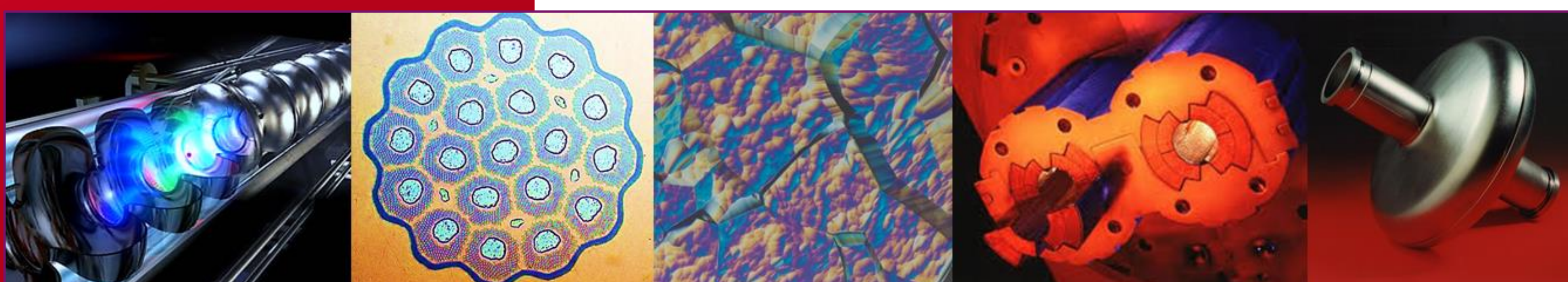
DE LA RECHERCHE À L'INDUSTRIE

(SELECTED) SRF R&D ACTIVITY AT CEA SACLAY



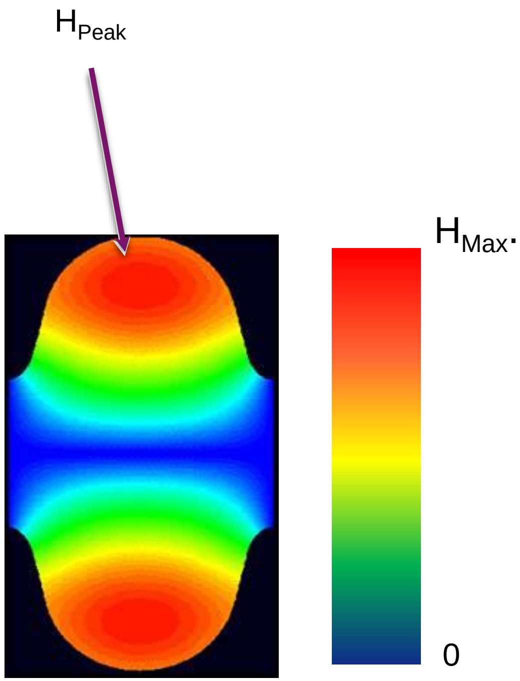
SRF group meeting @ KEK

C. Z. ANTOINE *(O. Napoly, F. Eozenou, T. Proslier…)*

www.cea.fr

Niobium cavities

- **Performances**
  - $E_{acc} \alpha H_{RF}$
  - Q_0 (α $1/R_S$) α T_C => **Nb_3Sn, MgB_2, NbN…**
  - Limit = magnetic transition of the SC material @ H_{peak}
- **Superconductivity only needed inside :**
  - Thickness ~ < 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
- **Issues : getting "defect free" superconductors (yes but not all defects are detrimental…)**



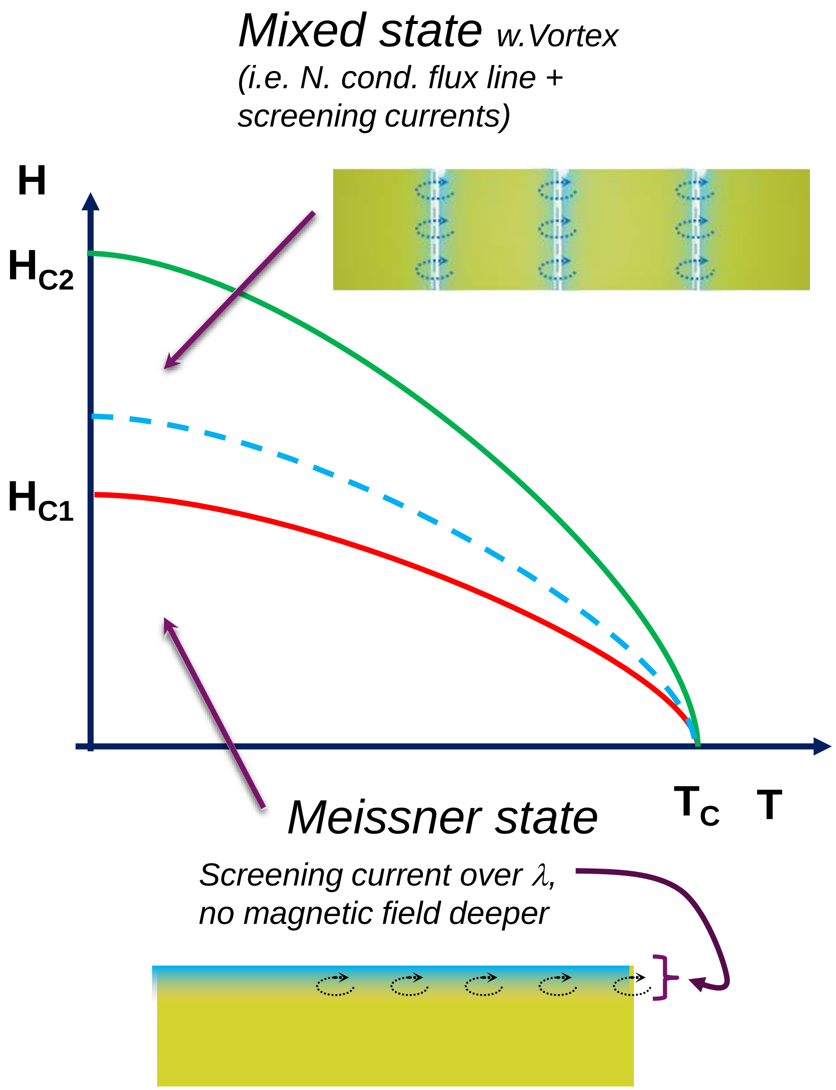
H field mapping in an elliptical cavity

SC phase diagram

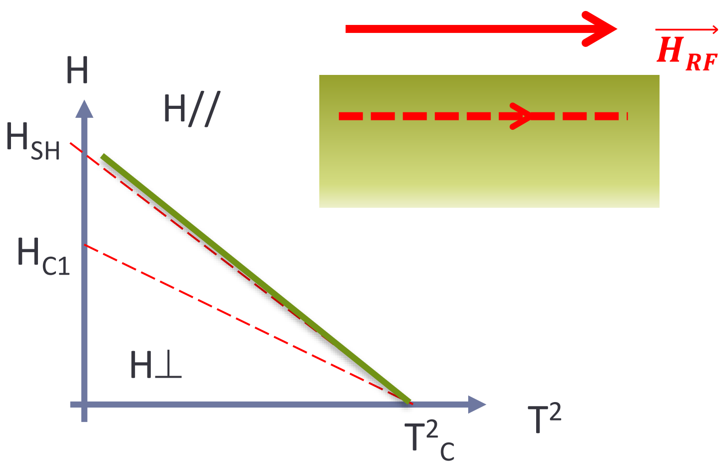
- All SC applications except SRF: mixed state w. vortex
  - Vortices dissipate in RF !
- SRF => Meissner state mandatory !
- H_{C1} = limit Meissner/mixed state
- Nb: highest H_{C1} (180 mT)
- "Superheating field"(?) :

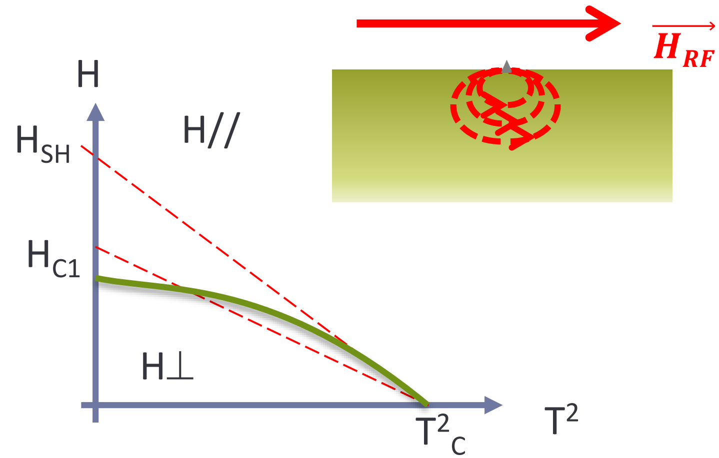
Metastable state favored by H // to surface

