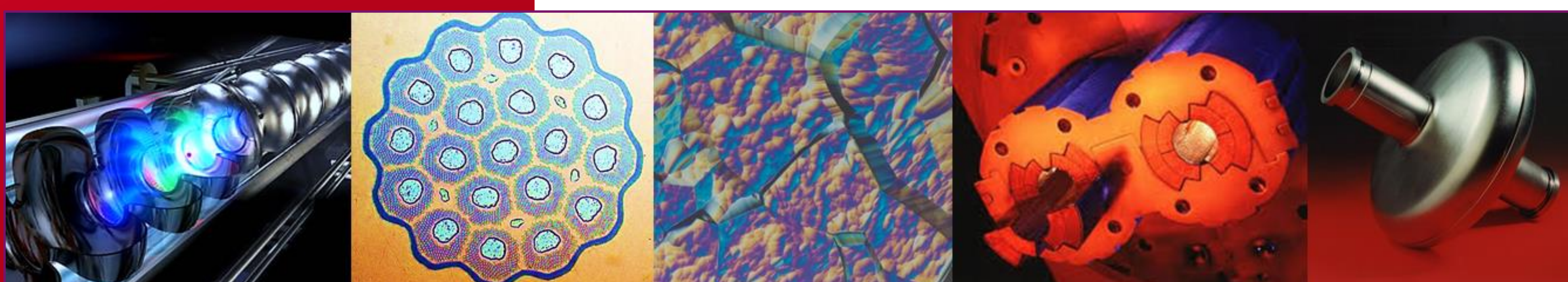
DE LA RECHERCHE À L'INDUSTRIE

STATUS AND EXPECTED PROGRESS ON SRF CAVITIES



Réunion d'information ILC -9avril 2018

C. Z. ANTOINE

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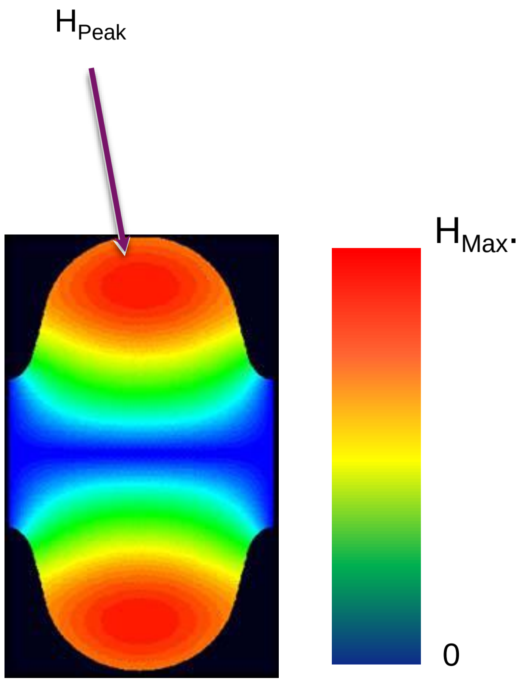
INTRODUCTION

SRF LIMITS

Niobium cavities

- **Performances**
  - $E_{acc} \propto H_{RF}$
  - Q_0 ($\propto$ $1/R_S$) $\propto T_C$ => **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…)**



