





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

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

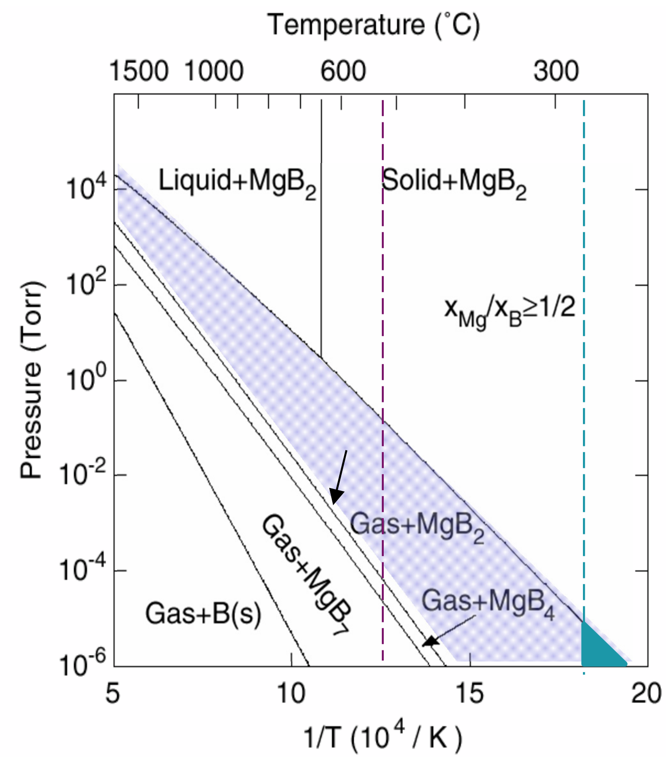


A. Floris et al., cond-mat/0408688v1 31 Aug 2004

MAGNESIUM DIBORIDE (MgB_2)

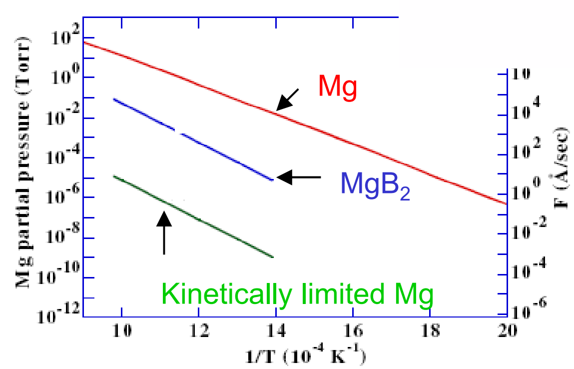
Phase diagram: at low Mg pressure only extremely low deposition temperatures can be used

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



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

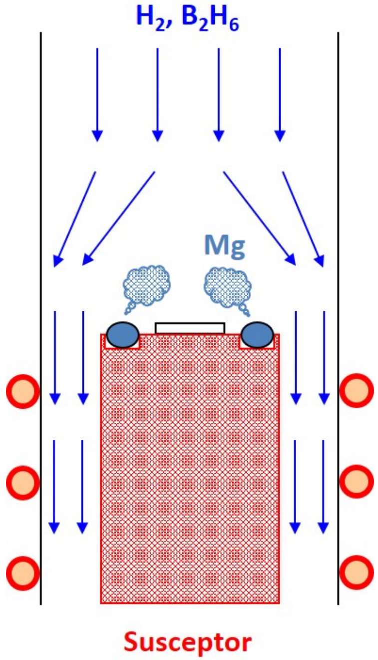
evaporation pressure of Mg from MgB2 < decomposition curve of MgB2 < Mg vapor pressure

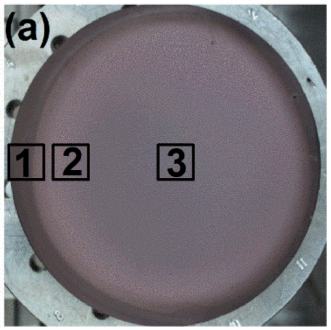


M. Naito and K. Ueda, SUST 17 (2004) R1

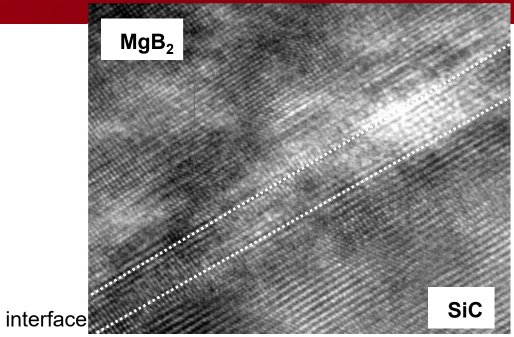
MgB_2 – HPCVD ON METAL SUBSTRATES
HYBRID PHYSICAL CHEMICAL VAPOR DEPOSITION

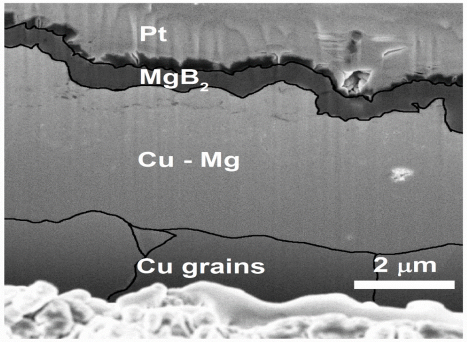
[X. Xi- TempleUniversity]

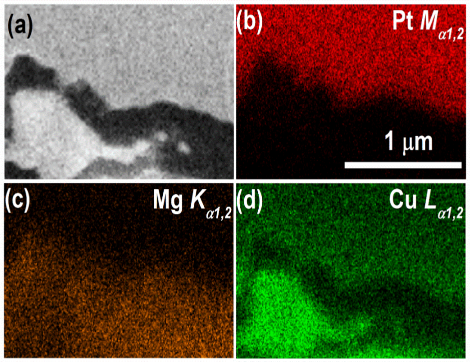




- **Polycrystalline MgB_2 films deposited:**
  - On stainless steel, Nb, TiN, and other substrates.
  - Flat samples and tubes *(conformational)*
  - Fitted for SRF apps:
    - *RRR>80*
    - *low resistivity (<0.1 μΩ) and long mean free path*
    - *high Tc ~ 42 K (due to tensile strain),*
    - *low surface resistance, short penetration depth*
    - *smooth surface (RMS roughness < 10 Å with N2 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
  - Prevent formation of spurious phase (e.g. Mg-Cu alloy islands on a Cu substrate





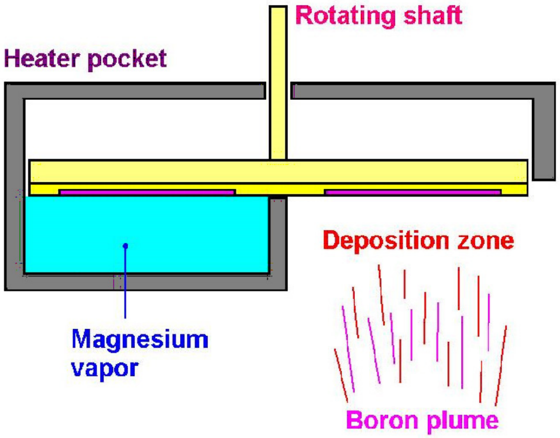


Reactor/reaction designs require complex calculation in thermodynamics and hydrodynamics

MgB_2 – OTHER ROUTE S

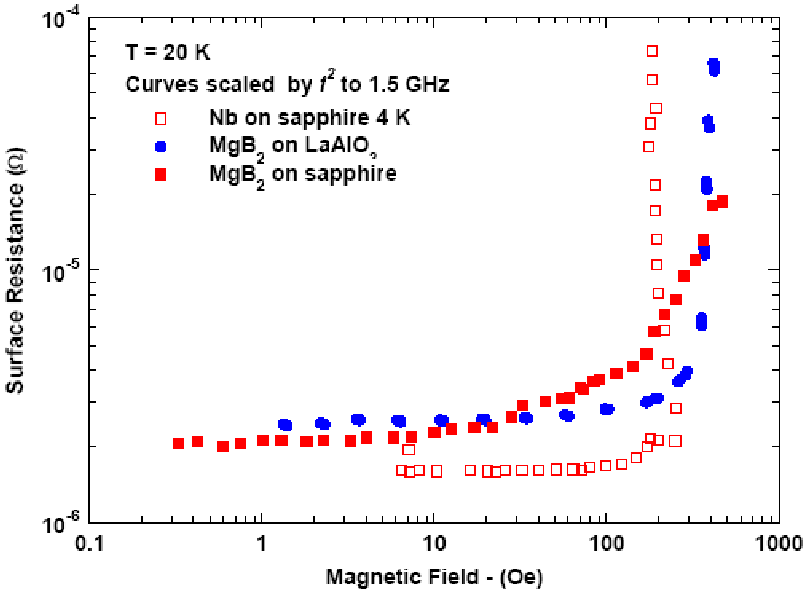
RF measurement @ MIT/Lincoln Lab

- **In-situ reactive evaporation @ 550˚C**
  - High quality flat samples
  - Difficult to apply to complex geometries

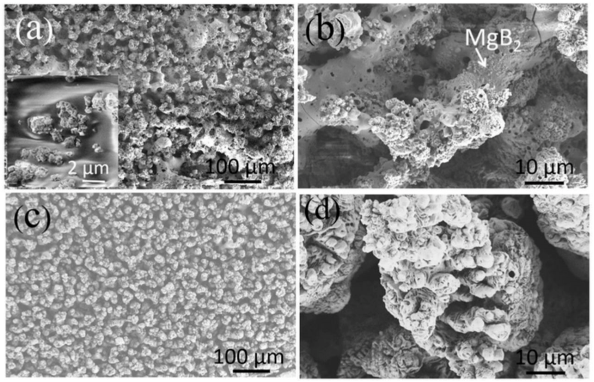


[T. Tajima, LANL]

Superconducting Technologies Inc.



- **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*

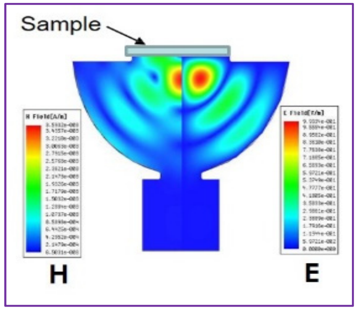


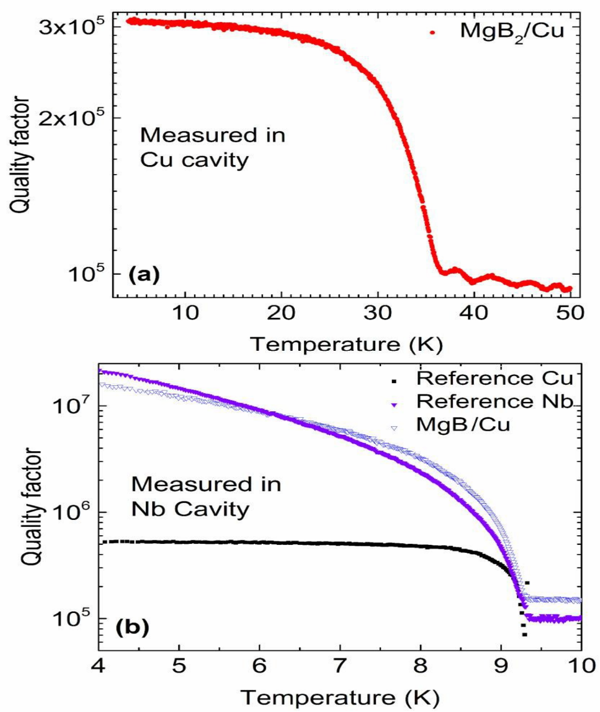
[R. Valizadeh, STFC]

HPCVD MgB_2 – RF MEASUREMENTS

11.4 GHz TE013 cavity @ SLAC

- The MgB_2 coatings were also characterized at 11.4 GHz 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.

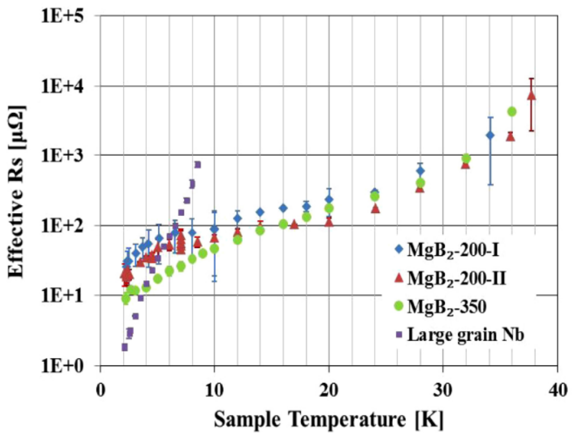




[P. Welander, SLAC]

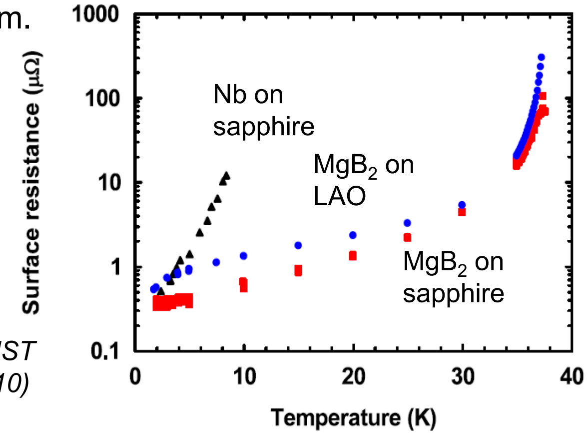
7.5 GHz sapphire-loaded TE011 cavity at JLab

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



Stripline resonator

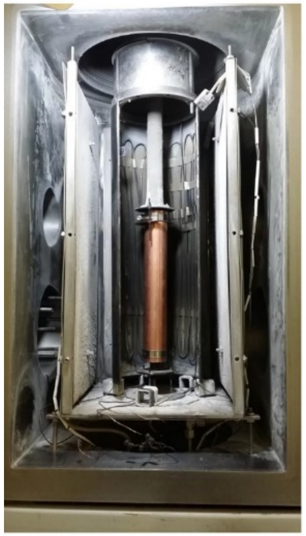
- Scaled to 1,5 Ghz
- Lower surface resistance comparable to Nb film.