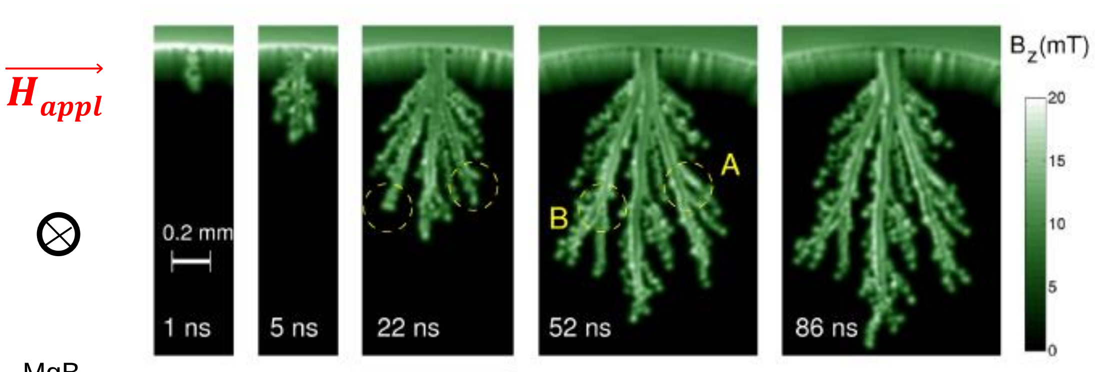
- Difficult to get in real life !



- 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







- ~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

EFFECTS OF LOCAL DEFECTS

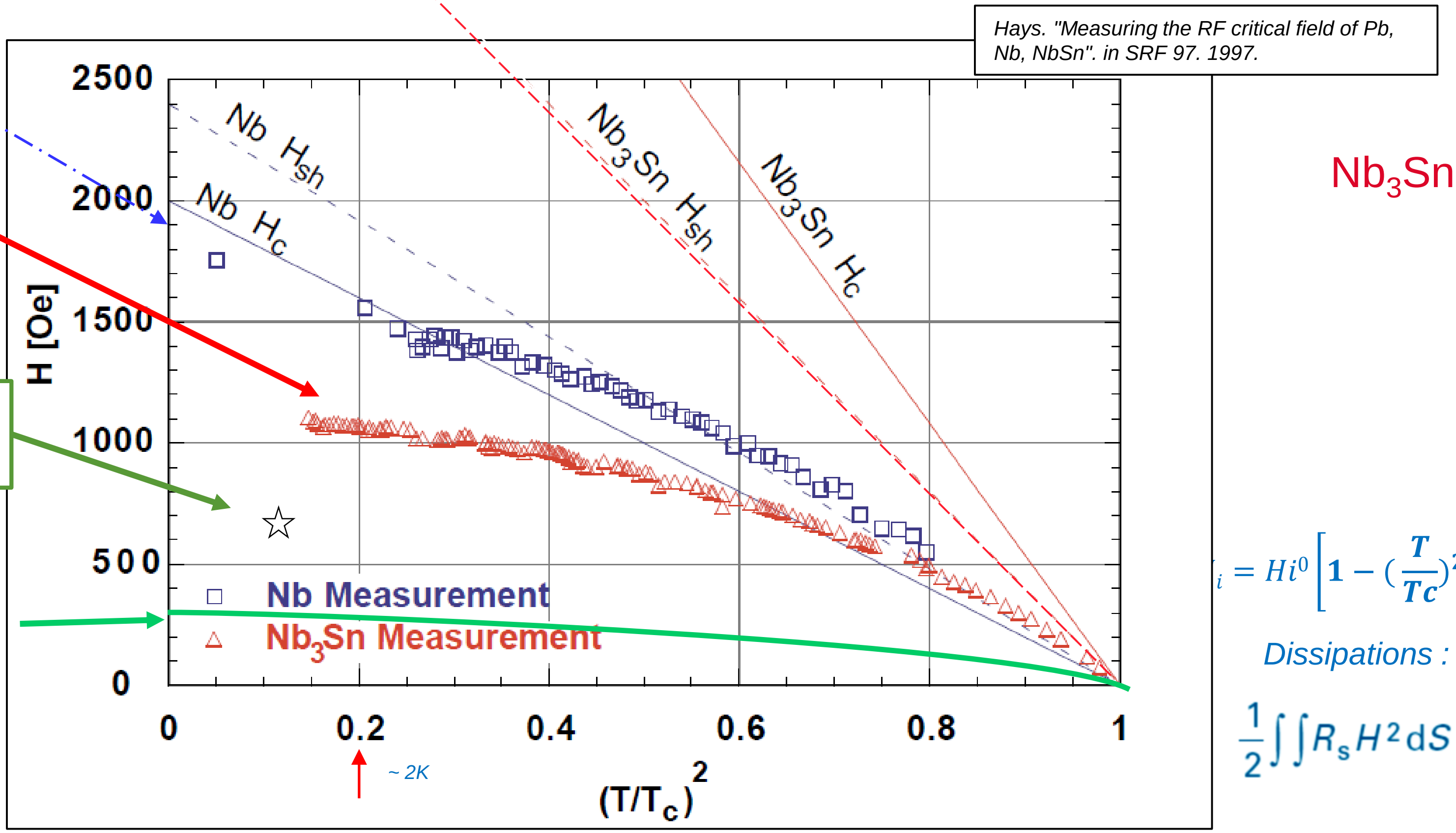
H_{SH}^{Nb3Sn}
(~ 400 mT @ 0 K)

Nb H_{C1}
(170 à 200 mT)

Cornell, 1997
pulsed

Recent results from Cornell **CW** (Posen, 2015 (17 MV/m))

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



Nb$_3$Sn

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

Dissipations :

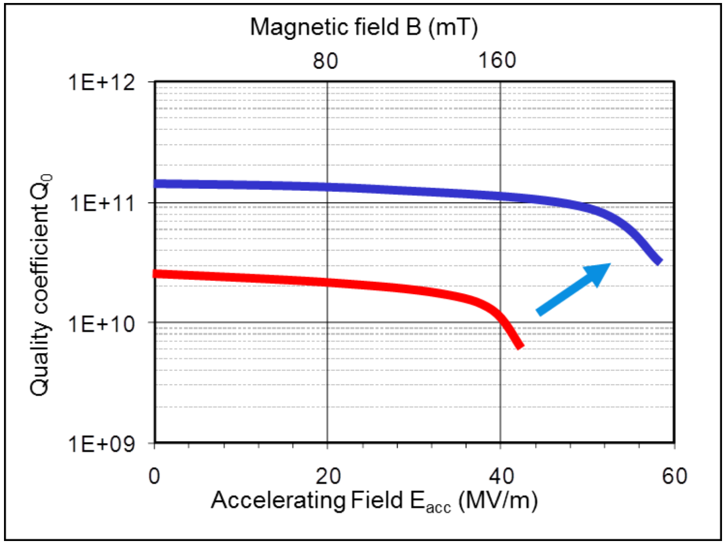
$$\frac{1}{2}\int\int R_s H^2 dS$$

- **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

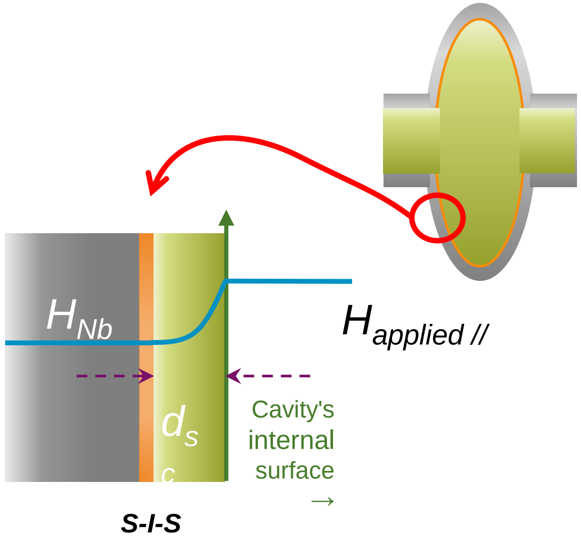
=> We have to reduce defect density **(yes but which ones?)**