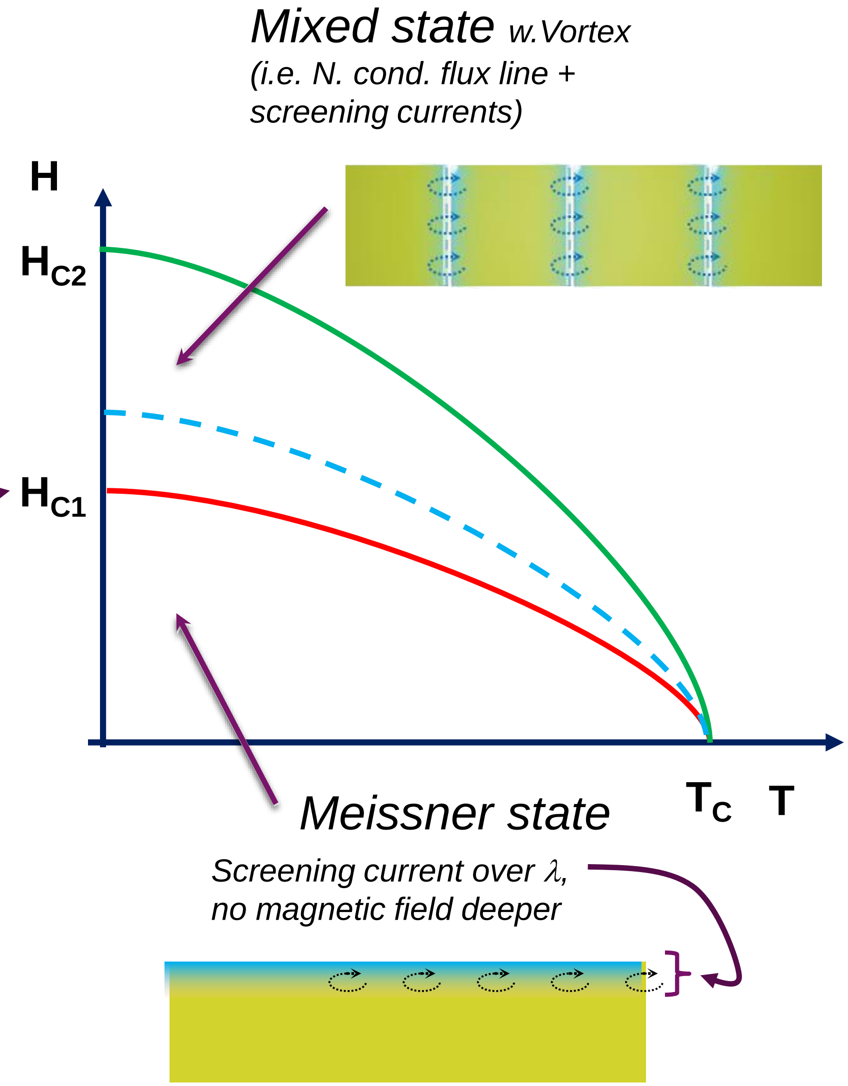
H field mapping in an elliptical cavity

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"(?) :

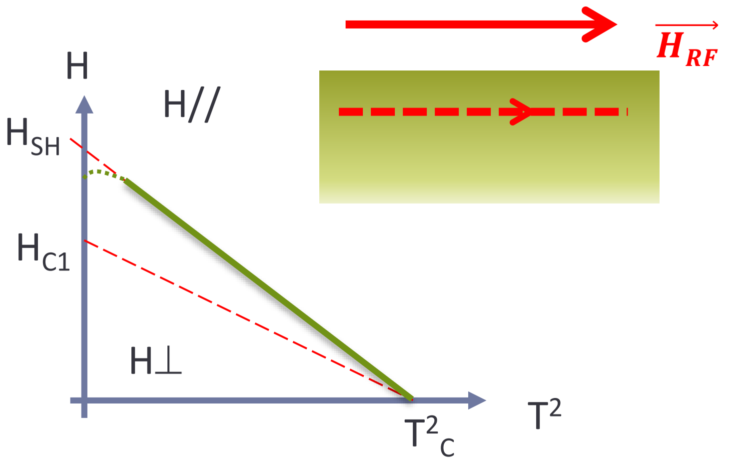
Metastable state favored by H // to surface

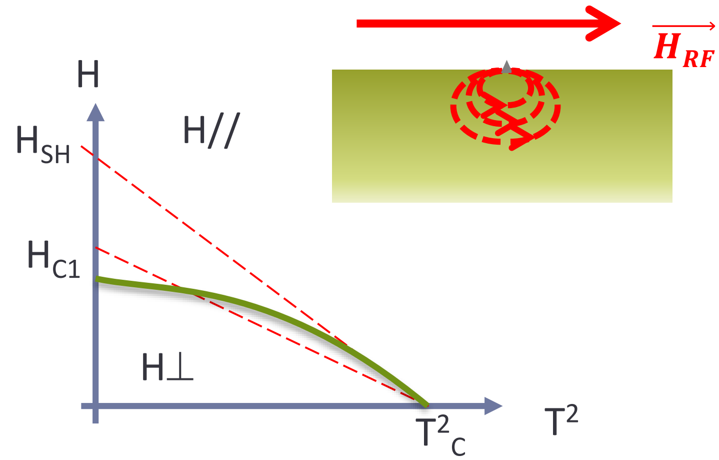
- Difficult to get in real life !