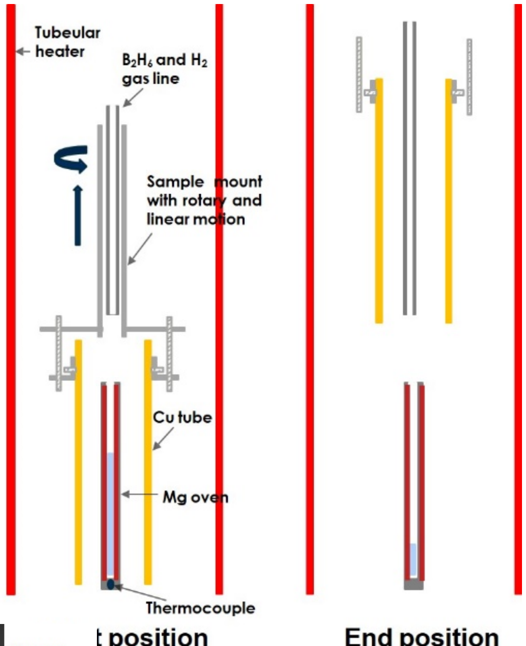


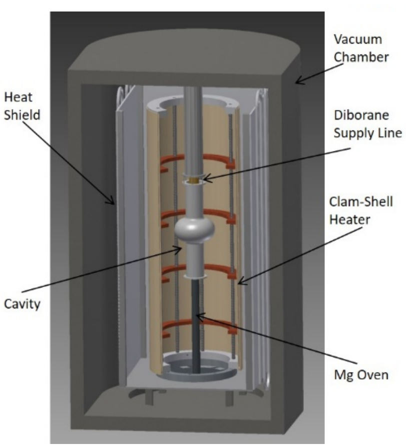
Oates et al., SUST 23, 034011 (2010)

MGB$_2$ - SRF CAVITY COATING

Coating SRF Cavity with a 2-Step Process





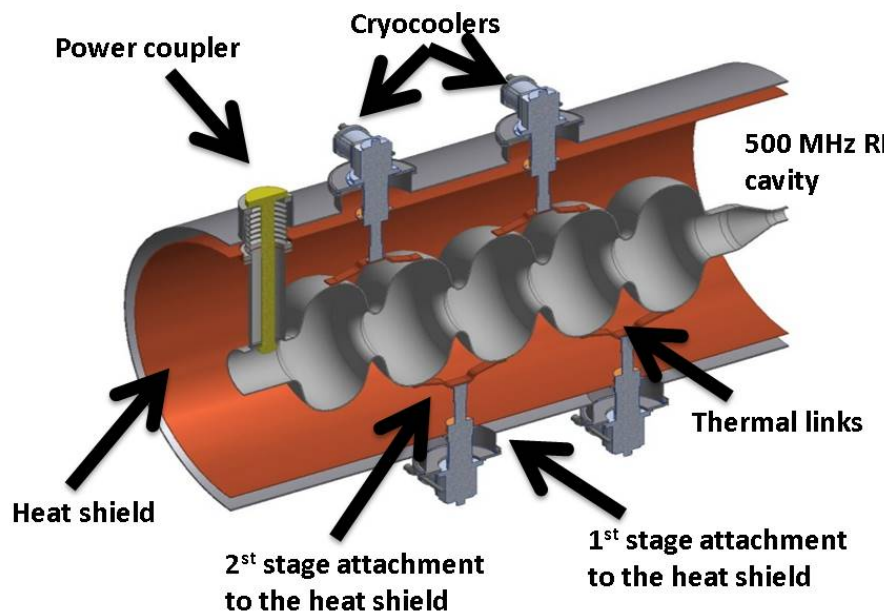


X. Xi, Temple Univ.

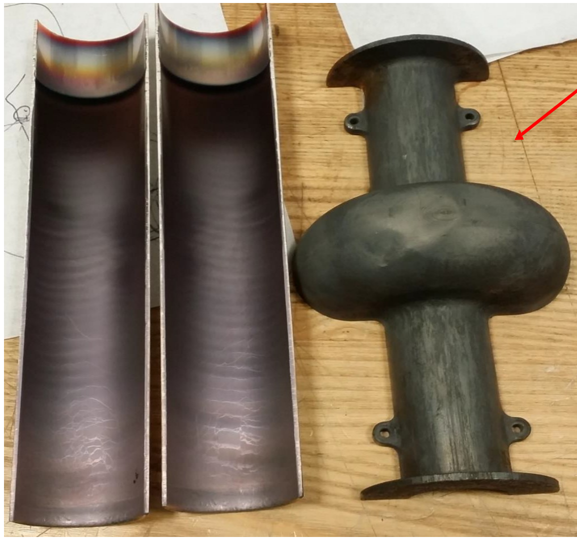
Cryocooler-Cooled MgB$_2$-Coated Cu Cavities

A. Nassiri et al., ANL

Coating of MgB$_2$ /Cu makes operation at 8-12 K possible
Temperature range can be achieved with efficient cryocoolers, providing significant benefit with reduced cost.
Goal: 500 MHz MgB$_2$-coated Cu cavity



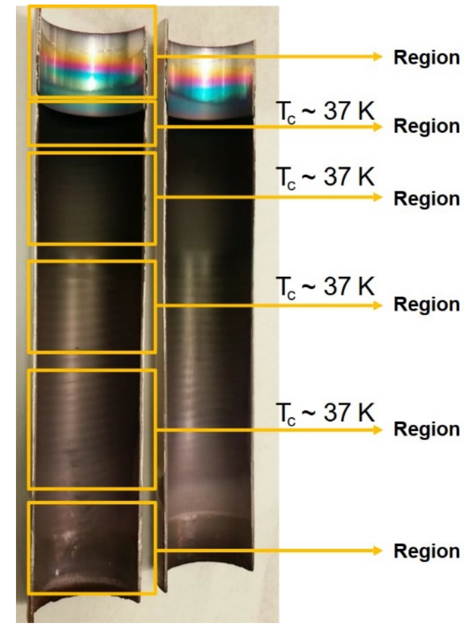
HPCVD MgB_2: Cu tube coating-testing for 3.9 GHz cavity



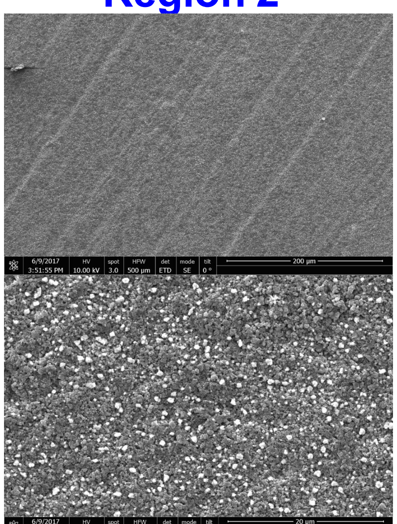
3.9 GHz mock cavity

- B_2H_6 flow rate: 20 sccm
- H_2 flow rate: 100 sccm
- Total pressure: 5 Torr
- Deposition time: 20 - 30 min

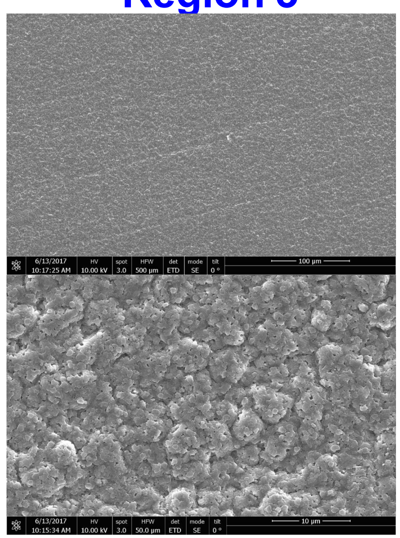
Small piece from each region are tested for superconducting and surface properties

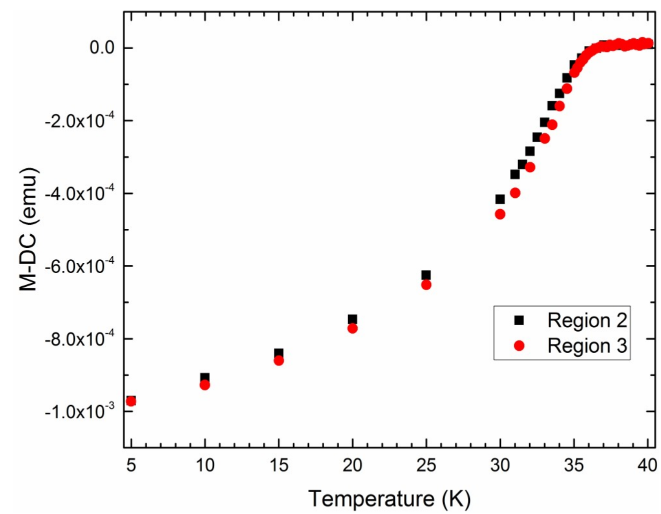


Region 2



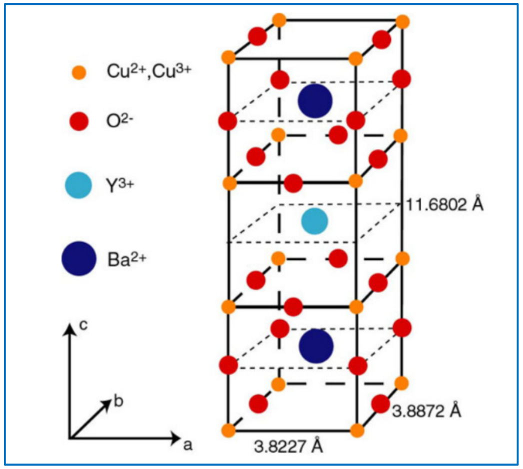
Region 3



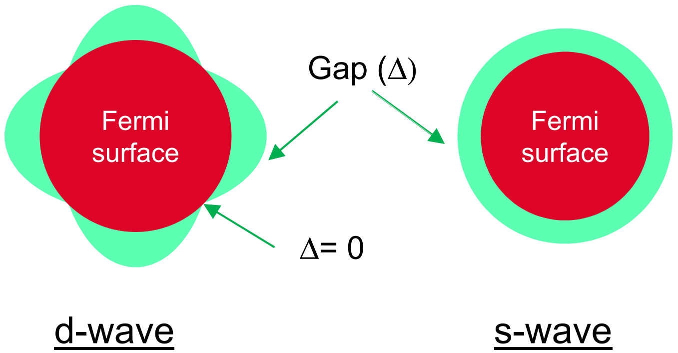


YBCO FAMILY… NOT FOR SRF !

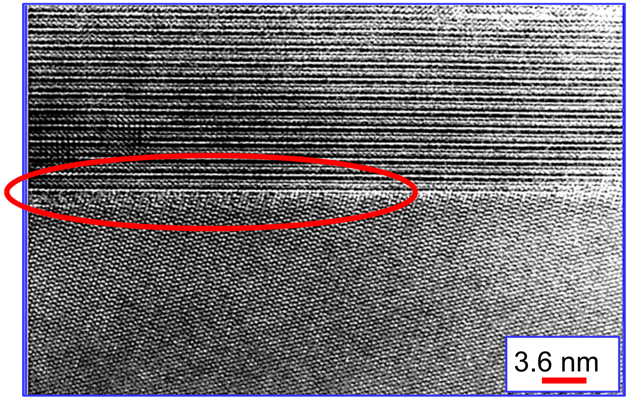
- MonoXt[al] : Jc maximum for (a,b) planes and minimum when // c axis
  - $\xi\chi$ (~0,03 nm) <<ξa, ξb (~1-2 nm) => "layered material"
- Realistic material : polycrystalline, ceramic, fragile…
  - ξc << disordered area at G.B => grains are decoupled (weak links)
  - => try to introduce preferential 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 four line nodes located at the diagonals of the Brillouin zone
  - Δ= 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 $e^{-\Delta/T}$ (BCS resistance)



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



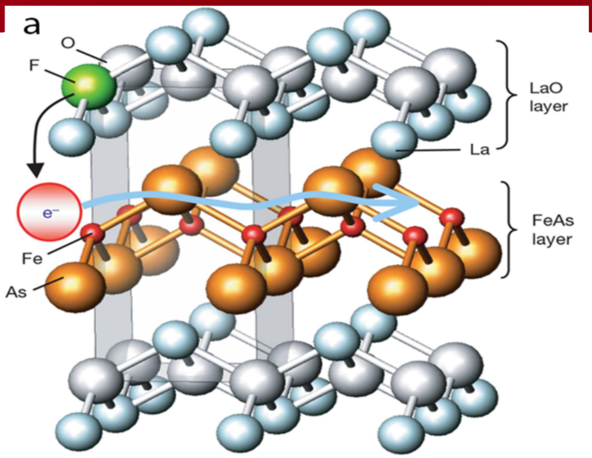
Crystal structure is also related to Brillouin zones. So the relative orientation of the grains can influence the way Cooper pairs are scattered by defects

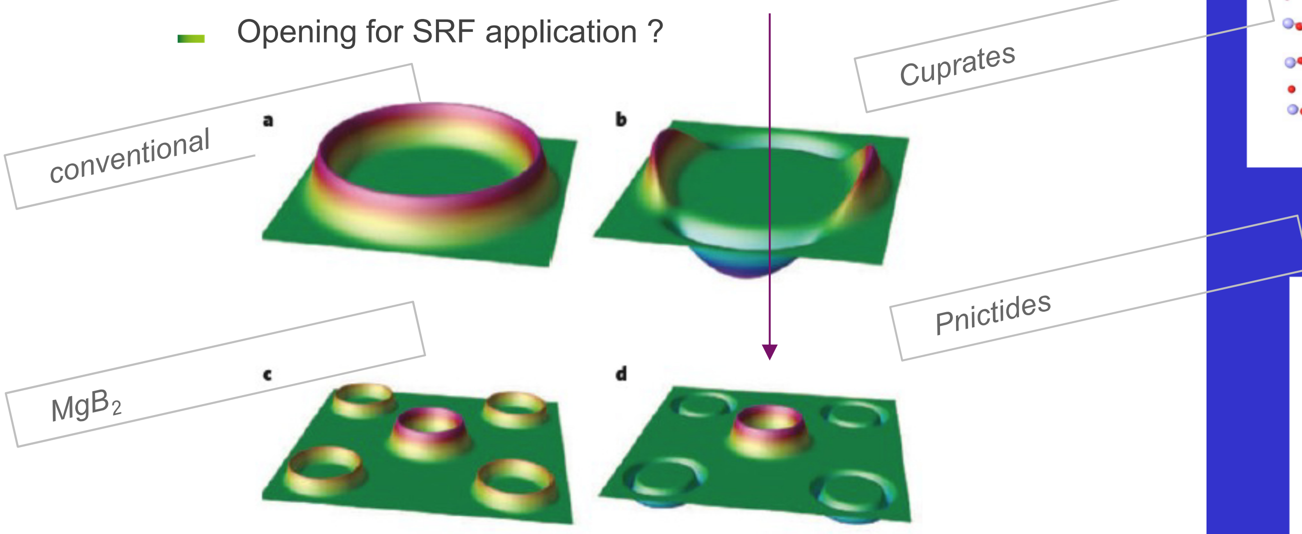


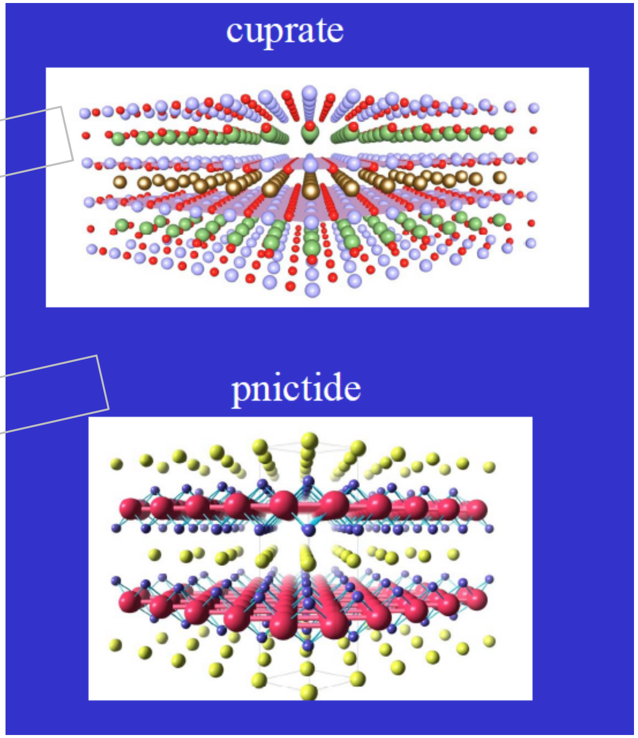
Twin boundary in YBCO https://areeweb.polito.it/ricerca/superconductivity/melt.htm

PNICTIDE FAMILY… MAYBE YES ?