AFTER NIOBIUM : NANOCOMPOSITES MULTILAYERS

Structures proposed by A. Gurevich in 2006, SRF tailored

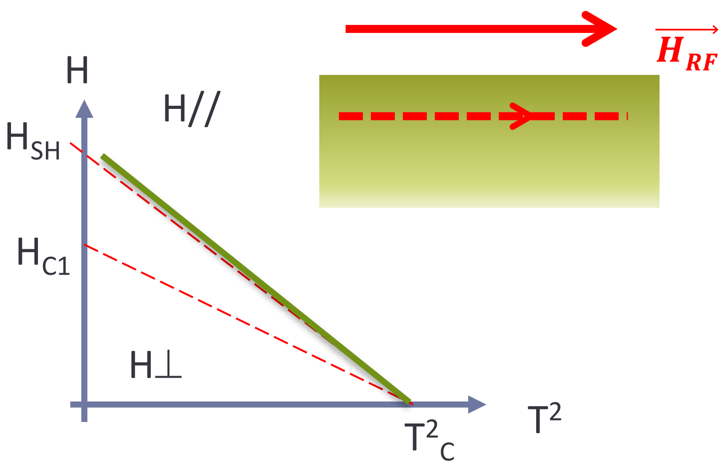


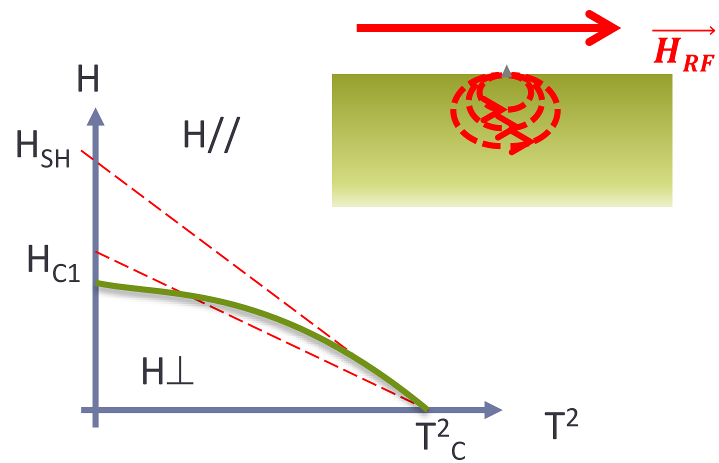
- **Dielectric layer**
  - Small ⊥ vortex (short -> low dissipation)
  - Quickly coalesce (w. RF)
  - Blocks avalanche penetration
  - => **Multilayer** concept for RF application
- **Nanometric I/S/I/ layers deposited on Nb**
  - SC nanometric layers (≤ 100 nm) => $H_{C1}\uparrow$ => Vortex enter at 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): $R_s^{NbN} \approx \frac{1}{10} R_s^{Nb}$ => $Q_0^{multi} >> Q_0^{Nb}$



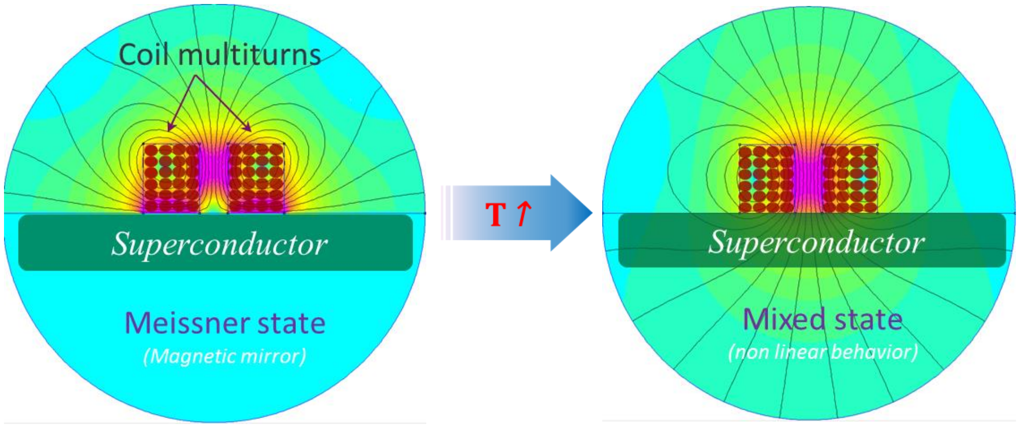
WHAT IS THE LIMIT ($H_P/H_{C1}/H_{SH}$) ?

- 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

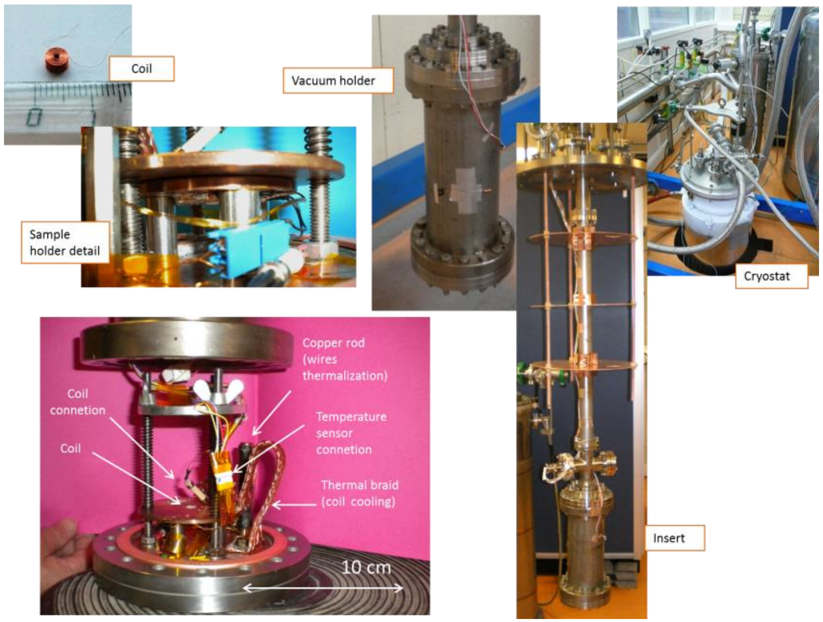


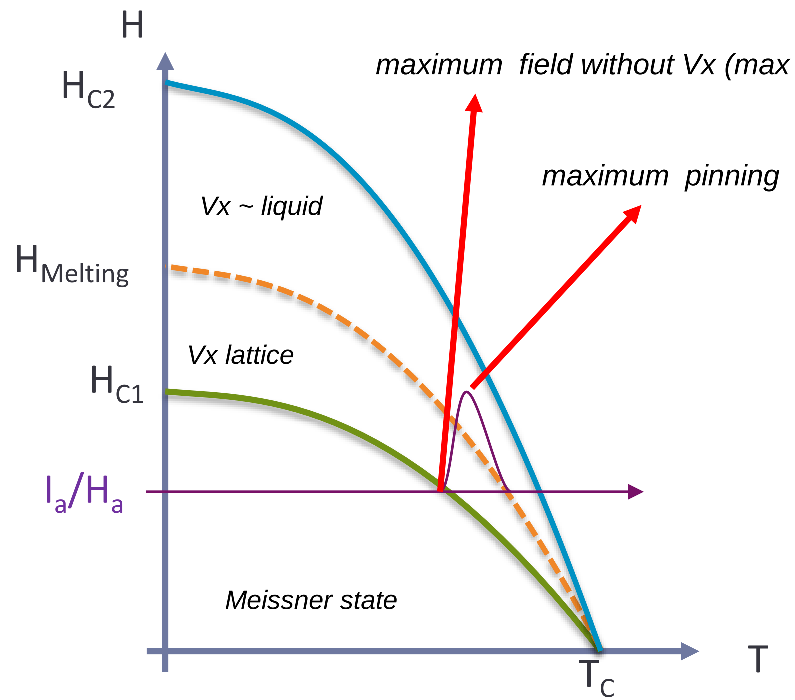


- Local magnetometry
  - ~ Same geometry as cavities
  - No shape/edge effect (vs DC/ Squid magnetometry)
  - No demagnetization effect
  - Measures actual penetration field wherever it is $H_P/H_{C1}/H_{SH}$