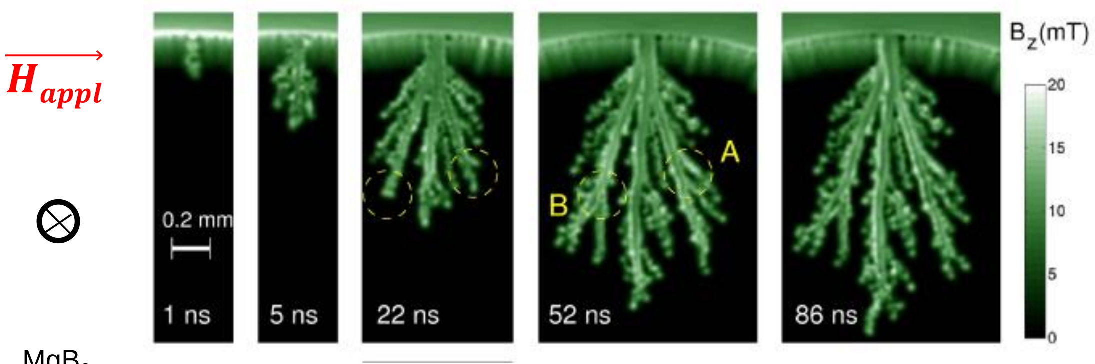


WHAT IS THE LIMIT ($H_P/H_{C1}/H_{SH}$) ?

- 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







- ~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)

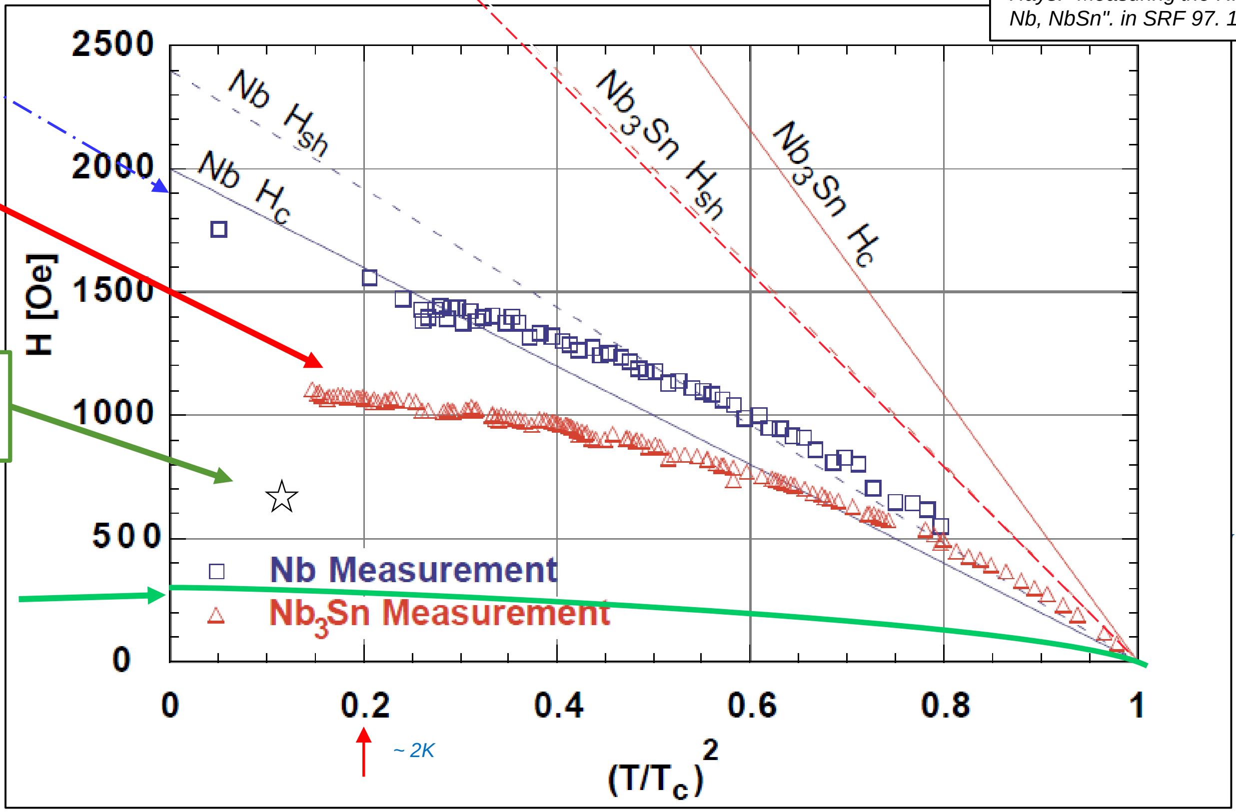
Nb H_{C1} (170 à 200 mT)