- Oxypnictide base: ReOMPn
  - M = Fe, Co, Ni
  - Pn = As or P
  - Re = La, Nd, Sm, Pr
- A lot of 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 ?







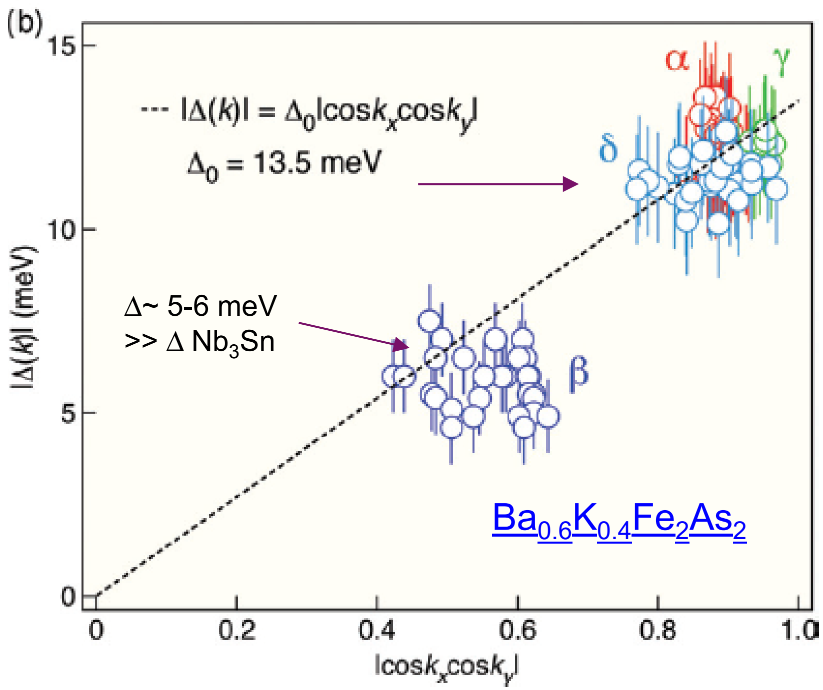
PNICTIDE FAMILY… MAYBE YES ?

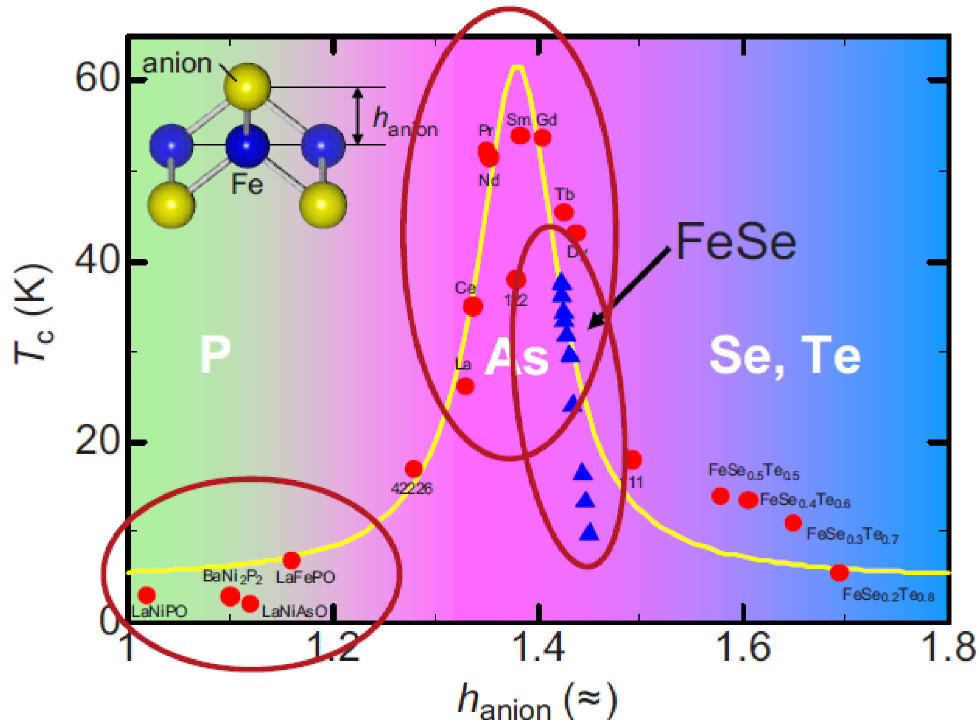
- A lot of common with YBCO
  - High T_C (10-55 K up today)
  - Layered structure
  - Brittle material

  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

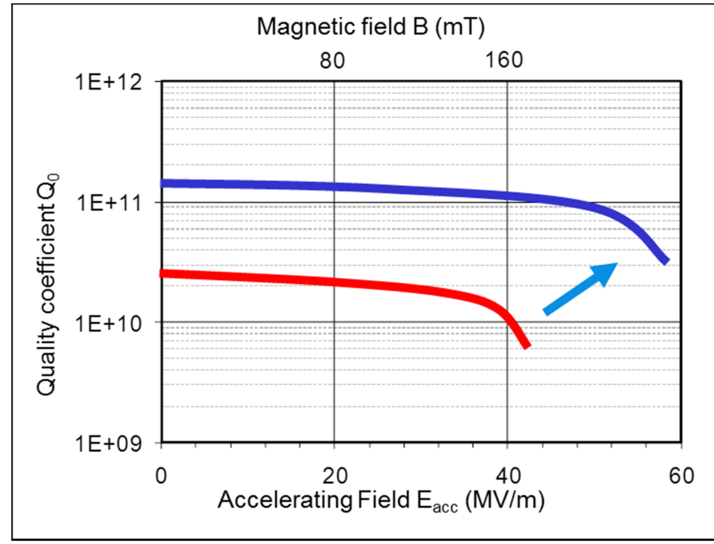




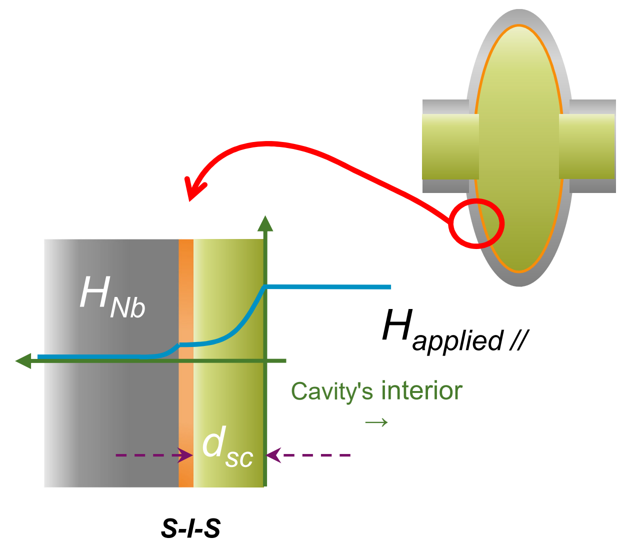
MULTILAYERS

AFTER NIOBIUM : NANOCOMPOSITES MULTILAYERS

Structures proposed by A. Gurevich in 2006, SRF tailored

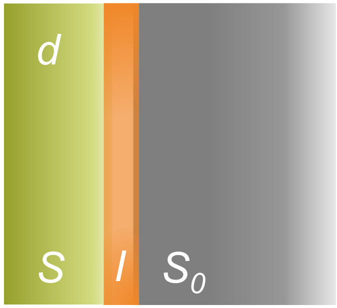


- **Dielectric layer**
  - Small ⊥ vortex (short -> low dissipation)
  - Quickly coalesce (w. RF)
  - Blocks avalanche penetration
  - => **Multilayer** concept for RF application
- **Nanometric I/S/I/ layers deposited on Nb**
  - SC nanometric layers (≤ 100 nm) => H_{C1}↑ => Vortex enter at higher field
  - Nb surface screening => allows high magnetic field inside the cavity => higher E_{acc}
  - SC w. high T_C than Nb (e.g. NbN): $R_s^{NbN} \approx \frac{1}{10} R_s^{Nb}$ => $Q_0^{multi} >> Q_0^{Nb}$



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!!!**

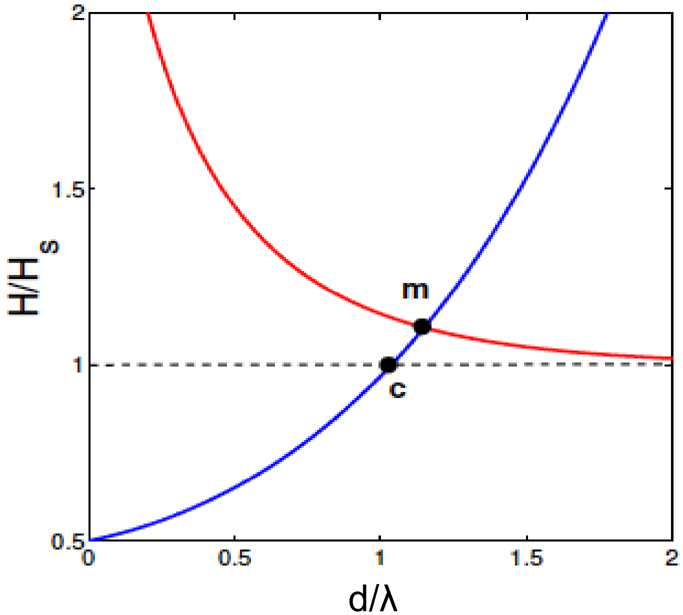


$$\frac{(e^{2d/\lambda} - k)H}{e^{2d/\lambda} + k} \leq H_s, \qquad \frac{H(1+k)e^{d/\lambda}}{e^{2d/\lambda} + k} \leq H_{s0}$$

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

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

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



TRILAYERS ON NIOBIUM

H_m at the optimum thickness exceeds the bulk superheating fields of both Nb and the layer material because of counterflow induced by Nb in the S layers with $\lambda > \lambda_0$
For $\lambda >> \lambda_0$, practically for $\lambda > 160$ nm for a S layer on the Nb cavity with $\lambda_0 = 40$ nm, H_m approaches the limit

$$H_m \to \sqrt{H_s^2 + H_{s0}^2}$$

- **Dirty Nb layer:** $H_c = 200$ mT, $H_s = 170$ mT, $l = 2$ nm, and $\lambda = \lambda(\xi_0 / l)^{1/2} = 180$ nm
  $H_m = 288$ mT, $E_{acc} = 70$ MV/m $d_m = 0.44\lambda = 79$ nm. +20% compared to $H_{SH}^{clean\ Nb} = 240$ mT

- **Nb_3Sn:** $H_s = 0.84 H_c = 454$ mT and $\lambda = 120$ nm (moderately dirty):
$H_m = 507$ mT, $E_{acc} = 120$ MV/m, $d_m = 1.1\lambda = 132$ nm x2 $H_{SH}^{clean\ Nb}$

- **Fe-pnictides on Nb:** Hs = 0.84Hc = 840 mT and $\lambda = 200$ nm:
Hm = 872 mT, Eacc = 206 MV/m, dm = 1.78λ = 356 nm x4 $H_{SH}^{clean\ Nb}$

Kubo et al, APL, 104, 032603 (2014); SUST, 30, 023001 (2017);
(London calculations)
Posen, et al, Phys. Rev. Appl. 4, 044019 (2015)
(London and GL calculations)
A. Gurevich, SUST 30, 034004 (2017)

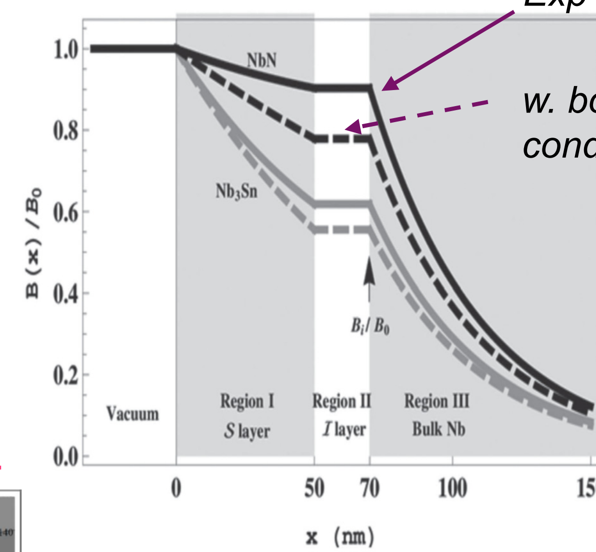
SIS OPTIMIZATION: IMPORTANCE OF MODELS

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

A. Gurevich, T. Kubo

Exp decay

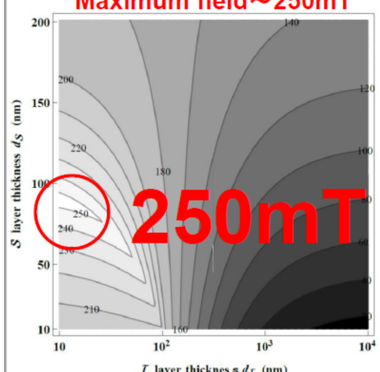
w. boundary cond.