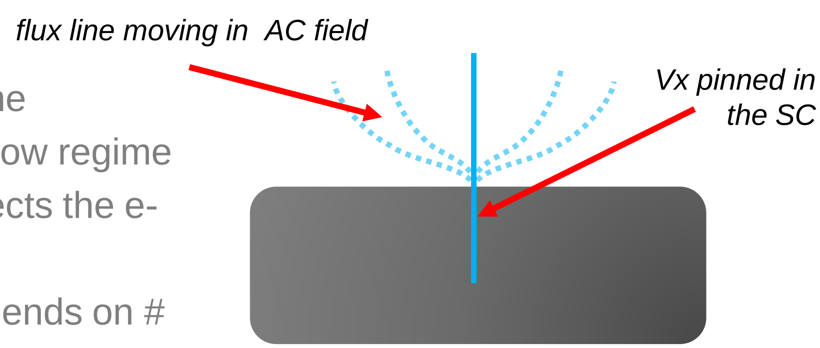


EXPERIMENTAL DETAILS





- **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

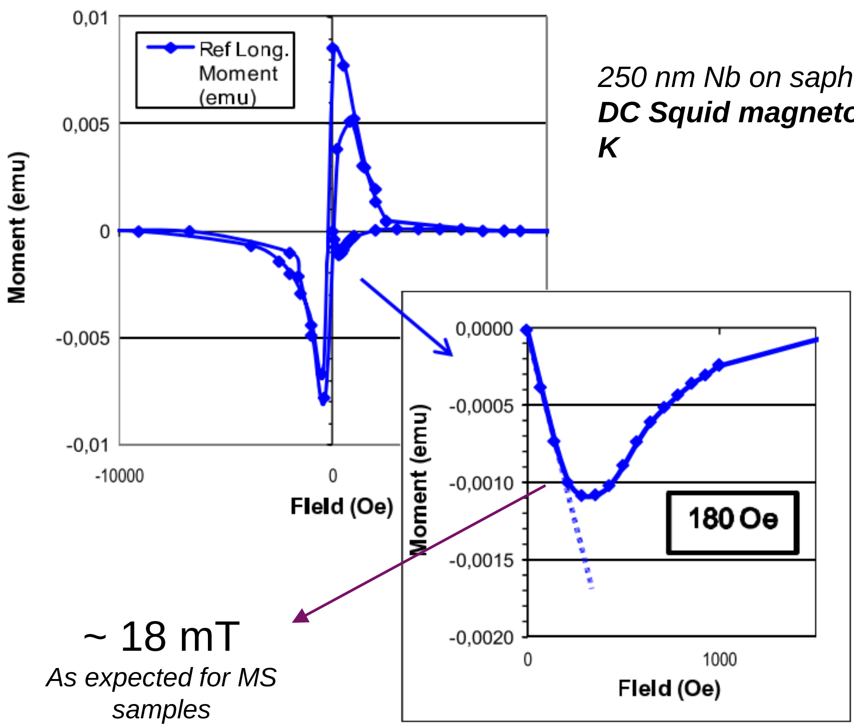
- **NbN single layers series**
  - NbN SL / “thick” Nb layer
    - Magnetron sputtered
    - MgO as dielectric layer
  - Far from perfect…

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*

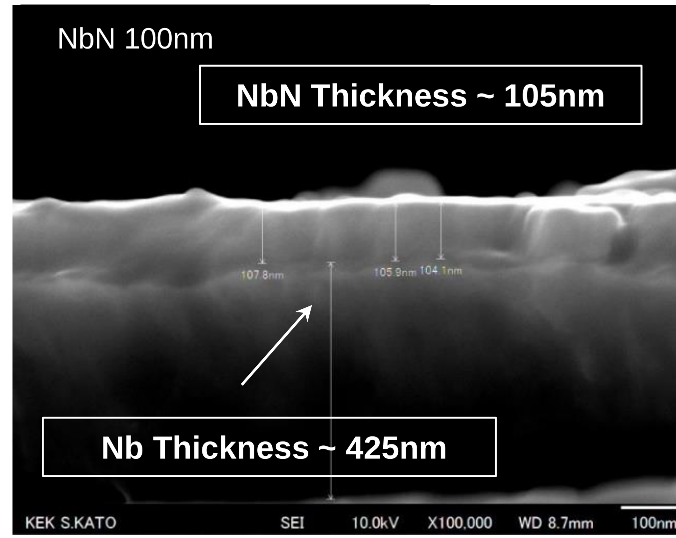
† Not same batch, deposited on the same conditions, but substrate = sapphire
*As determined with magnetometry, see below.

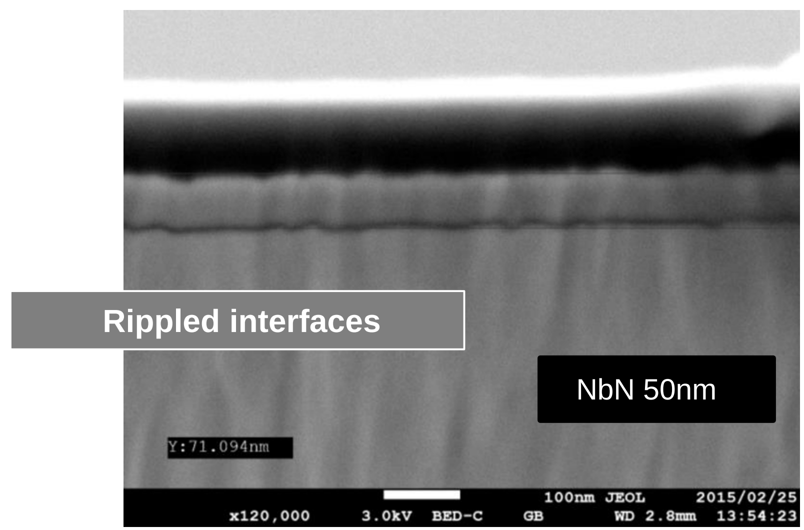
Typical defects…

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



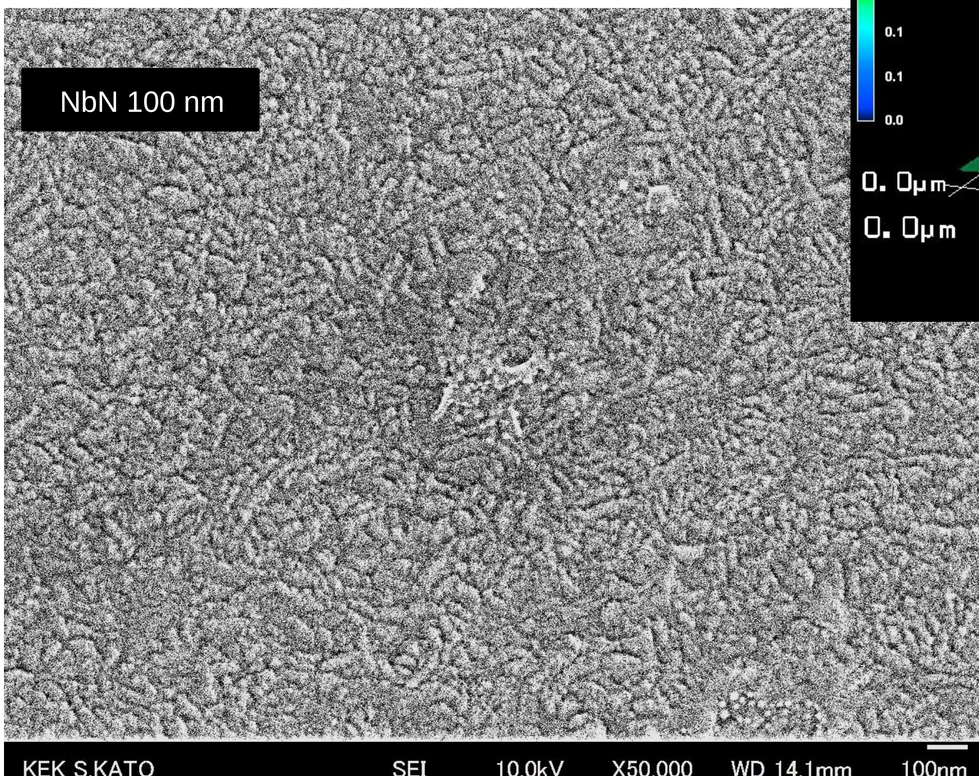
250 nm Nb on saphire
DC Squid magnetometry @ 4.5 K