Cornell, 1997 **pulsed**

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

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

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



Nb_3Sn

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

Dissipations :

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

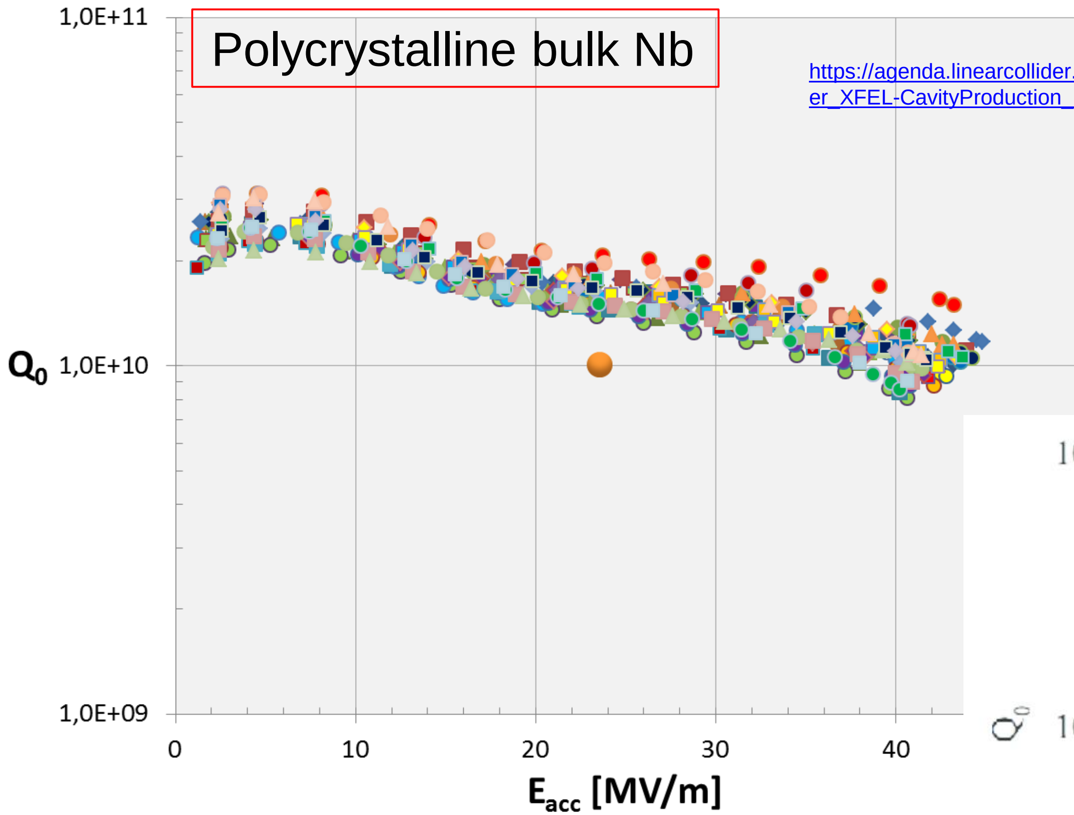
- **Vortices enter more easily at lower temperature (counter intuitive !)?**
  - @ T~T_C : H is low => low dissipations => easy to thermally stabilize
  - @ T<<T_C : H is high=> even if small defect => high dissipations => Favors flux jumps