← Quasiclassical Approach, Can be further improved…

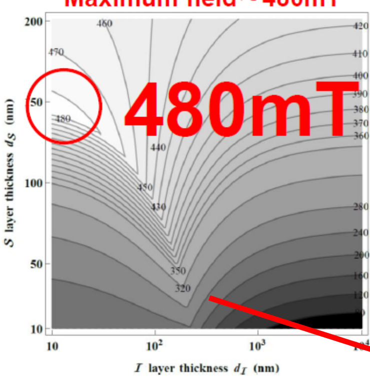
Dirty Nb / *I* / Nb

Optimum d_s~90nm
Maximum field~250mT



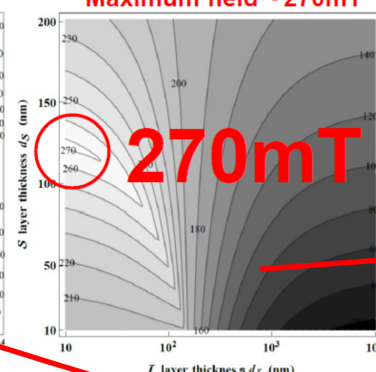
Nb_3Sn / *I* / Nb

Optimum d_s~150nm
Maximum field~480mT

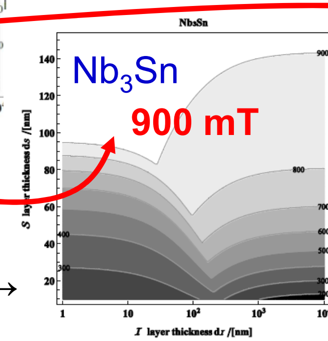


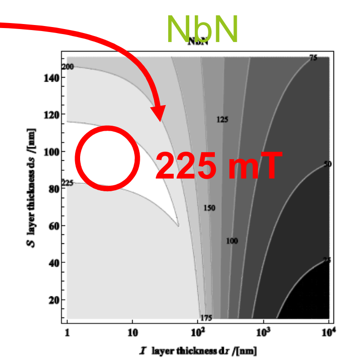
NbN / *I* / Nb

Optimum d_s~130nm
Maximum field~270mT



[Kubo 2013-17]





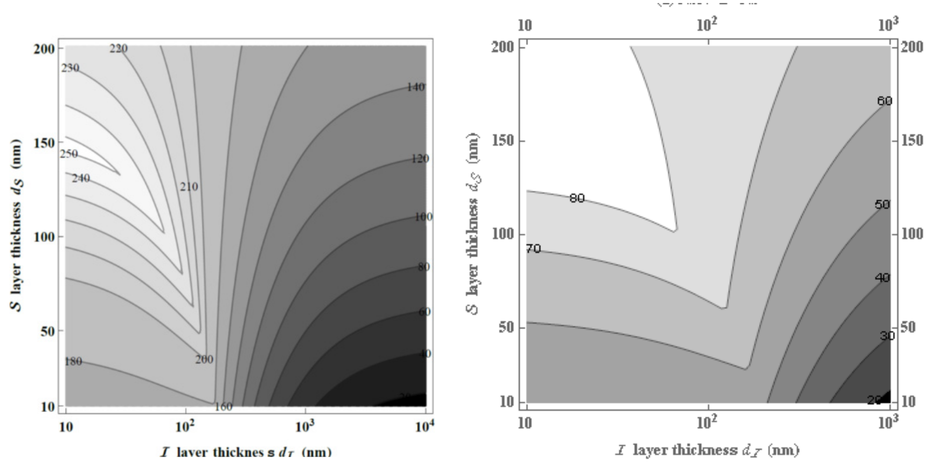
Previous calculation w. London theory only: not realistic →

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 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



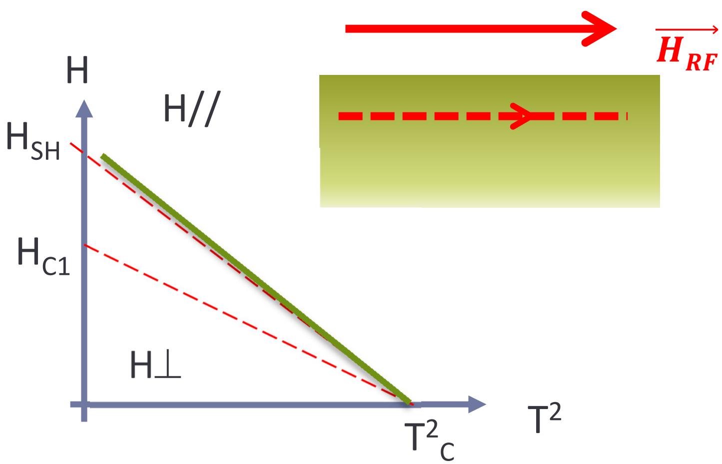
Nb with defects, with B_{C1}=50 mT*

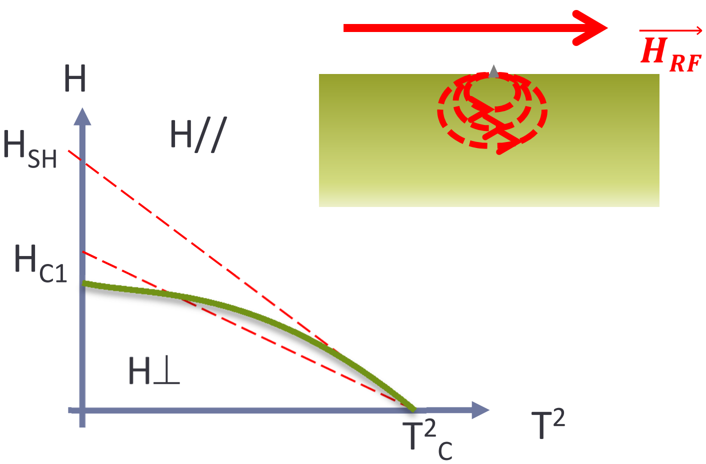
** e.g. morphologic defects that allow earlier vortex penetration*

See exp proof later on

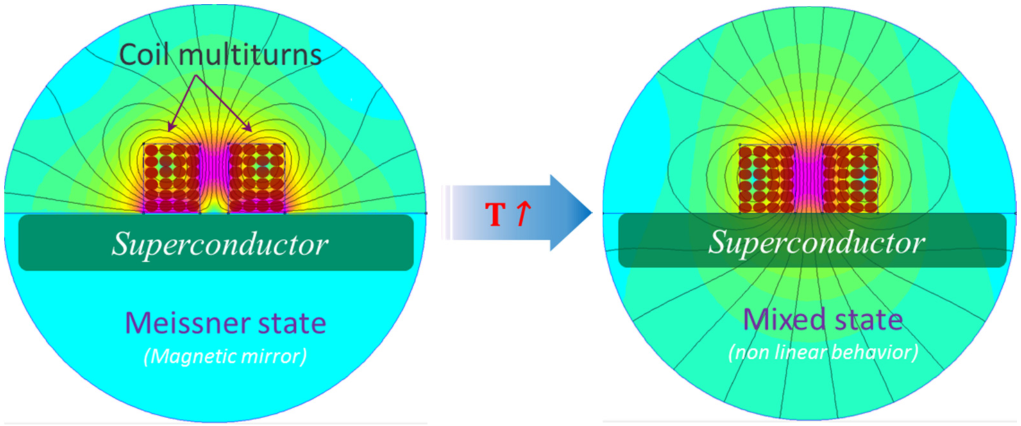
WHAT IS THE LIMIT ($H_P/H_{C1}/H_{SH}$) ?

- 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

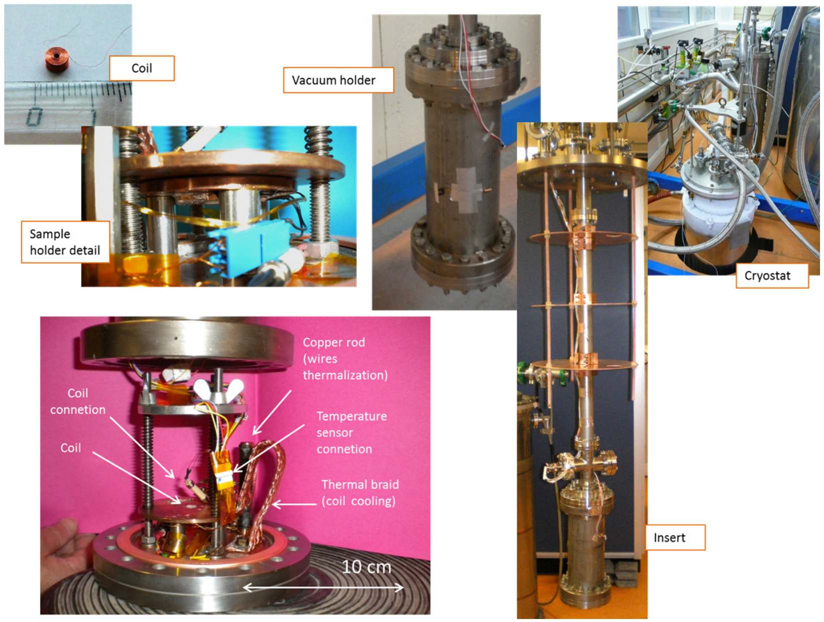


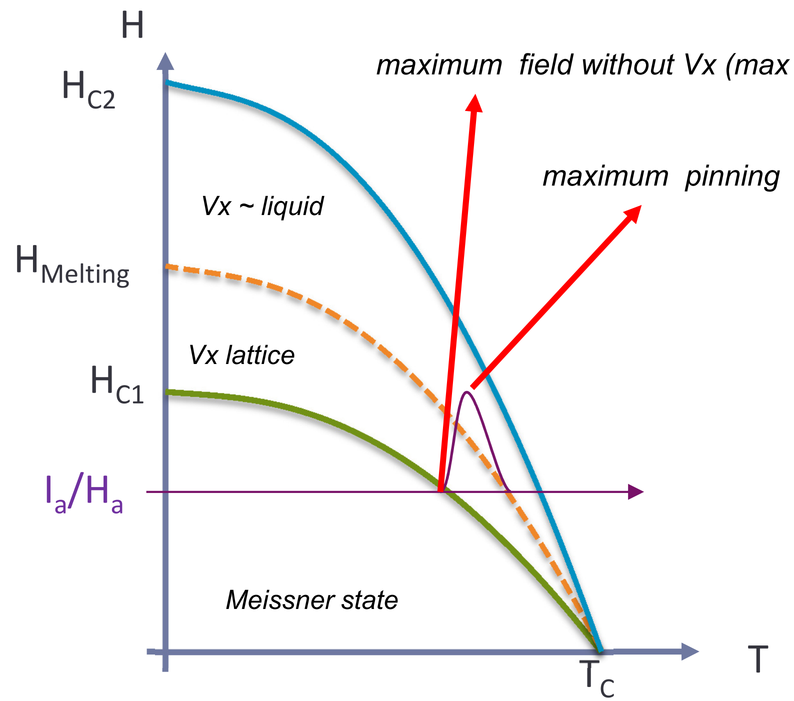


- Local magnetometry
  - ~ Same geometry as cavities
  - No shape/edge effect (vs DC/ Squid magnetometry)
  - No demagnetization effect
  - Measures actual penetration field wherever it is $H_P/H_{C1}/H_{SH}$

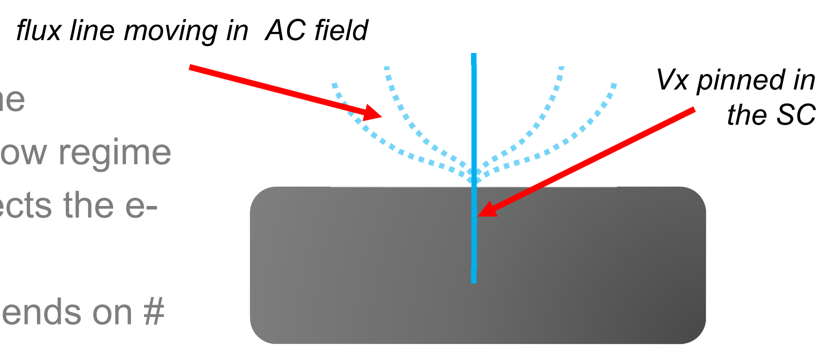


EXPERIMENTAL DETAILS





- **Low frequency ≡ DC :**
  - $0 < H_a < H_{C1}$ => R=O, Meissner state
  - $H_{C1} < H_a < H_M$ =>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).



NbN coating by Magnetron Sputtering

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

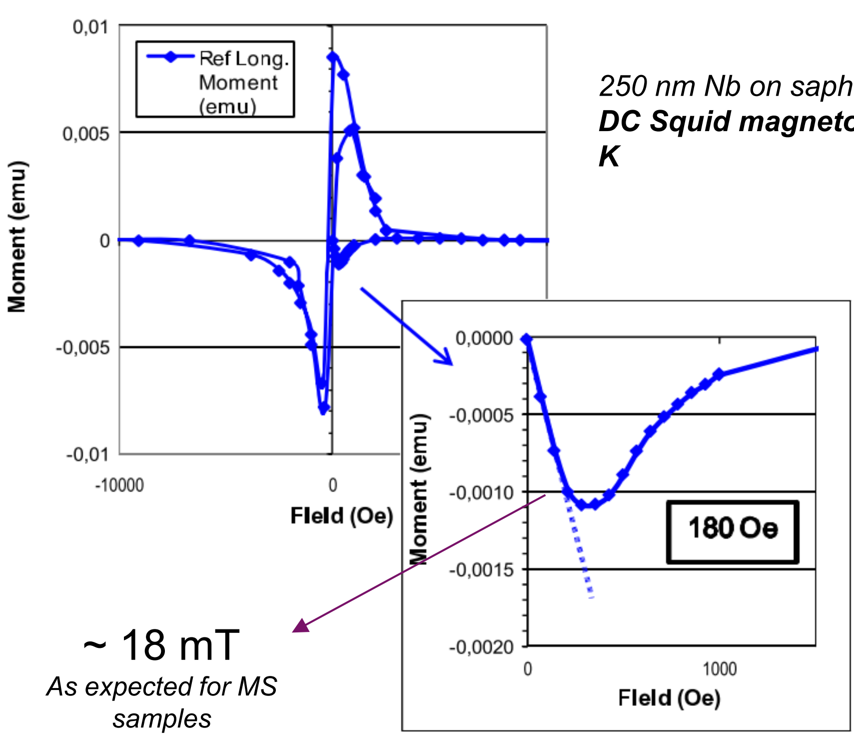
Nb (nm)	MgO (nm) Calc(actual)	NbN (nm) Calc(actual)	T_C (K)
250†	14	0	8.9
250†	14	25	15.5
500	10 (10.3)	50 (65)	15*
500	10 (8.4)	75 (72)	14.1*
500	10 (9.8)	100 (94)	14*
500	10	125	14.3*
500	10 (6.7)	150 (132)	15.9*
500	10 (10.4)	200 (164)	15*