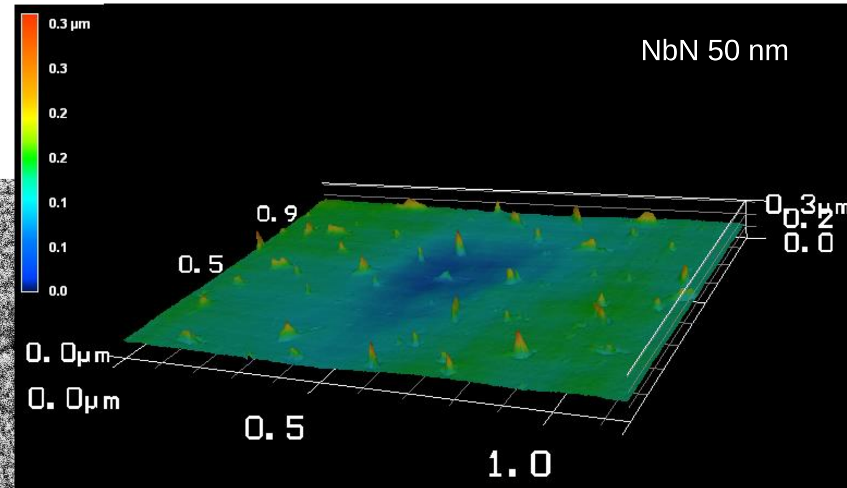


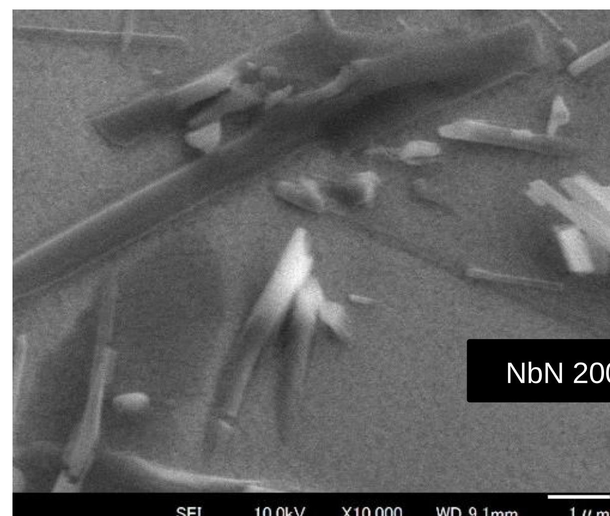


Morphology

- Rough surface



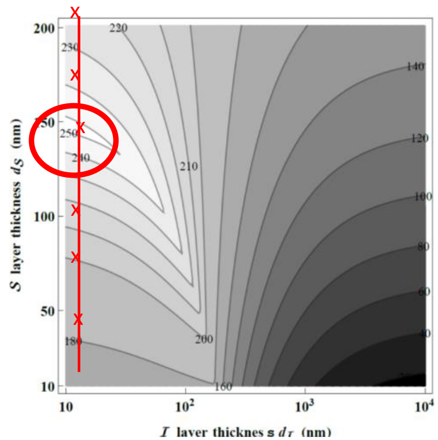


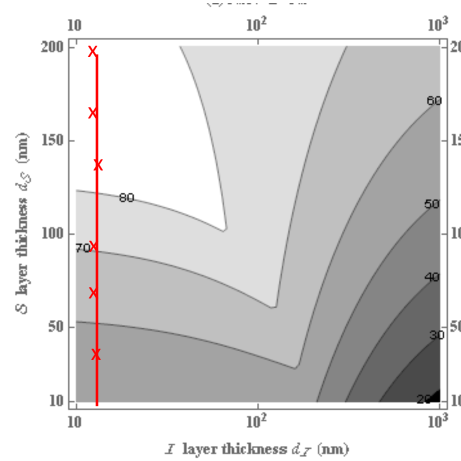


MgO needle ?
(capping material)

Theoritical predictions from T. Kubo (KEK)

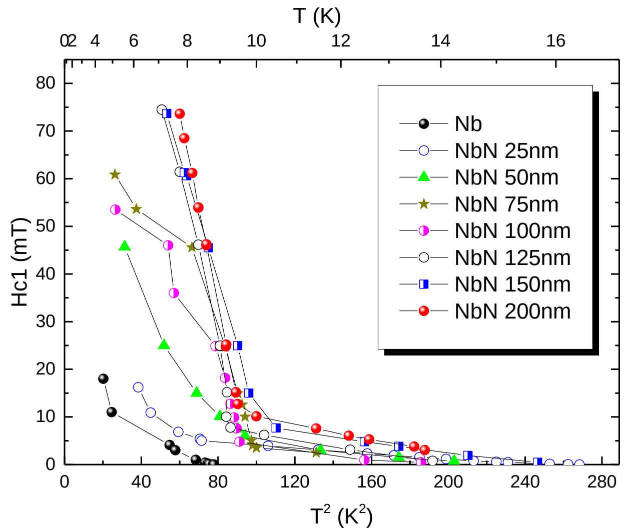
Ideal Nb substrate with B_{C1}=170 mT





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)

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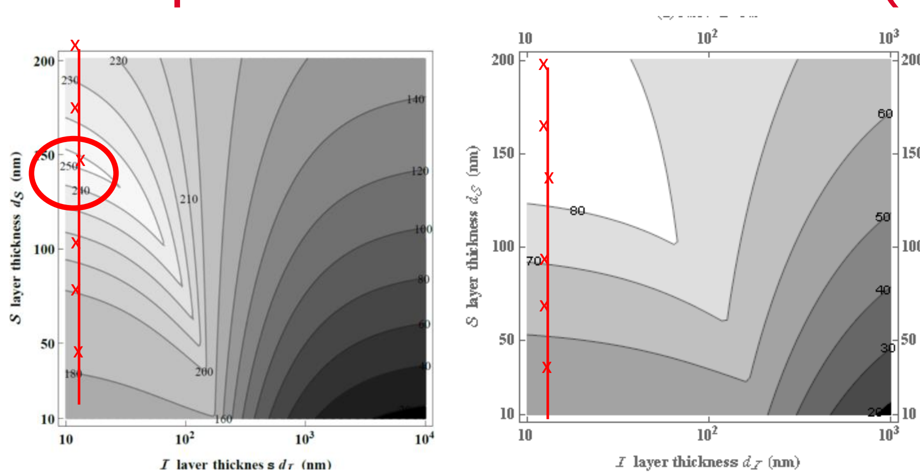
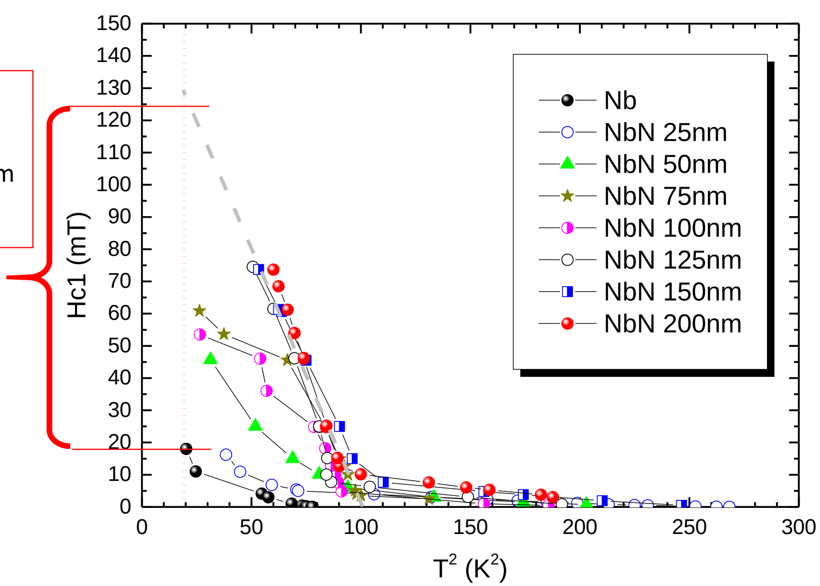


Nb with defects, with B_{C1}=50 mT*

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

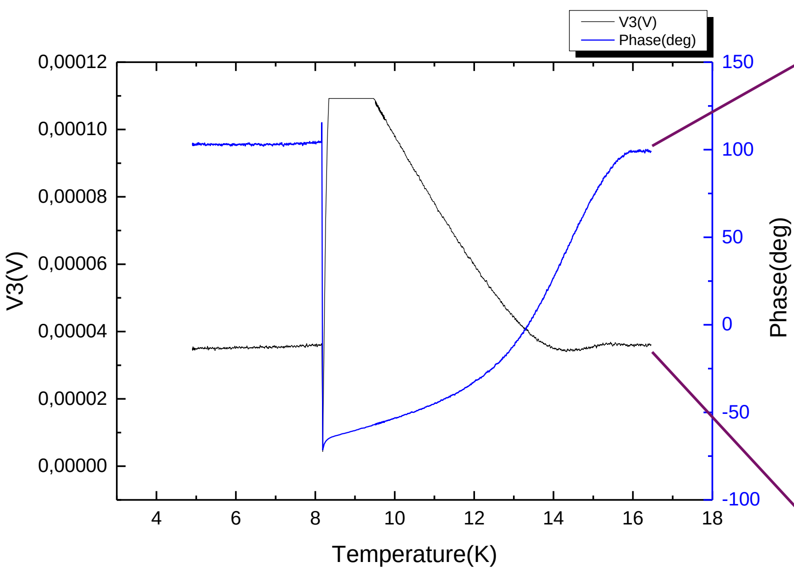
@ 4.5 K
~ + 110 mT?
~25-30 MV/m
ILC shape