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

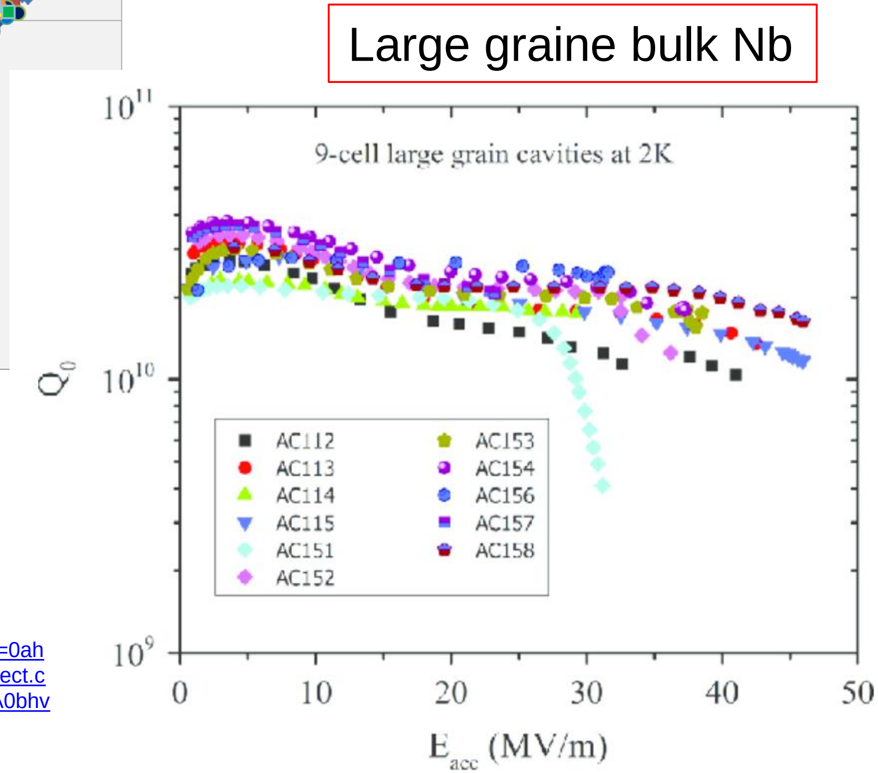
BULK NIOBIUM

PRESENT STATUS

TYPICAL PRODUCTION SCORES FOR 9-CELLS



https://agenda.linearcollider.org/event/7645/contributions/40185/attachments/32340/49084/Pekeler_XFEL-CavityProduction_ResearchInstruments.pdf



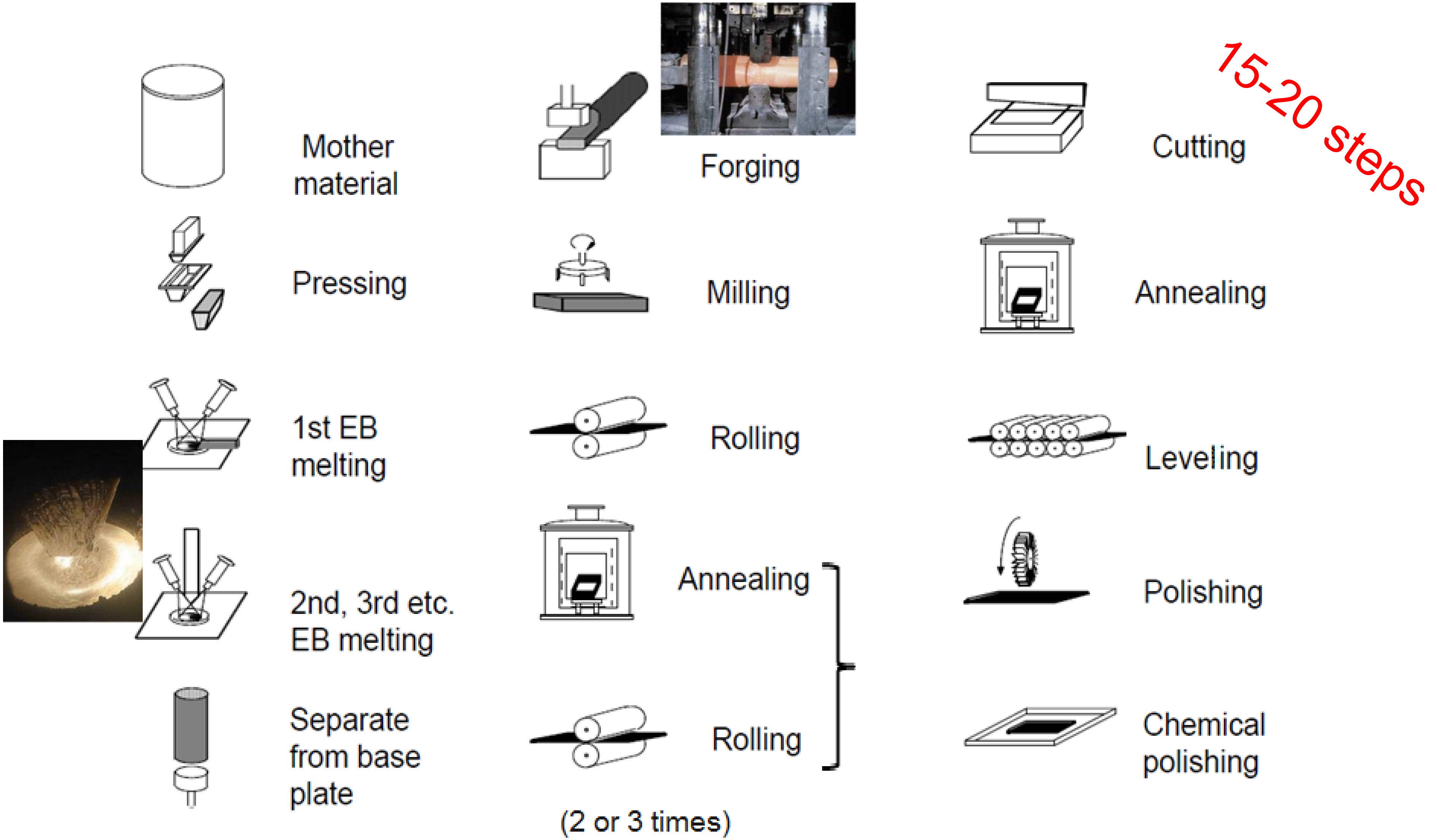
https://www.google.fr/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjH57Di8qzaAhULuRQKHbUeBh4QFggsMAA&url=https%3A%2F%2Fwww.sciencedirect.com%2Fscience%2Farticle%2Fpii%2FS0168900214013977&usg=AOvVaw2_X7xJ6spZFAA0bhvMpfxf