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

SPUTTERED (DEFECTIVE) MATERIALS…

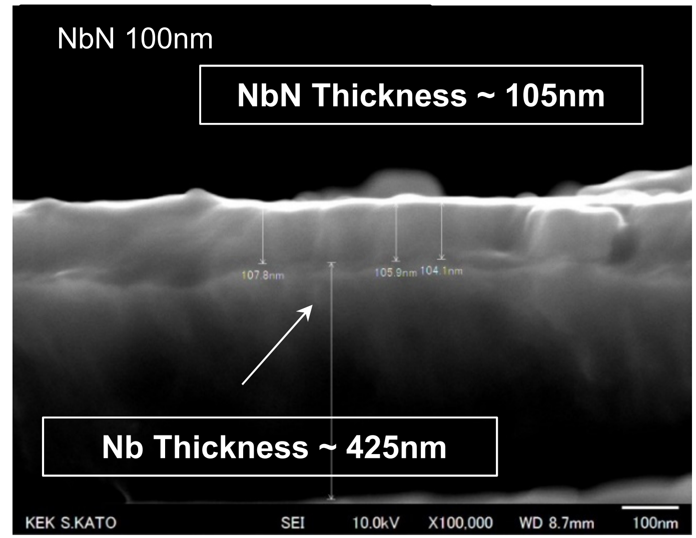
Typical defects…

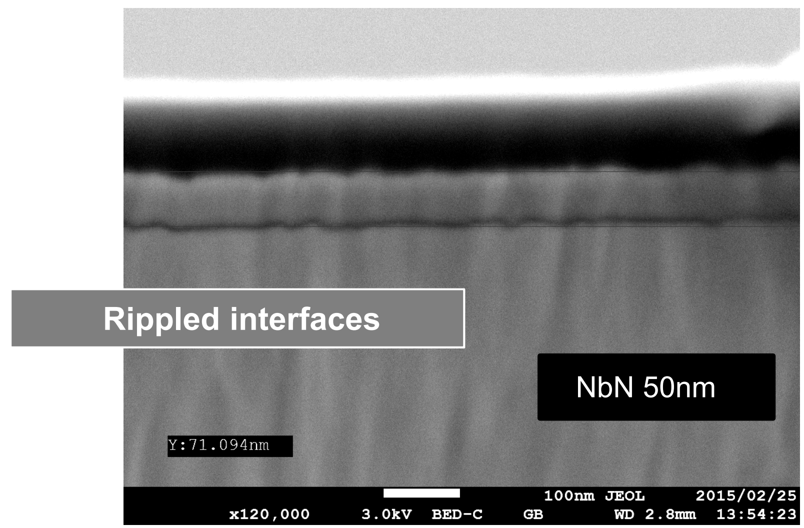
- Low H_{C1}
- Thickness ≠ uniform
- …



250 nm Nb on saphire
DC Squid magnetometry @ 4.5 K

~ 18 mT
As expected for MS samples

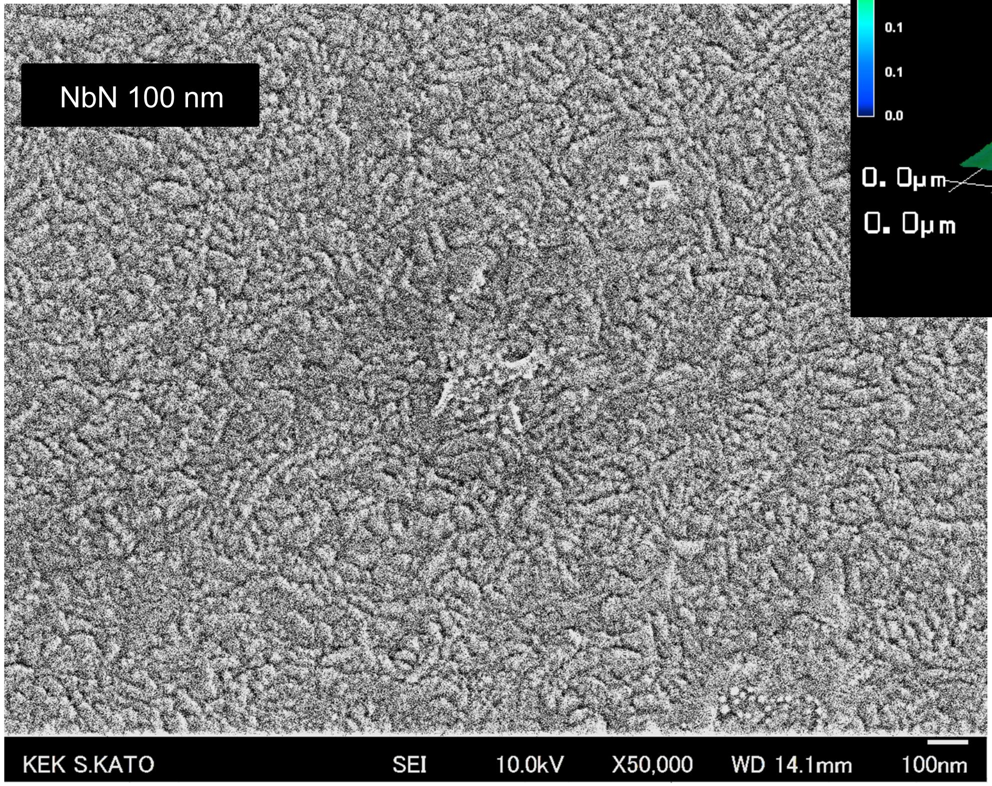


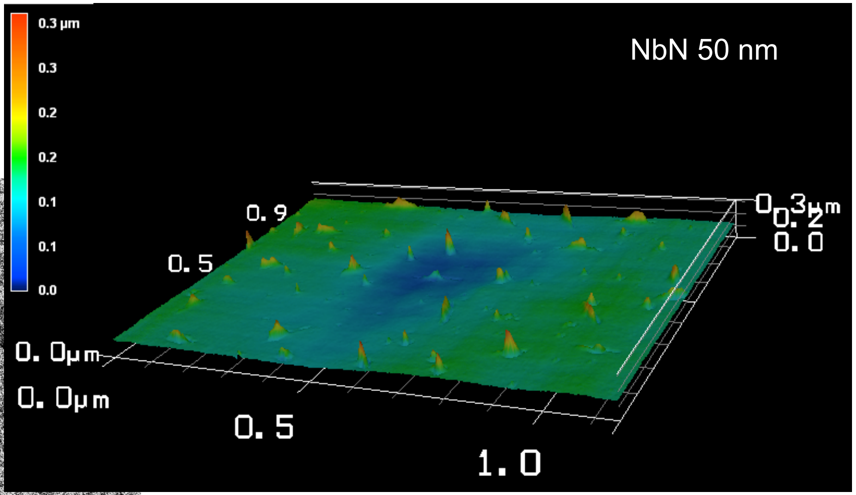


FAR FROM PERFECT....

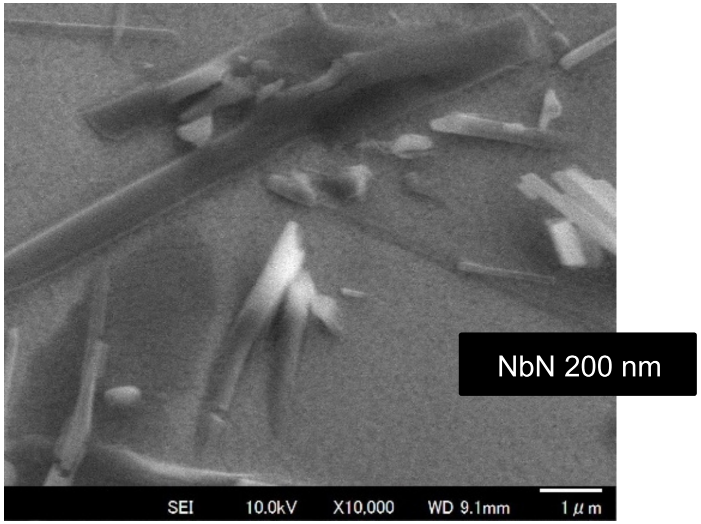
Morphology

- Rough surface



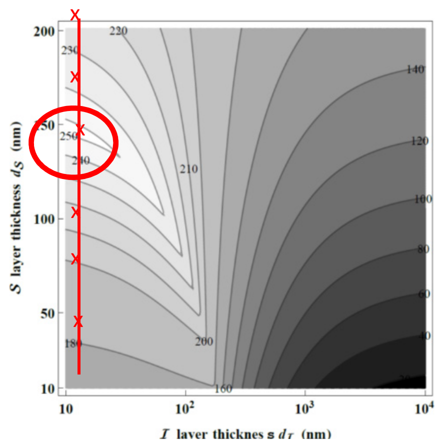


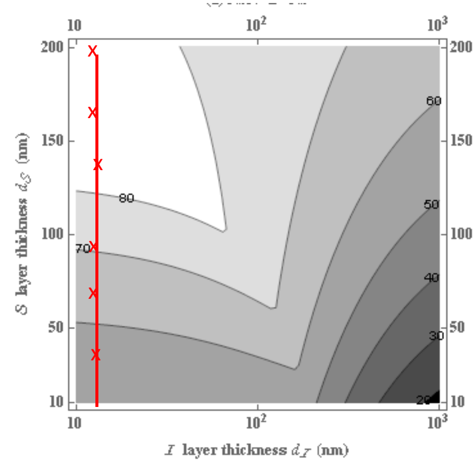
MgO needle ?
(capping material)



Theoritical predictions from T. Kubo (KEK)

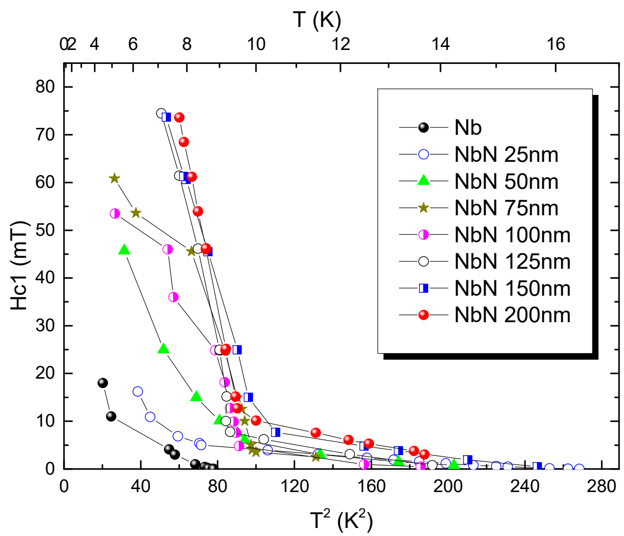
Ideal Nb substrate with B_{C1}=170 mT





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

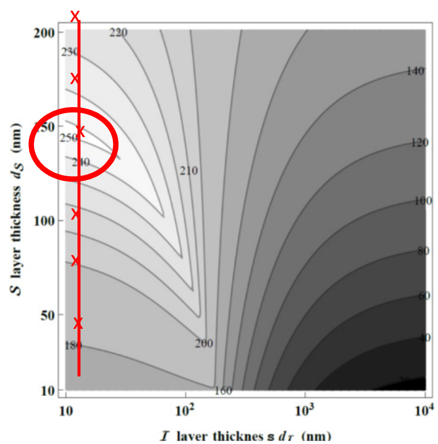
** e.g. morphologic defects that allow earlier vortex penetration See SST paper cited earlier*

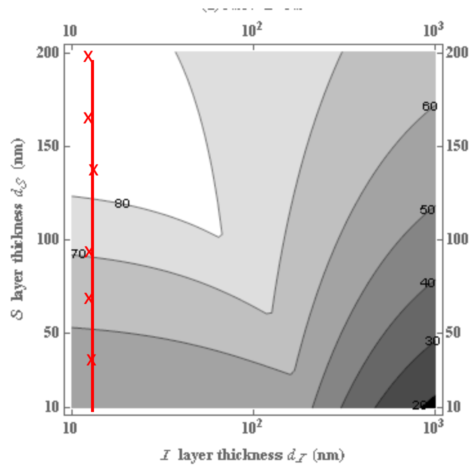


- The enhancement of the field penetration increases with thickness of NbN
- It reaches a saturation at thicknesses > 100 nm

Theoritical predictions from T. Kubo (KEK)

Ideal Nb substrate with B_{C1}=170 mT

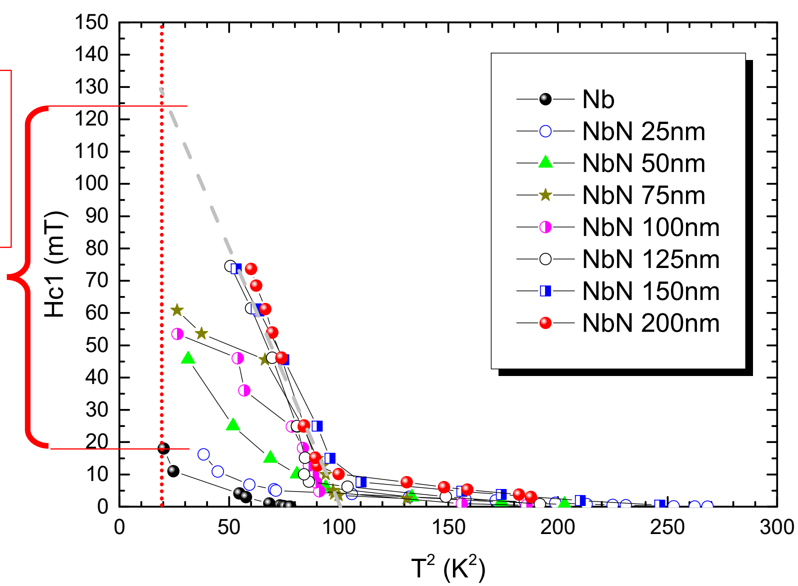




Nb with defects, with B_{C1}=50 mT*

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

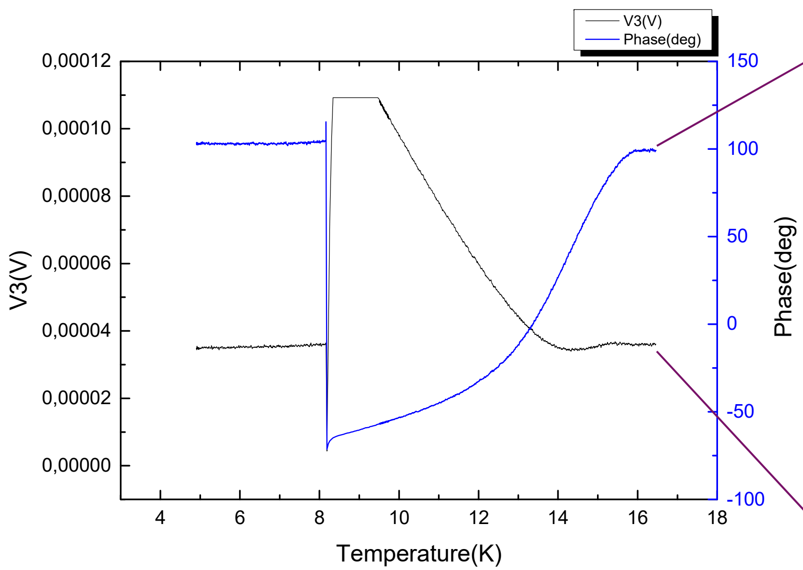
@ 4.5 K
~ + 110 mT?
~25-30 MV/m
ILC shape



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

CLOSEUP OF 3rd HARMONIC SIGNAL

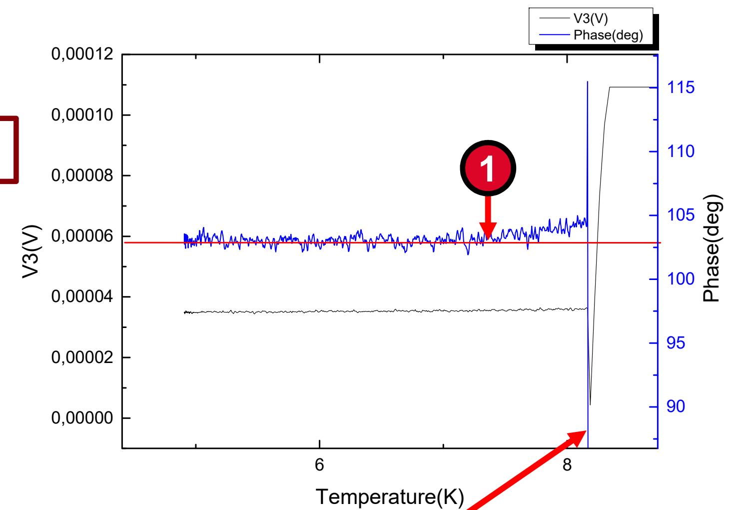
- For a given H_{appl}, we observe 3 ≠ transition temperatures