- 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

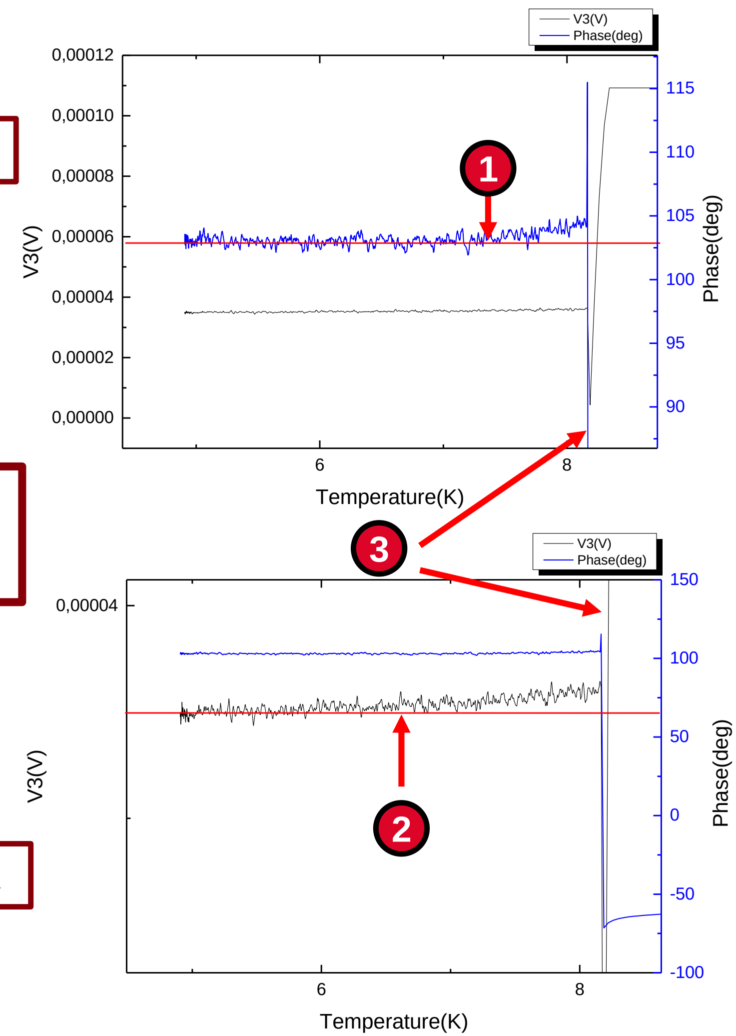


Phase signal

T❶~T❷

T ❸>>T❷

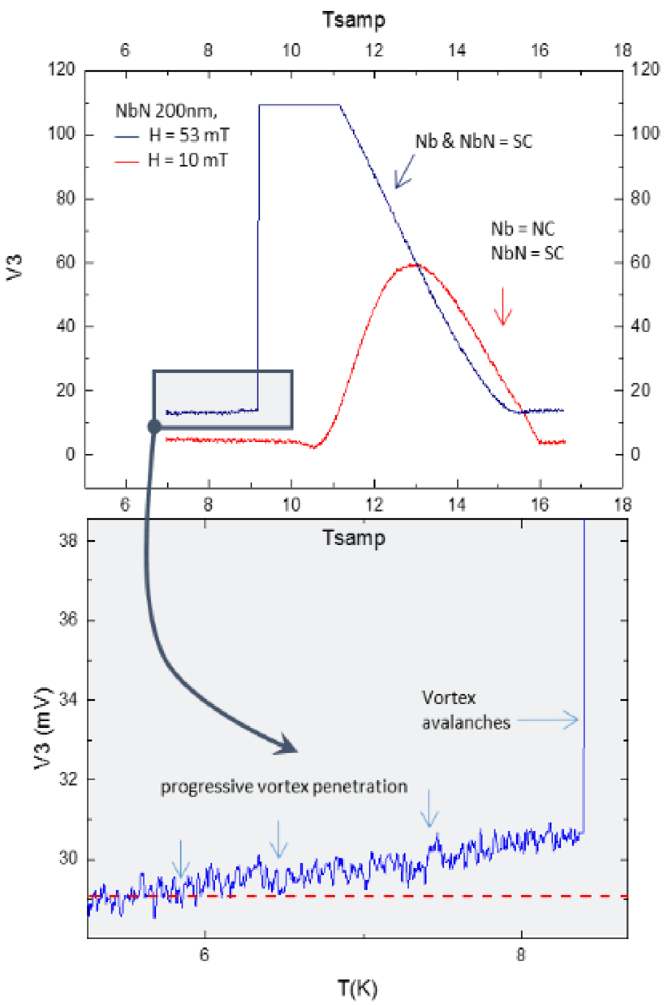
Voltage signal

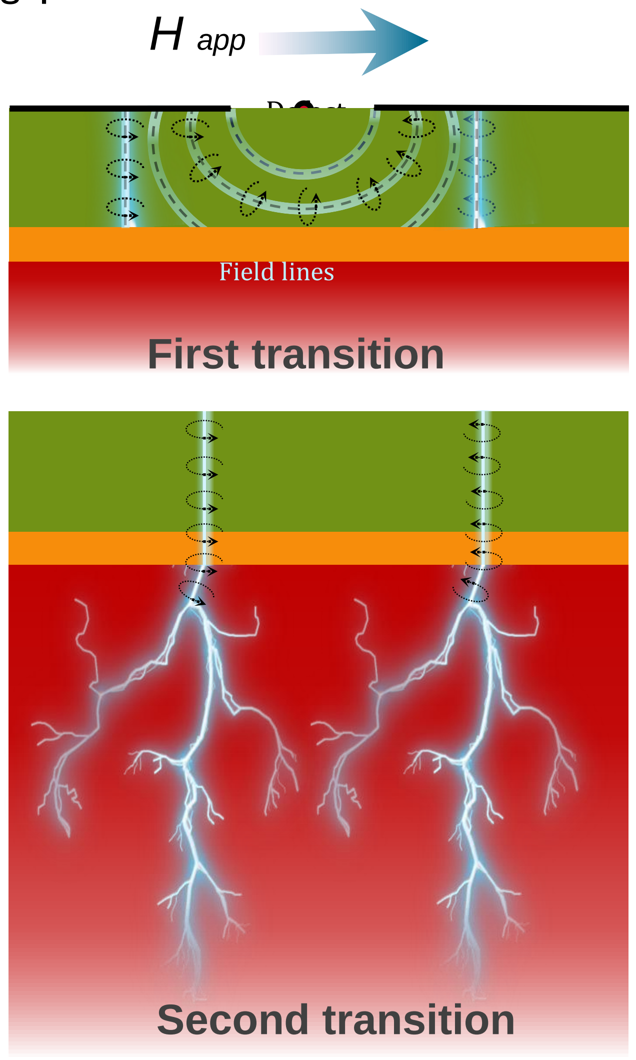


- T❶~T❷: within noise level
- T ❸>>T❷: dramatic transition

ROLE OF THE DIELECTRIC LAYER !

- Why do we have two transitions ?



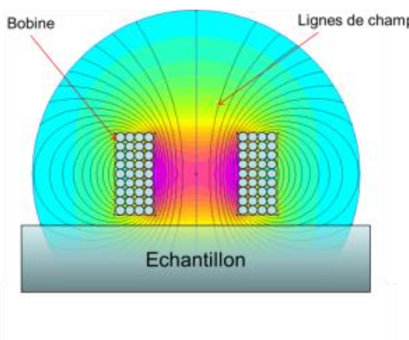


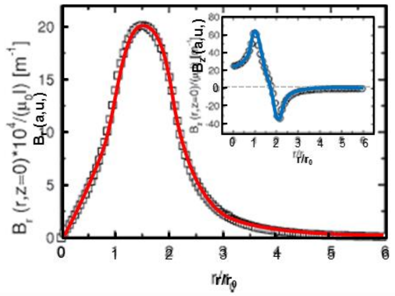
- H // surface => surface barrier†
- A defect locally weakens the surface barrier
- 1st transition, vortex blocked by the insulator ~100 nm => low dissipation.
- 2nd transition, propagation of vortex avalanches (~100 µm) => high dissipation.
- **Dielectric layer = efficient protection !!!**