Many trails explored…

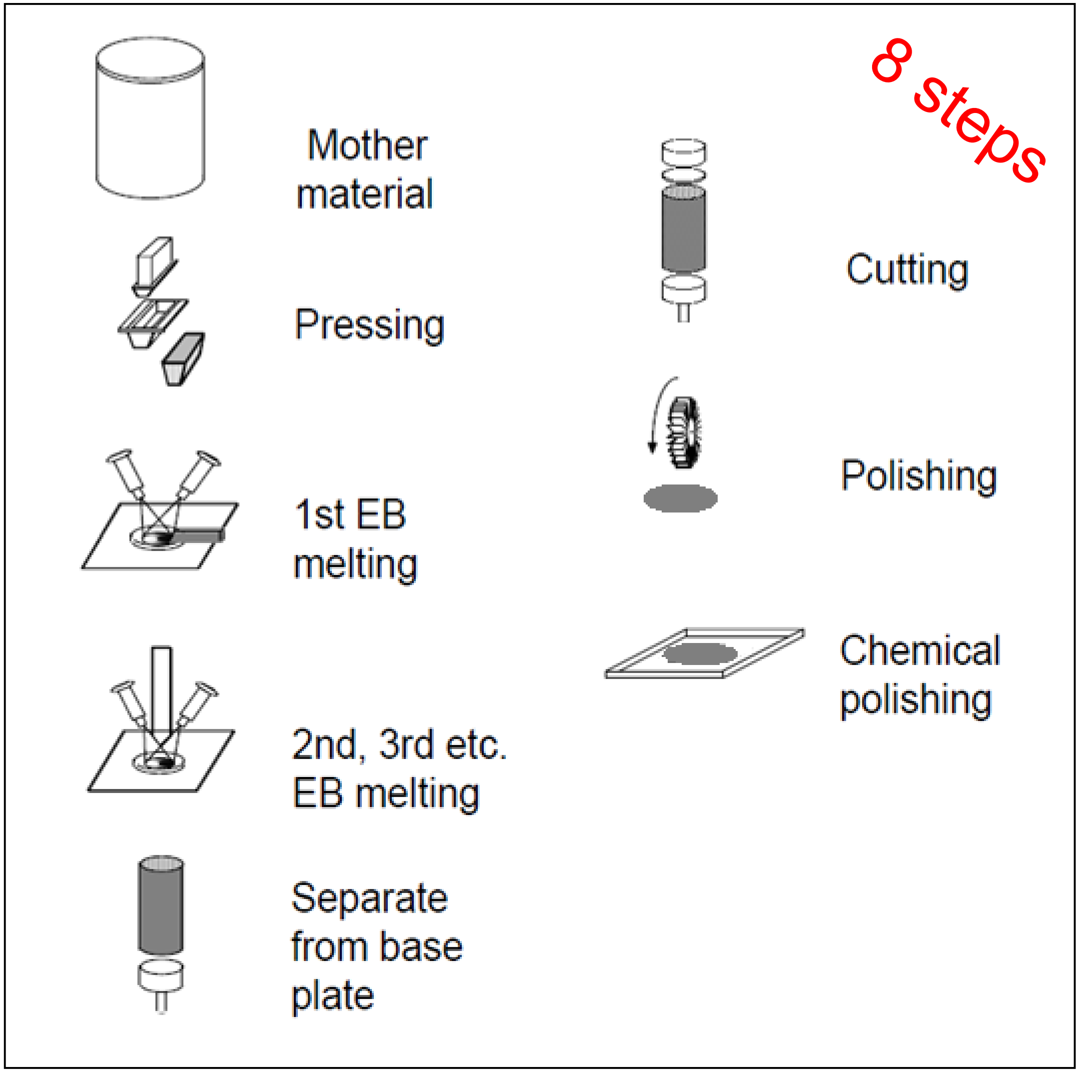
- **Large grain material**
  - Economy in Nb Weigth
- **Nitrogen (Oxygen ?) doping/infusion**
  - Today Nb is optimized for thermal conduction (stabilization), not for superconductivity
  - Modification of the surface without loosing the bulk properties
- **Multilayer :**
  - Route to realistic material with higher Q_0 and E_{acc} (and even defects)
  - Protection against vortex avalanche
- **Getting rid of the damage layer**
  - Only explored at lab level