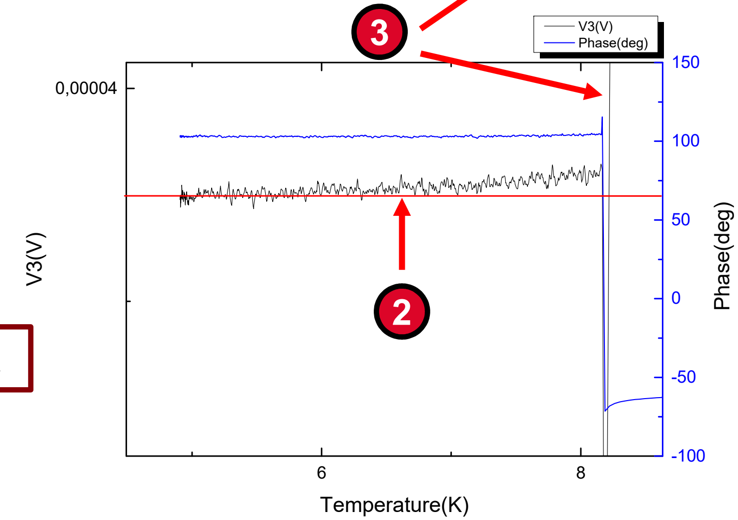


Phase signal

T❶~T❷
T ❸>>T❷

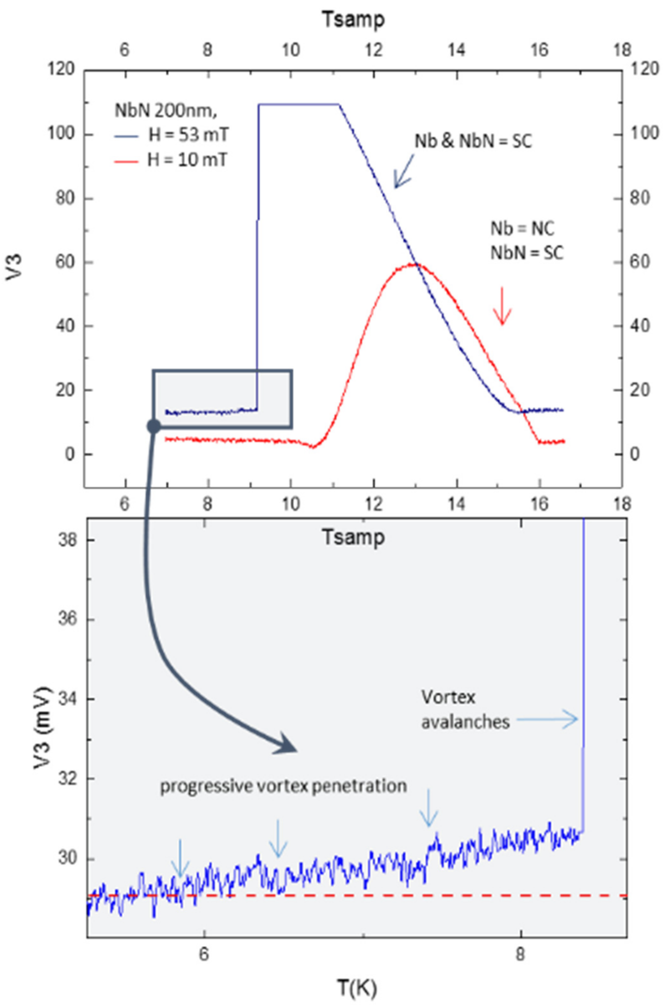
Voltage signal

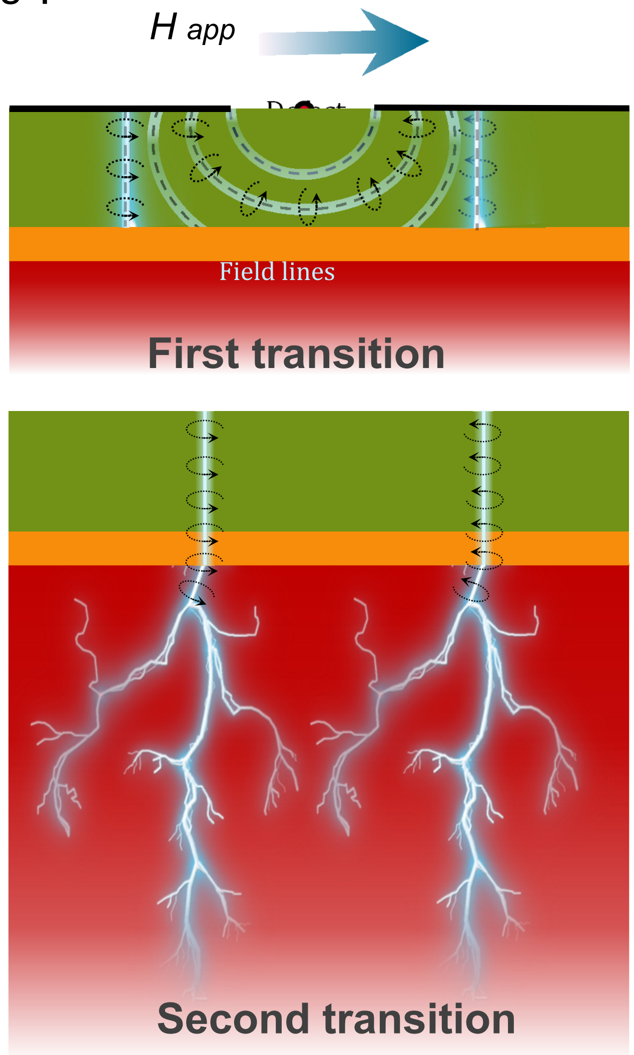




- T❶~T❷: within noise level
- T ❸>>T❷: dramatic transition

- Why do we have two transitions ?



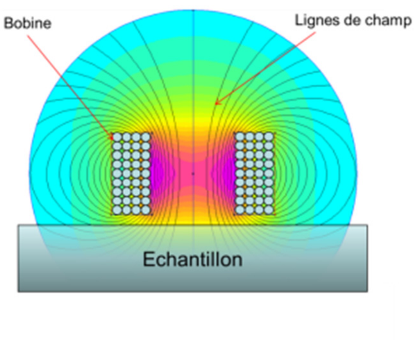


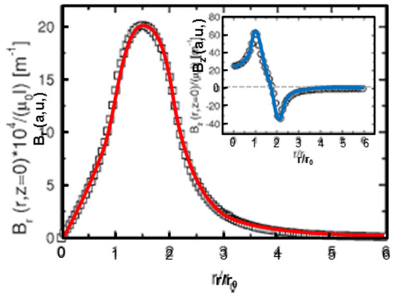
- H // surface => surface barrier†
- A defect locally weakens the surface barrier
- 1st transition, vortex blocked by the insulator ~100 nm => low dissipation.
- 2nd transition, propagation of vortex avalanches (~100 µm) => high dissipation.
- **Dielectric layer = efficient protection !!!**

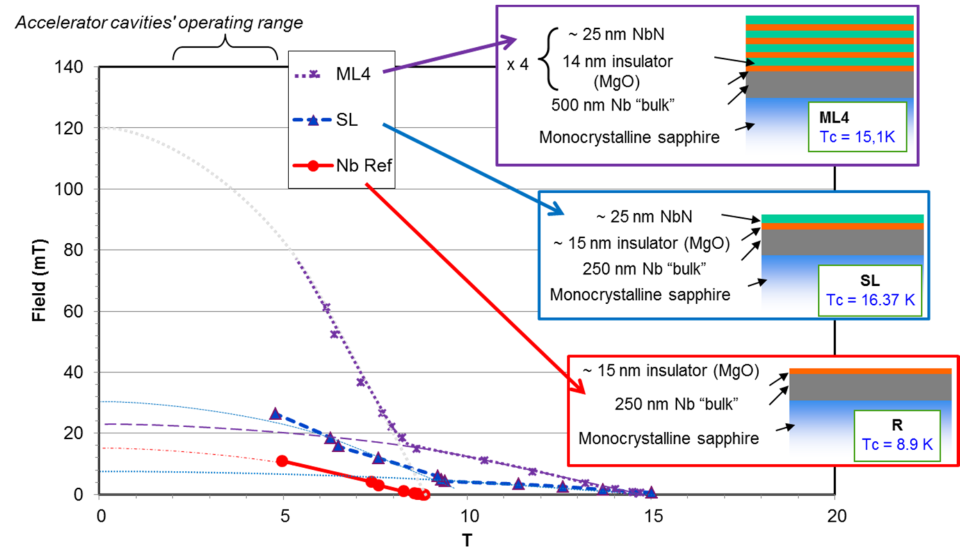
† *B. Bean and J. D. Livingston, Phys. Rev. Lett. 12, 14 (1964).*

H_{C1} (E_{ACC}^{MAX}) AND R_S (Q_0^{MAX}) ESTIMATION

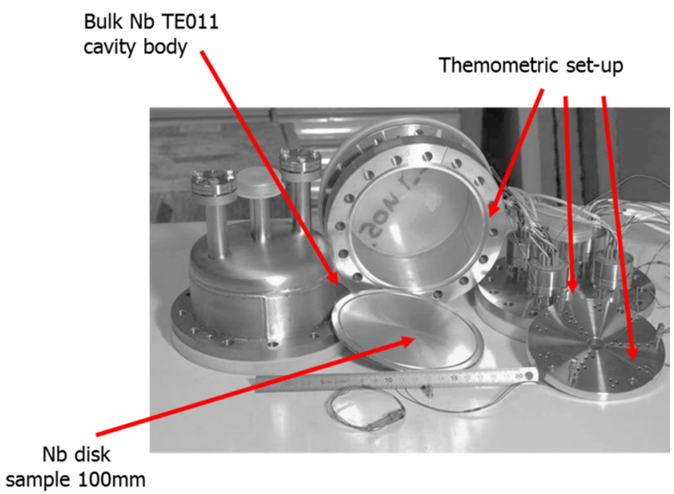
- Local magnetometry:

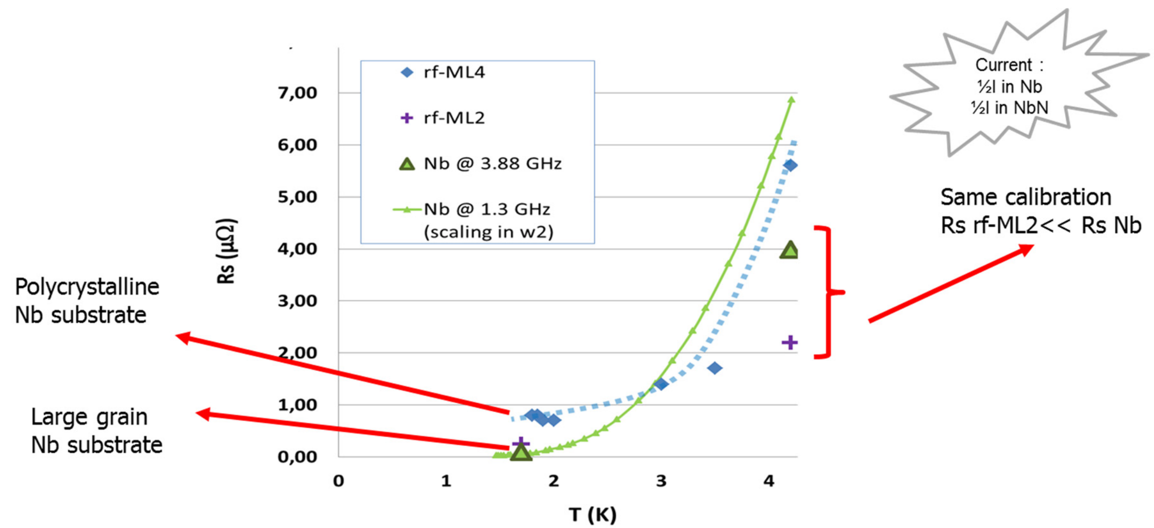




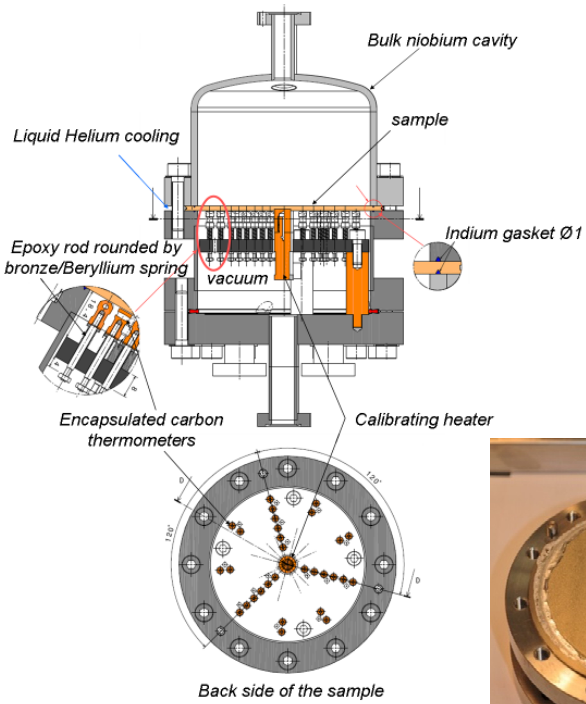


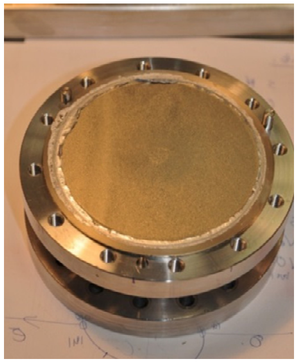
- RF test (collaboration IPNO)

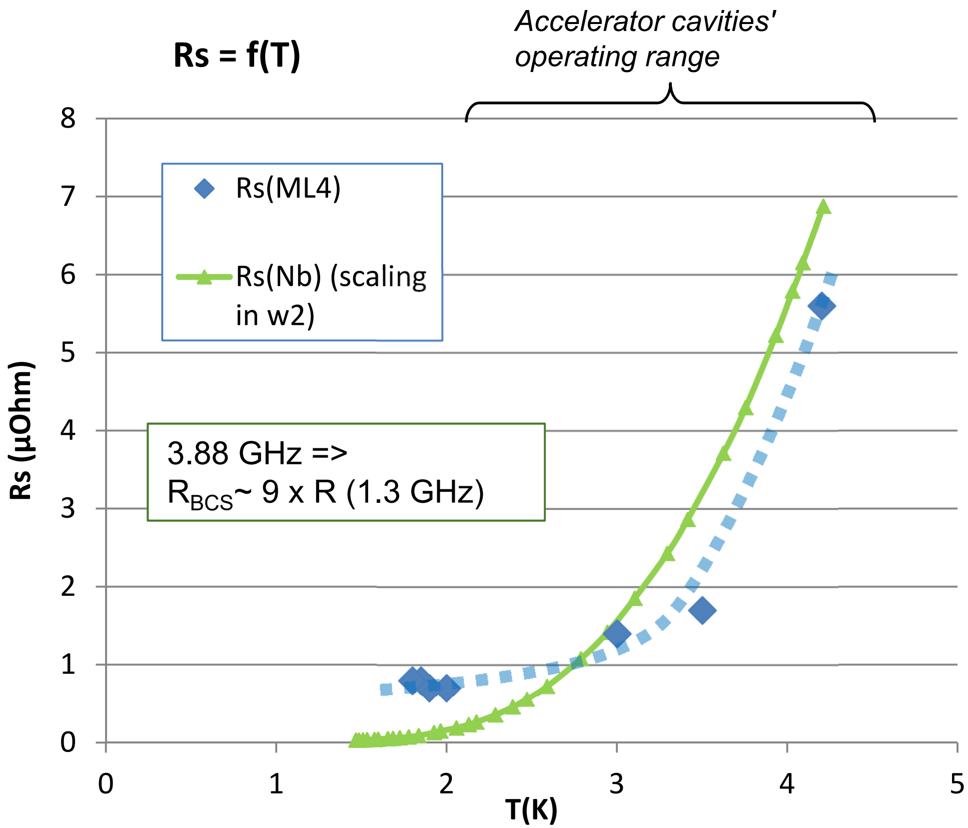




1^{st} TEST RF @ 3,88 GHZ (4 25nm NbnN LAYERS)

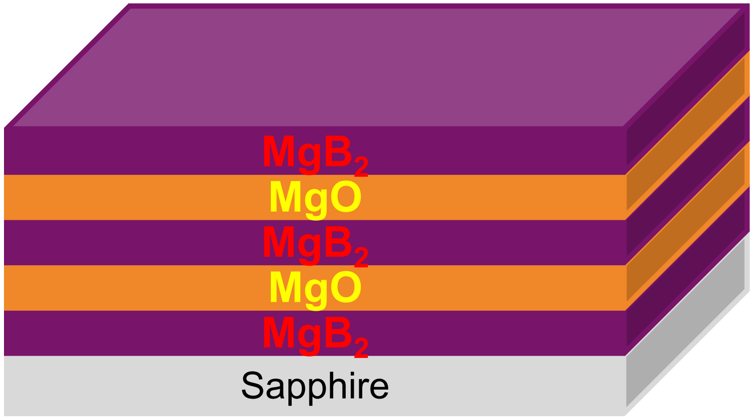






- Comparison is done with a high performance 1.3 GHz Nb cavity (scaling in ω^2)
- Indium gasket presents some defects measured with thermometric map => extra RF losses
- Residual resistance comes from NbN + bulk Nb substrate + indium gasket. Further investigations needed.