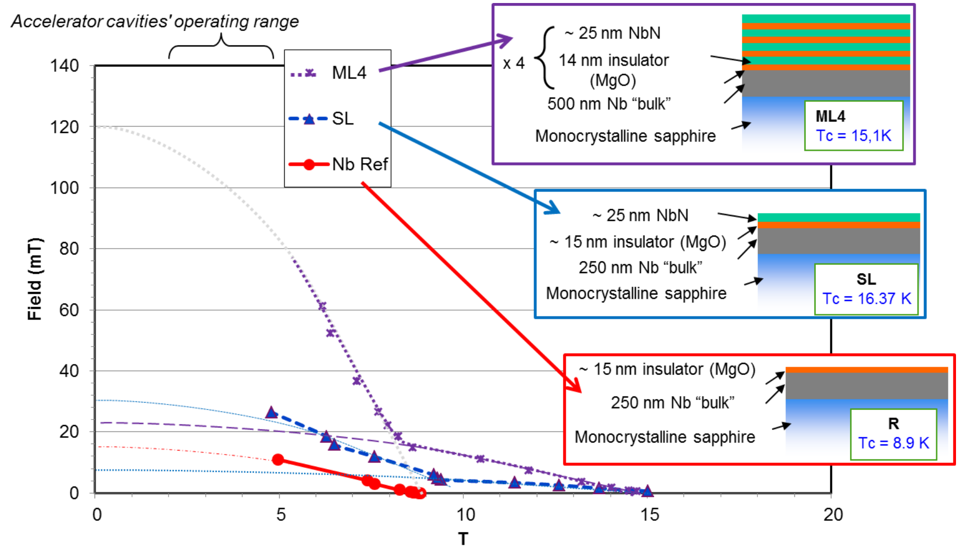
†*B. Bean and J. D. Livingston, Phys. Rev. Lett. 12, 14 (1964).*

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

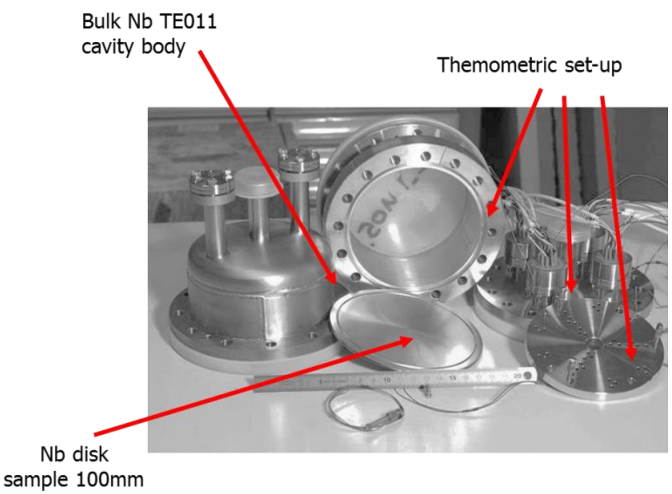
Local magnetometry:

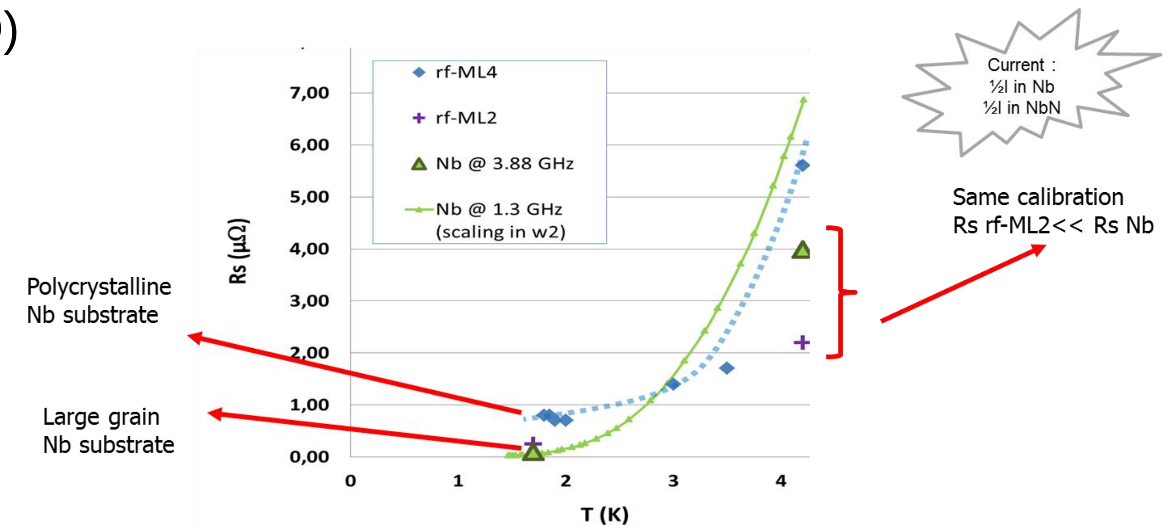






RF test (collaboration IPNO)





CONCLUSION AND OUTLOOK

- **Scientifically:**
  - Very challenging upstream, discovery, R&D
  - Efficiency of multilayer concept demonstrated
    - Field enhancement => higher SRF performances
    - Protection against “avalanches” => can accommodate defective (real) material
  - Results close from theory => will help optimization
- **Future :**
  - Developing deposition techniques e.g. ALD, ECR, HPIMS….
  - Up-grade of existing Nb cavities
- **Change of paradigm in SRF technology at hand**

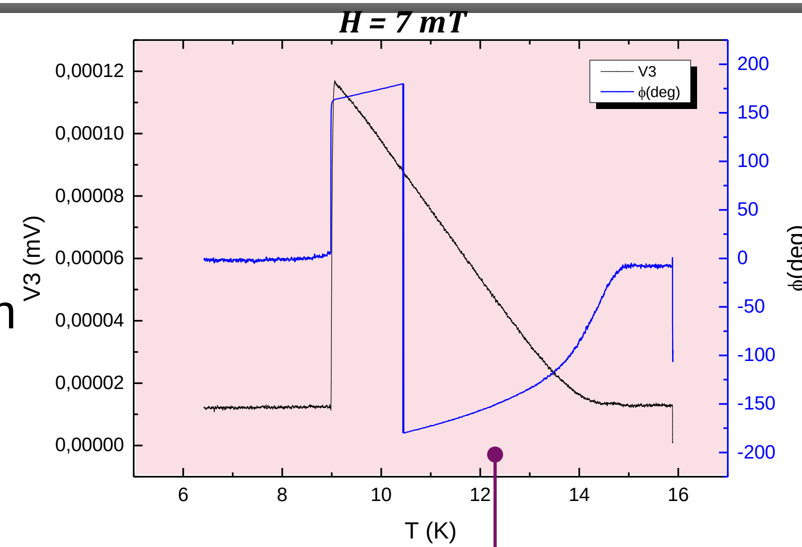
THANK YOU FOR YOUR ATTENTION

TiO_2 .ATOMIC LAYER DEPOSITION

Extract from http://www.youtube.com/watch?feature=player_detailpage&v=XMda8TXLIFk

What do we measure ?

- Determination of Hc1
  - Low field => one transition
  - High field => two transitions
    - » 1st transition with low dissipation
    - » 2nd transition very strong dissipation