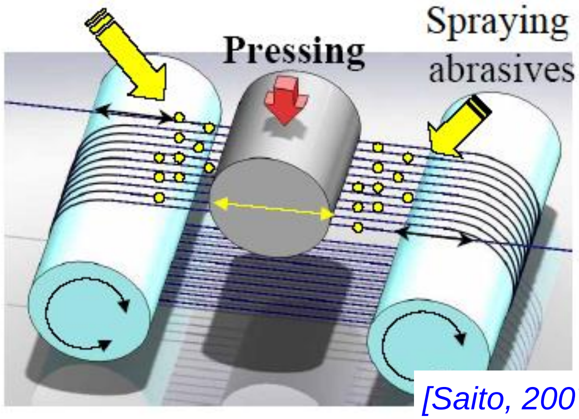
LARGE GRAIN MATERIAL

TYPICAL SHEET PREPARATION

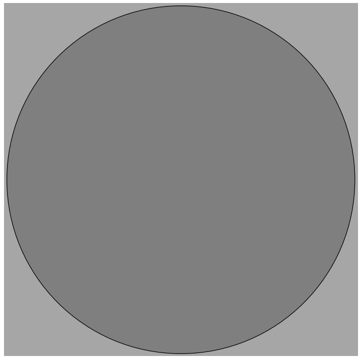


LARGE GRAIN DISK PREPARATION





[Saito, 2007]

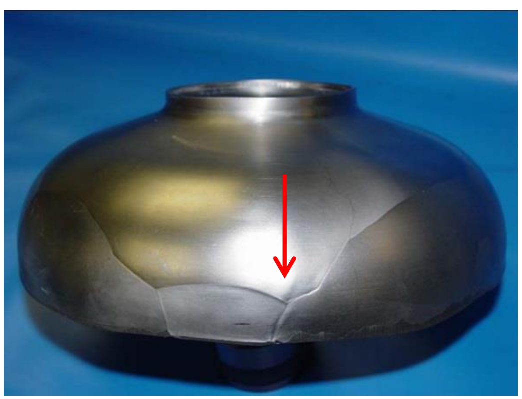


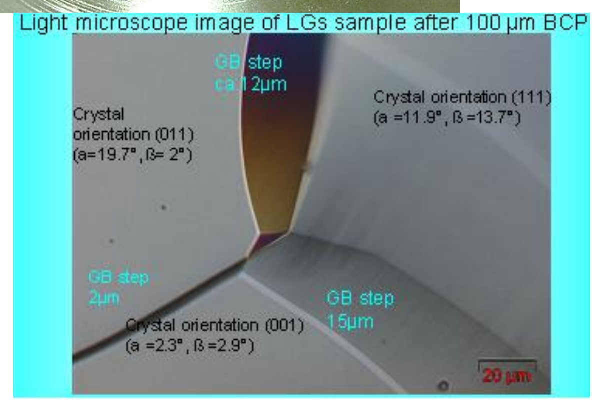
- Economy in weigth:
  - ≠ ~ 6 Kg/ 9-cell
  - ~ 3 k€ / 9-cell (compare w. 20 k€)
  - ~ 15% of the cost

LARGE GRAIN FORMING

But….