MgB_2-MgO MULTILAYER FILMS

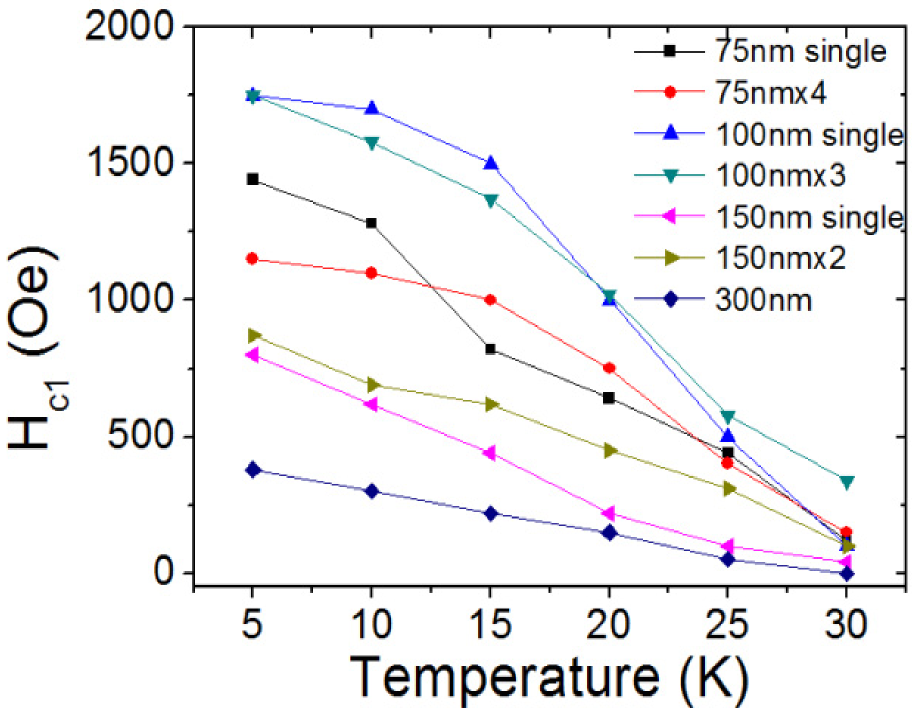


Alternating MgB_2-insulator structures have been fabricated on sapphire substrate:

- 40 nm MgO as insulating layer, sputtered.
- MgB_2 deposited by HPCVD *ex situ*. 150, 100, and 75 nm in thickness.

T_c near 40 K for 100 and 150 nm films. Lower for 75 nm film.

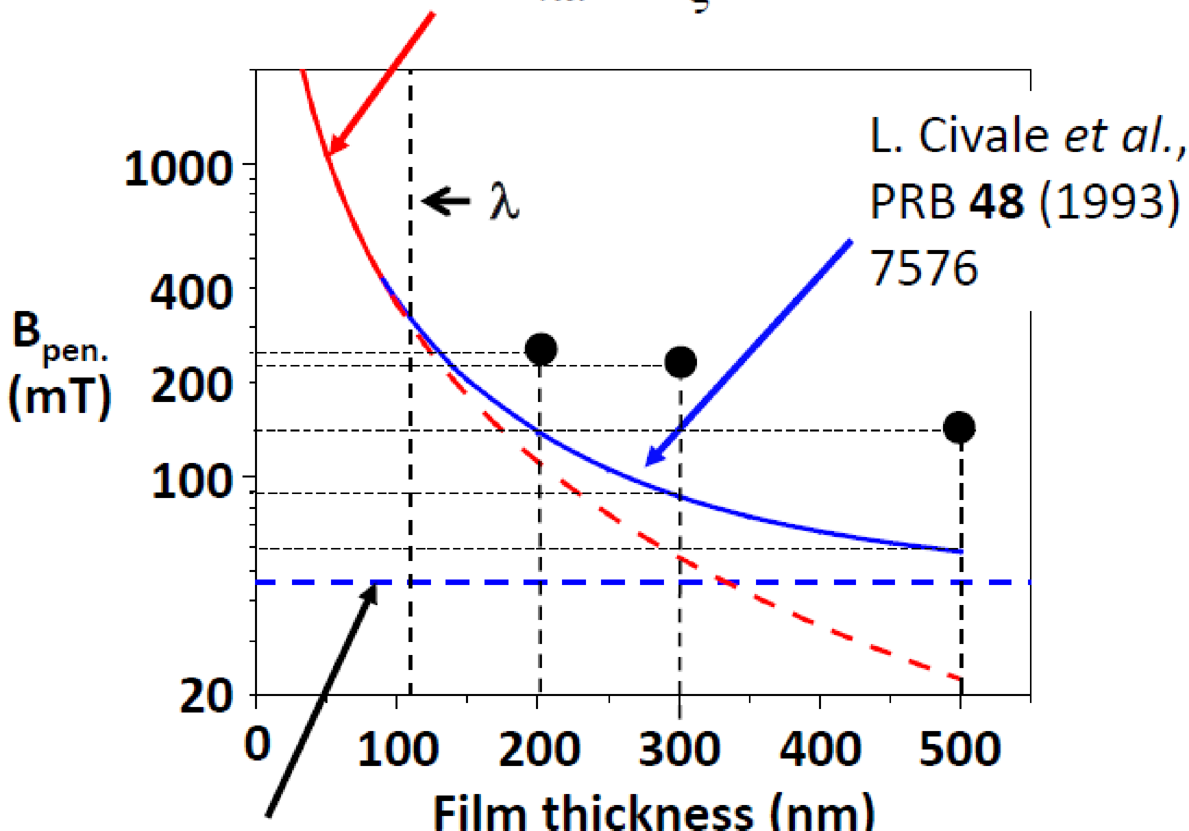
Multilayer films with thin MgB_2 layers show higher H_{C1} than the 300 nm film even though the total thickness are the same.



[Teng, Xi – Temple University]

B_{pen} data are higher than expected B_{c1} (λ=110 nm, ξ=6 nm)

$$H_{c1}(d \ll \lambda) \approx \frac{2\Phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}}$$ Gurevich, APL **88** (2006) 012511



[Tajima, SRF 2011]

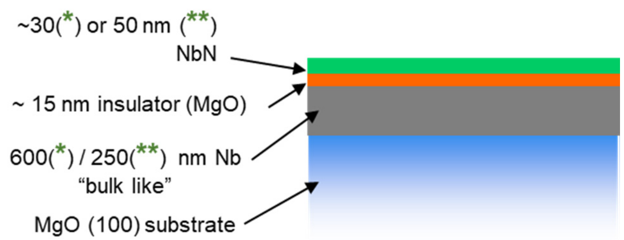
$$H_{c1}(d \gg \lambda) = \frac{\Phi_0}{4\pi\lambda^2} \ln \kappa \sim$$ **46 mT**

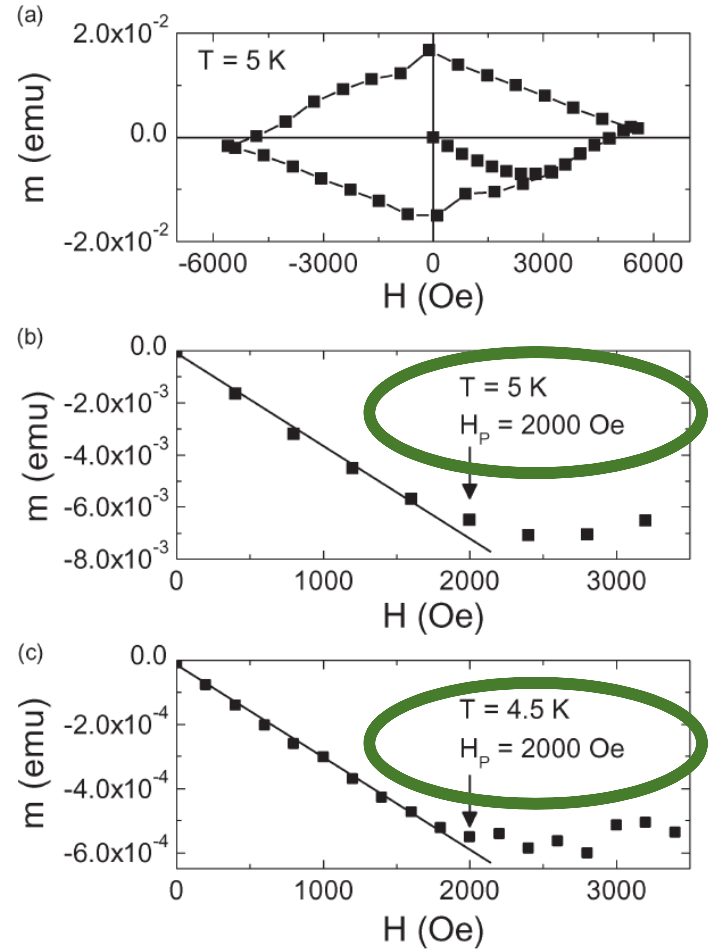
SRF2011, Chicago, IL, USA, 25-29 July 2011

8

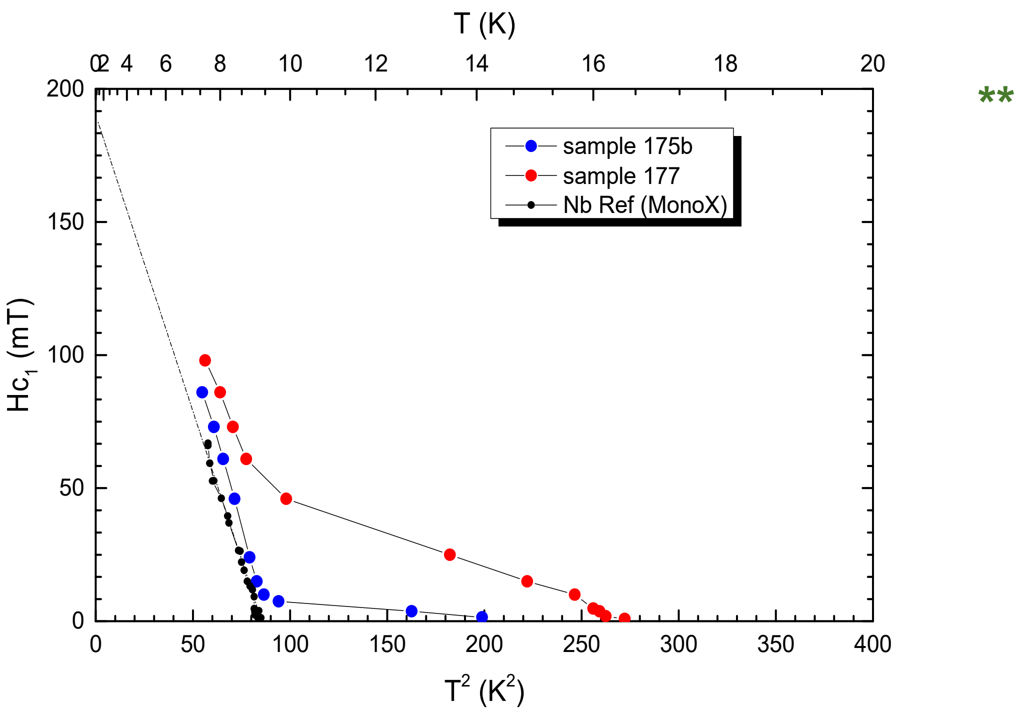
OTHER RESULTS ON NbN OR NbTiN ML

- **Nb/MgO/NbN Samples**
  [Lukaszew, 2012]





- **Nb bulk /AlN/NbTiN Samples** *[AM Valente-Felicianno, TBP]*



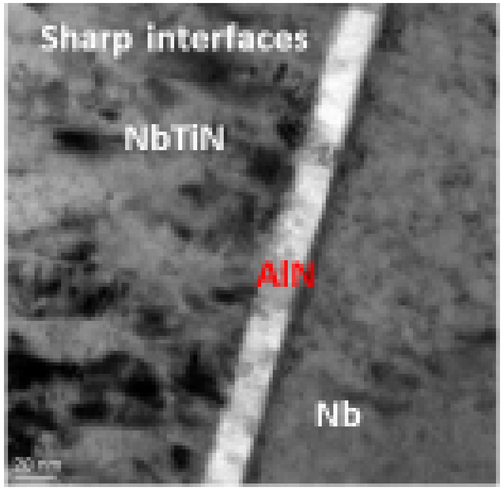
- **Compare with what is expected for bulk Nb : ~1300 Oe @ 4.5 K !**

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.