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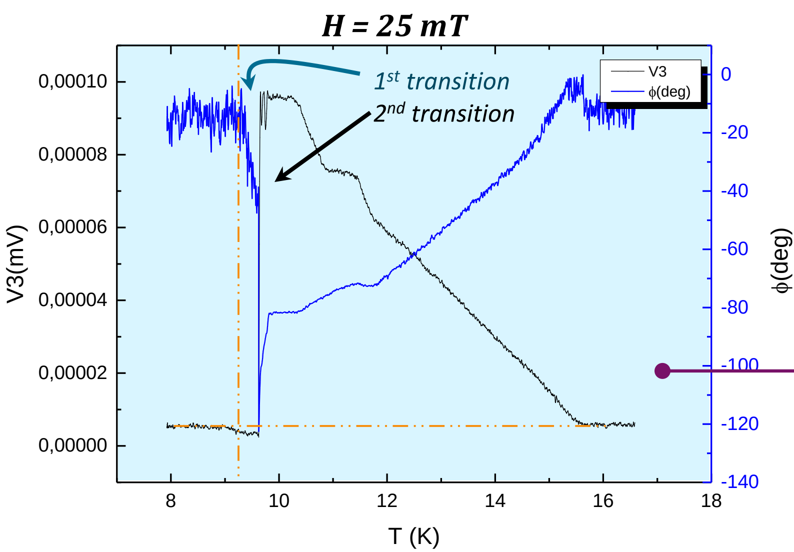
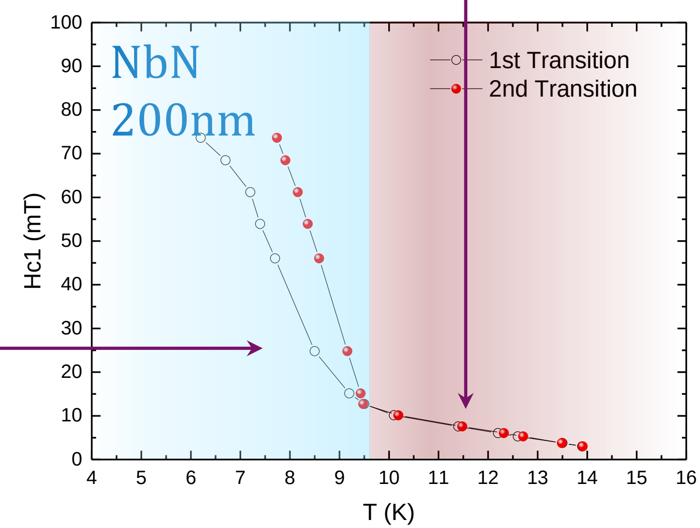
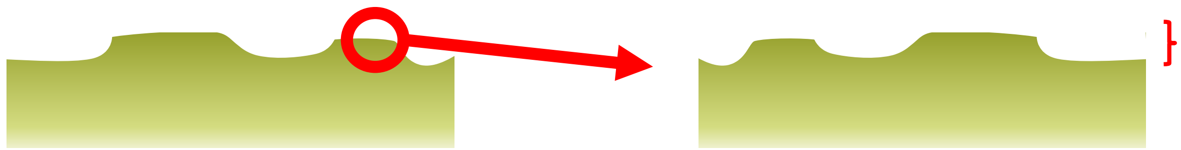




WHAT KIND OF DEFECTS ?

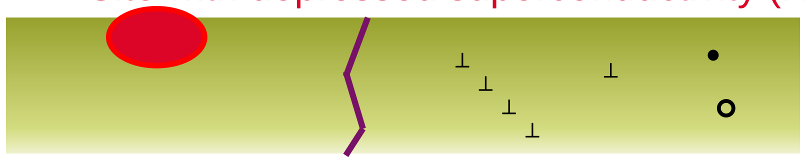
Morphologic defects (pores, steps, facets…)

~1 µm ~1 nm



Micro- to nano-roughness (go to fractal approach ?)

Site with depressed superconductivity (NC, SC but local change of κ, ξ...)



Early penetration / Flux trapping => same battle!!!

Crystalline defects :

Interfaces (inclusions) > GB >⊥ cells > ⊥(=dislocations) > vacancies or interstitials

3D — 2D — 1D → 0D

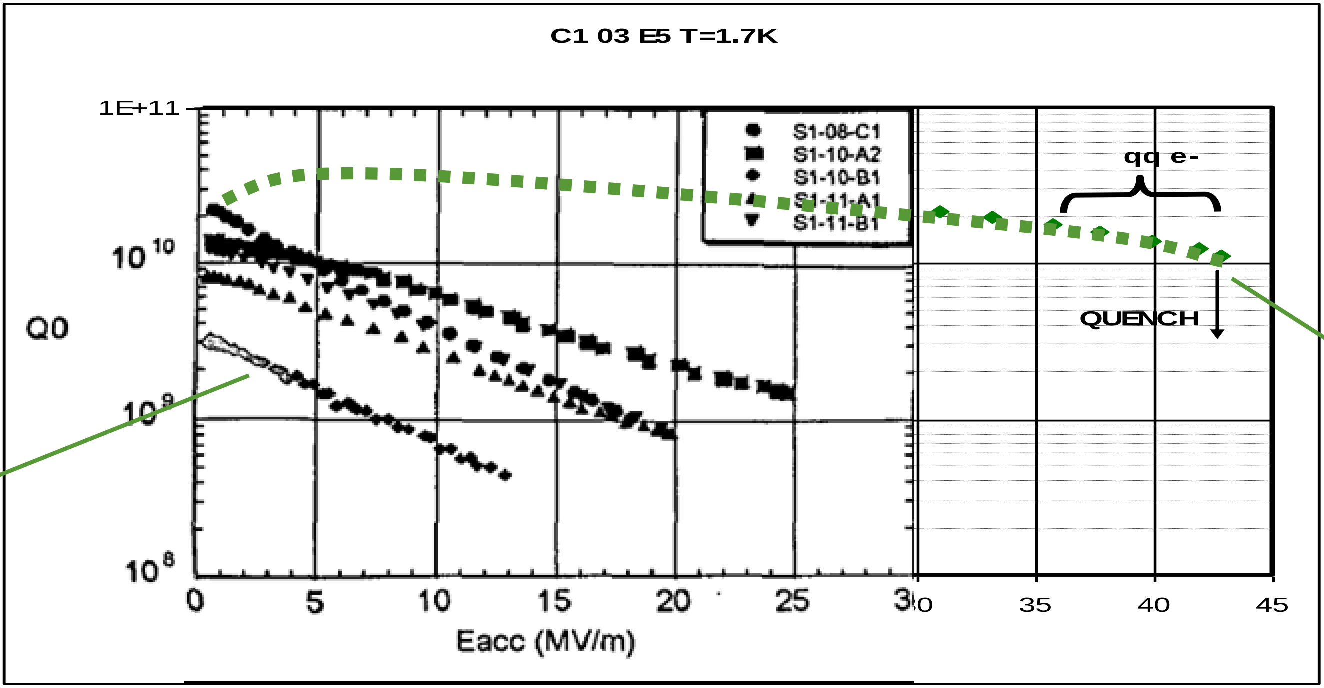
← Strain on the crystalline lattice

Plays on ℓ, κ...

WHY BULK NIOBIUM ?

- **Bulk Niobium:**
  - grains ∅>~ 50 µm to mms, good crystallographic quality
- **Niobium ~1-5 µm/Copper :**
  - ∅ <~ 100 nm, many crystallographic defects, grain boundaries…
  - sometimes better low field performance (thermal configuration and/or cost)

Typical sputtered Nb cavities 1.5 GHz



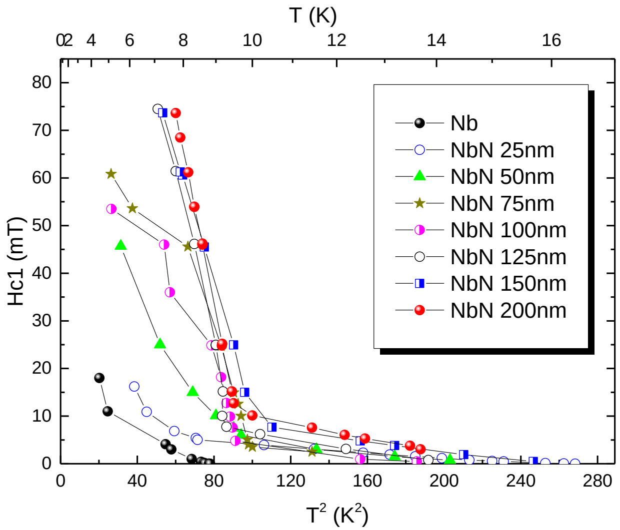
~~Typical~~ Good bulk Nb cavity 1.3 GHz

- **It is changing !!!: New emerging thin films techniques**

Nb-MgO-NbN TRILAYERS

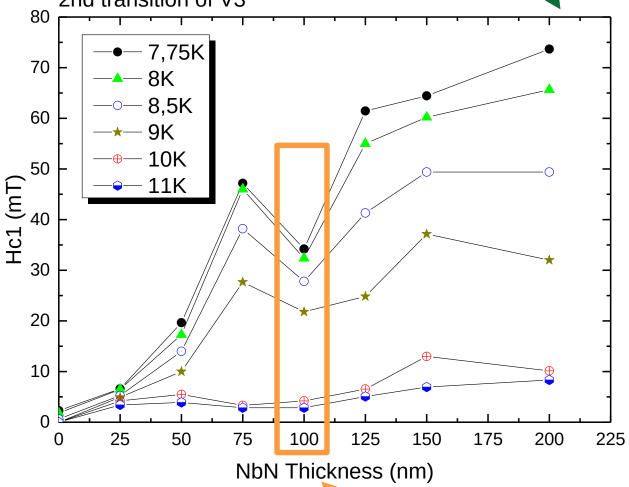
Transition field (H_{SH} here ?)

- NbN single layers series
  - NbN SL / "thick" Nb layer
    - Magnetron sputtered
    - MgO as dielectric layer



Saturation ? ***Maybe*** *it is still worth trying to go to thicker samples*

According to
2nd transition of V3



Maybe this sample quality is not good !

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