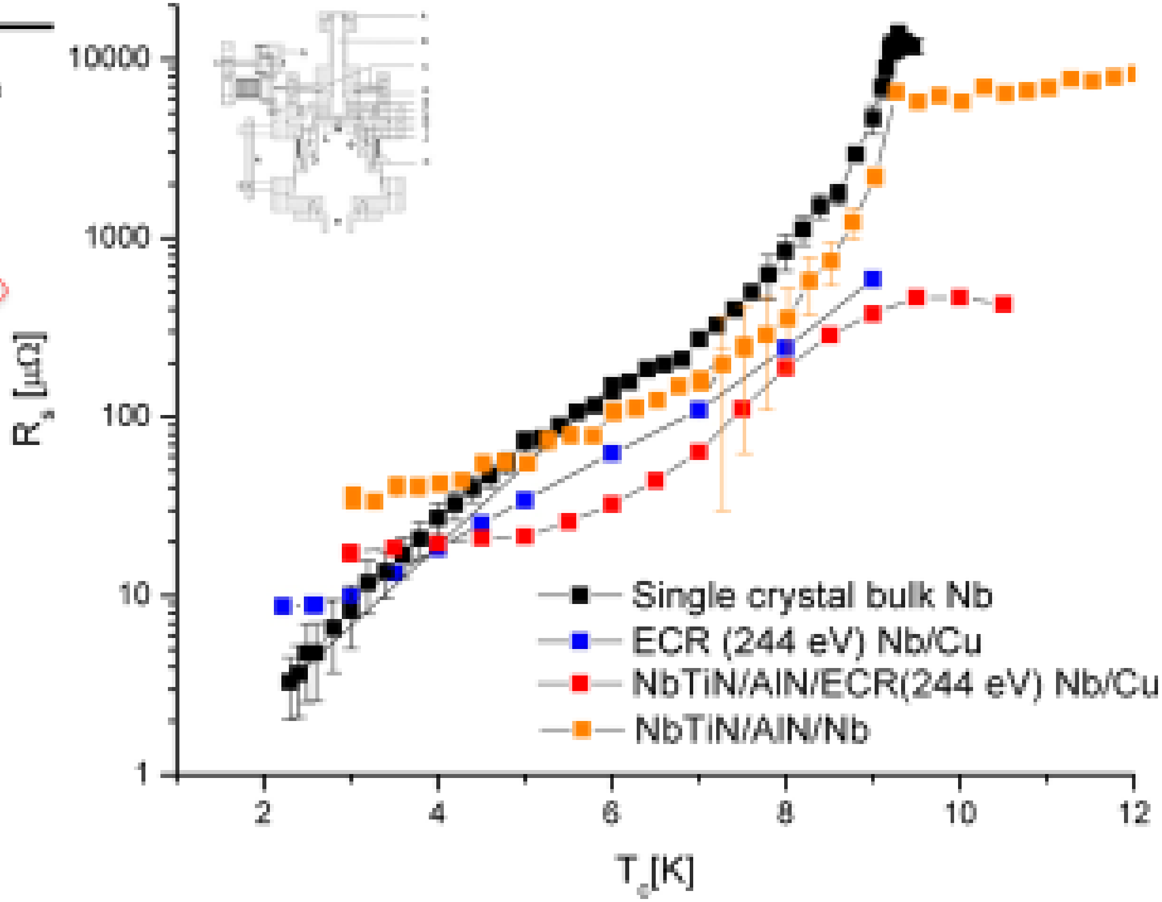
[A.M.Valente-Feliciano]

	AlN	NbTiN
N_2/Ar	0.33	0.23
Total pressure [Torr]	$2x10^{-3}$	$2x10^{-3}$
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

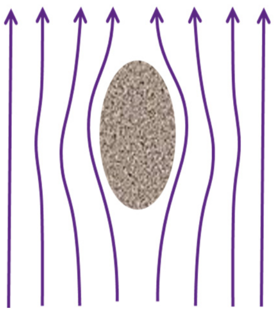
RF Measurement in 7.5 GHz sapphire-loaded TE_{011} cavity

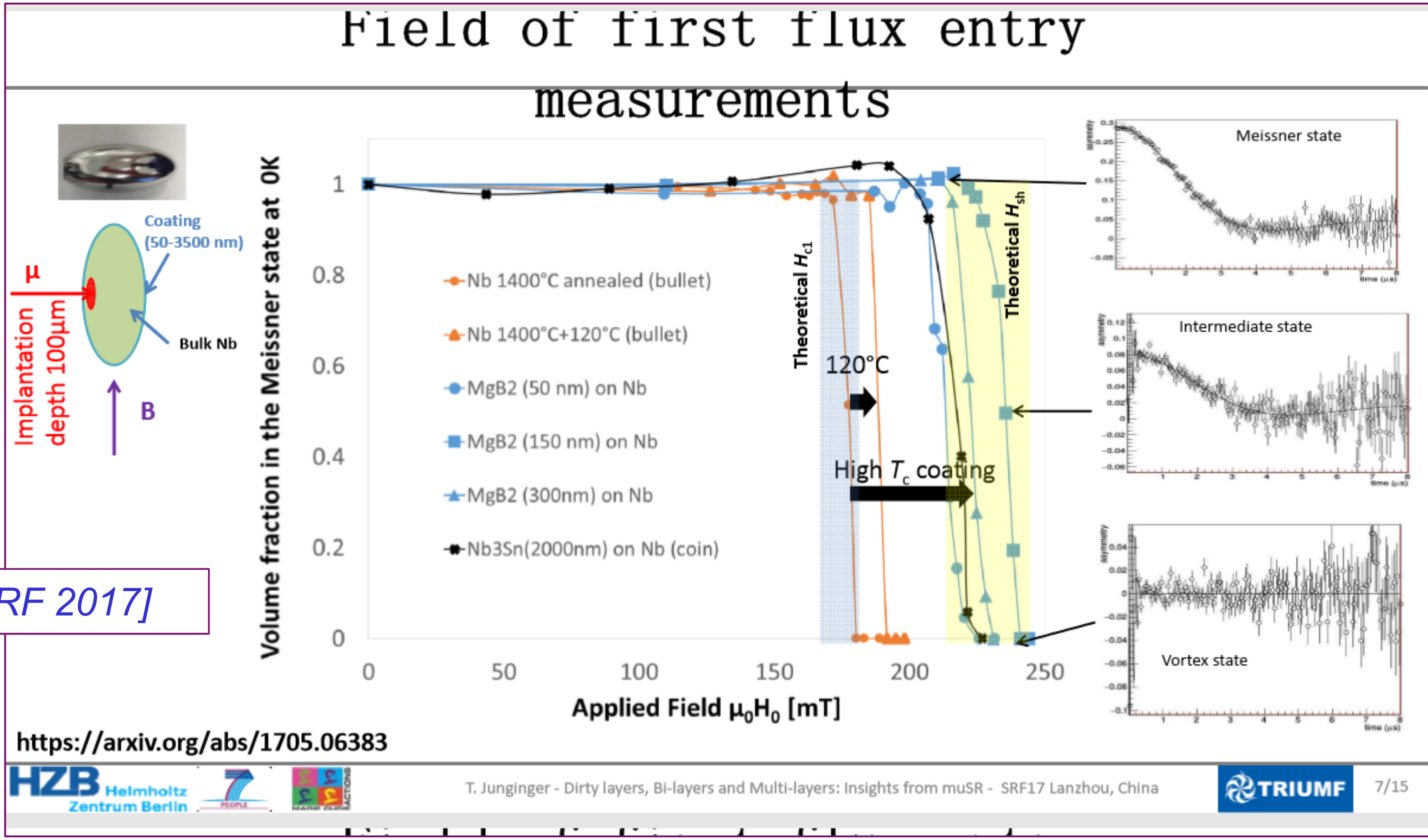


Lower BCS resistance beyond 4 K for SIS coated surfaces compared to standalone ECR film & bulk SC Nb.

ML WITHOUT DIELECTRIC INTERLAYER

μ-SR



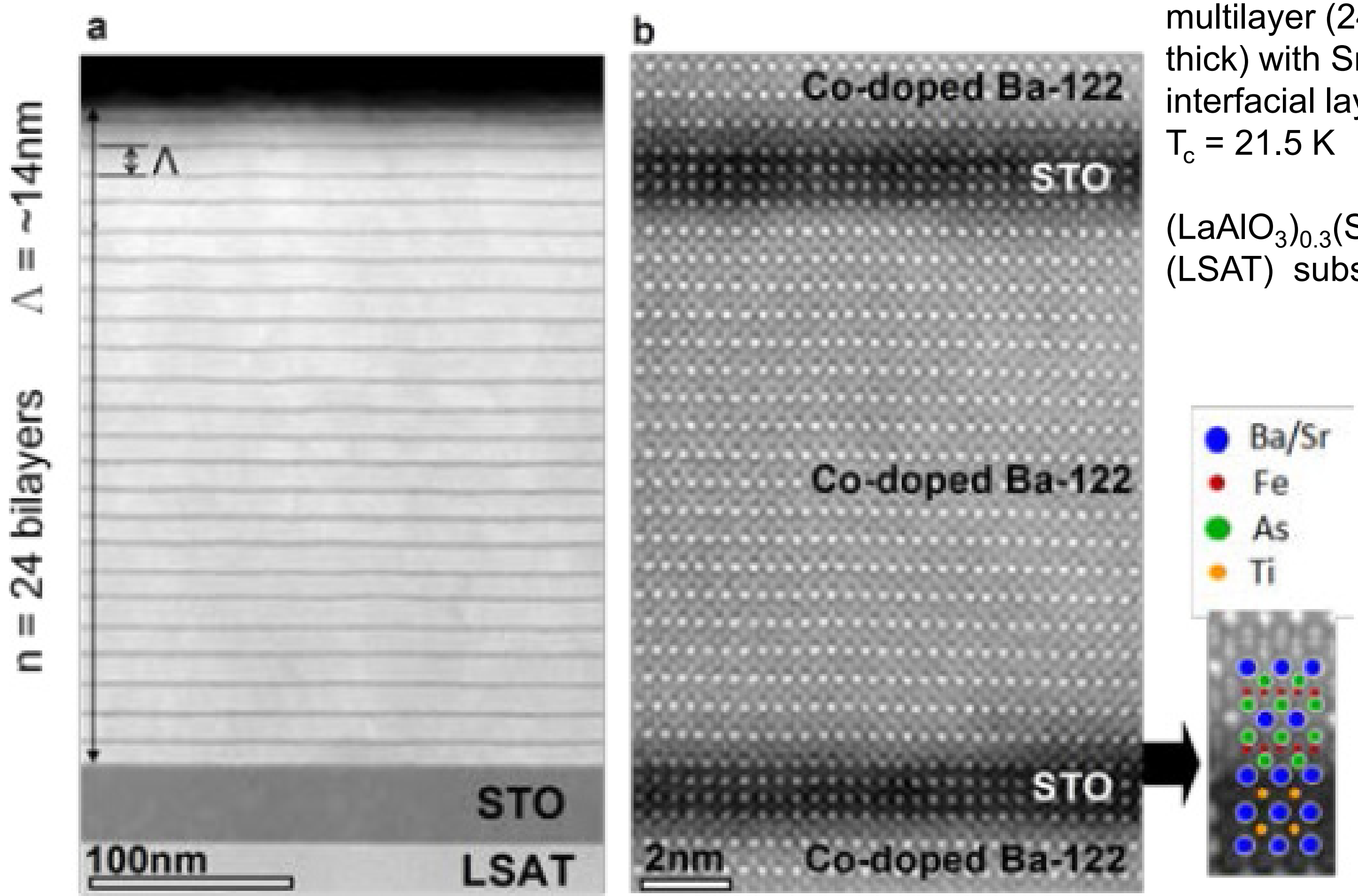


[Junginger, SRF 2017]

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]*

SUPERCONDUCTING IRON-PNICTIDE MULTILAYERS

S. Lee et al, Nature Materials, 12, 392 (2013)



PLD grown Co-doped BaF_2As_2 multilayer (24 layers, 13 nm thick) with $SrTiO_3$ (1.2 nm) interfacial layers

T_c = 21.5 K

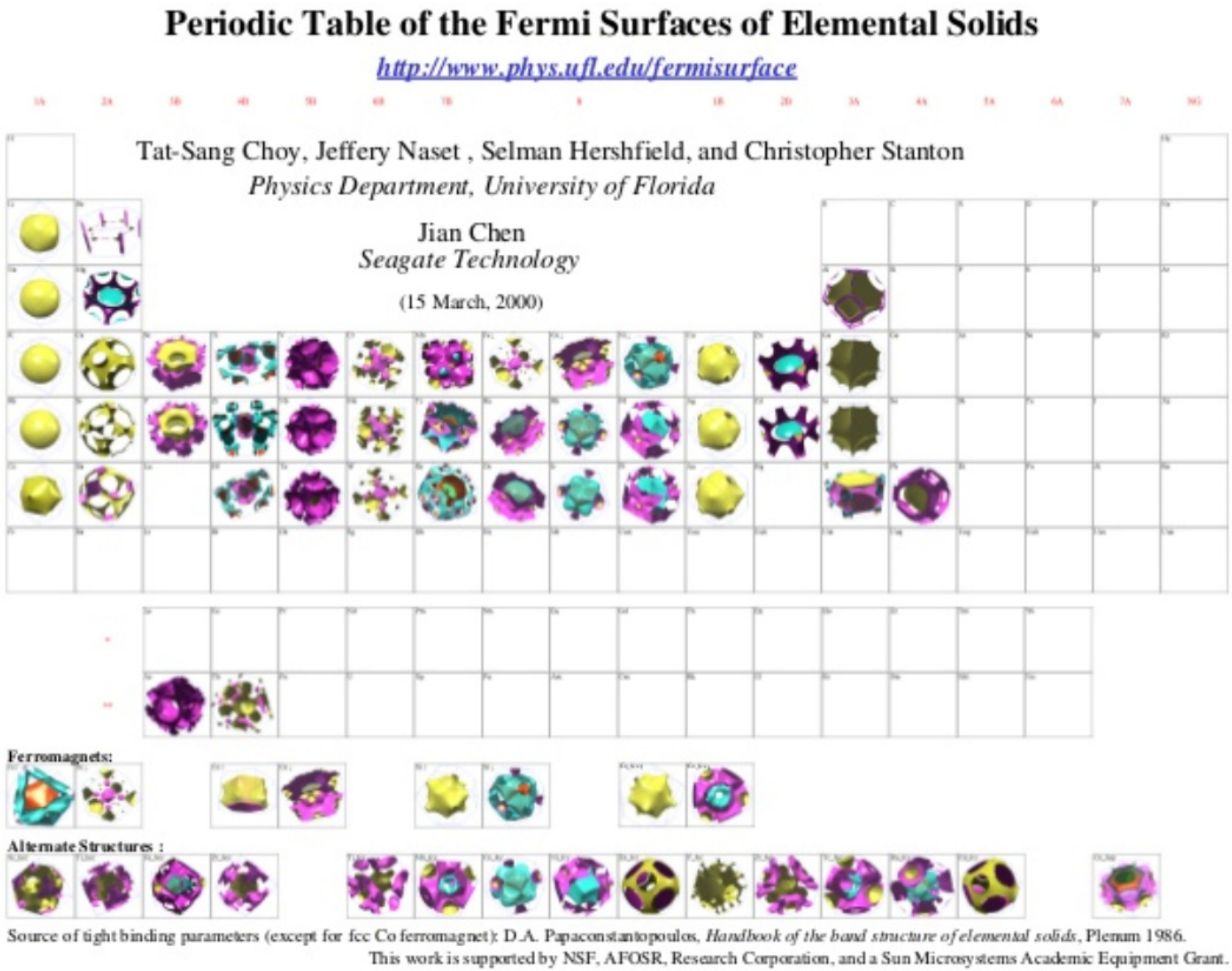
$(LaAlO_3)_{0.3}(Sr_2TaAlO_6)_{0.7}$ (LSAT) substrate:

Group of C-B Eom, U Wisconsin

First high quality epitaxial films have been grown by C.-B. Eom (UW)

CONCLUSIONS AND PERSPECTIVES

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


Periodic Table of the Fermi Surfaces of Elemental Solids
http://www.phys.ufl.edu/fermisurface
Tat-Sang Choy, Jeffery Naset , Selman Hershfield, and Christopher Stanton
Physics Department, University of Florida
Jian Chen
Seagate Technology
(15 March, 2000)
Ferromagnets:
Alternate Structures :
Source of tight binding parameters (except for fcc Co ferromagnet): D.A. Papaconstantopoulos, Handbook of the band structure of elemental solids, Plenum 1986.
This work is supported by NSF, AFOSR, Research Corporation, and a Sun Microsystems Academic Equipment Grant.