- Non uniform forming
  - asymmetric deformation
  - risk of tearing (irises)
  - risk of holes during welding
  - larges steps @ GB





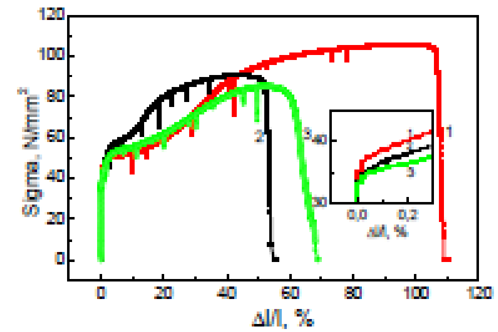


Figure 5. Elongation tests results for 3 single crystal samples with different orientations.

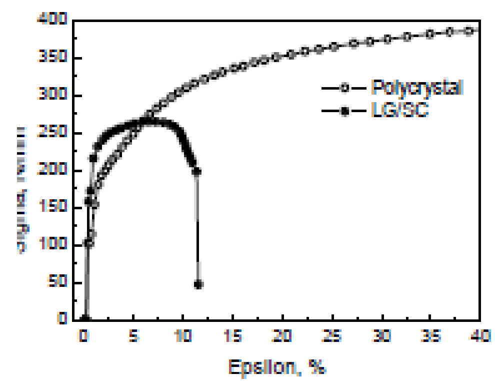


Figure 7. Biaxial bulging test results on large grain Nb sample. Curve for polycrystalline

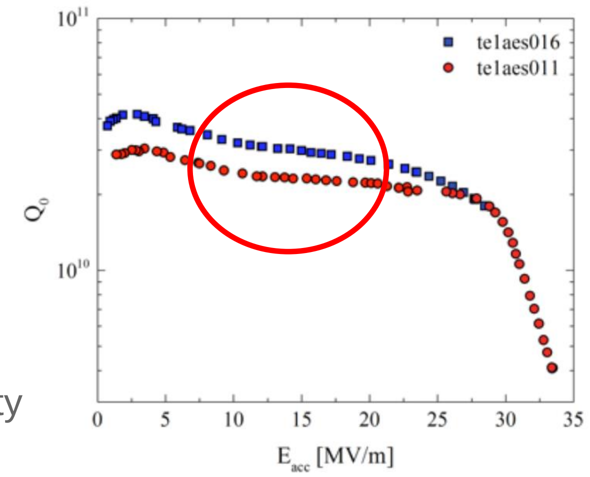
[Singer, 2008]

=> a lot of forming failure
=> a whole new industrial process need to be developed

LARGE GRAIN CONCLUSION

- RF performances : ~ same as smaller grain cavities
  - Medium Q ~ a little better for EP cavities
- Savings for (very) large Nb sheet production (small elliptical cavities only)
  - Less fabrication steps
  - Ingot => disks : no losses of material in the corners
  - High purity material with intrinsically good crystalline quality

  But not fitted for ∅ > 30 cm (typical ingot ∅)



- Increased costs and delay for Cavity forming
  - More fabrication steps, higher failure risks

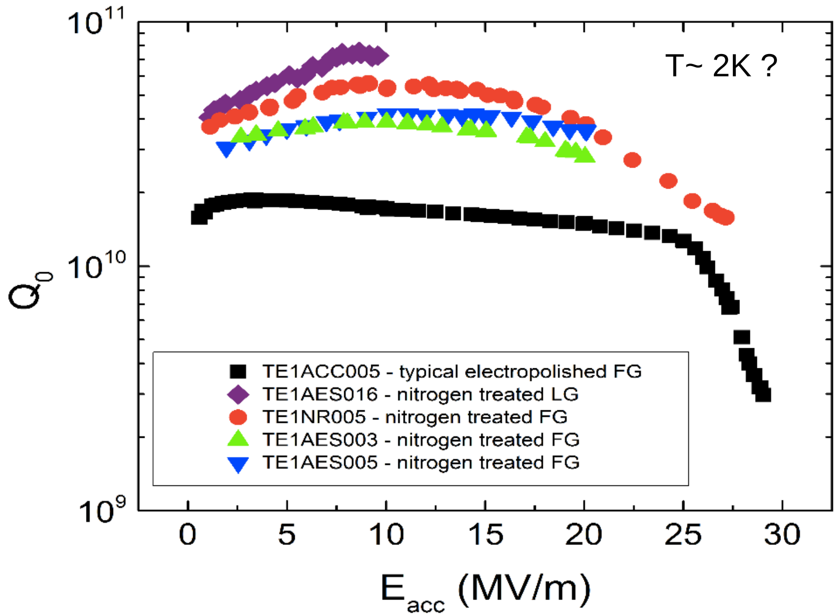
Large cost savings on material, …might be lost on fabrication

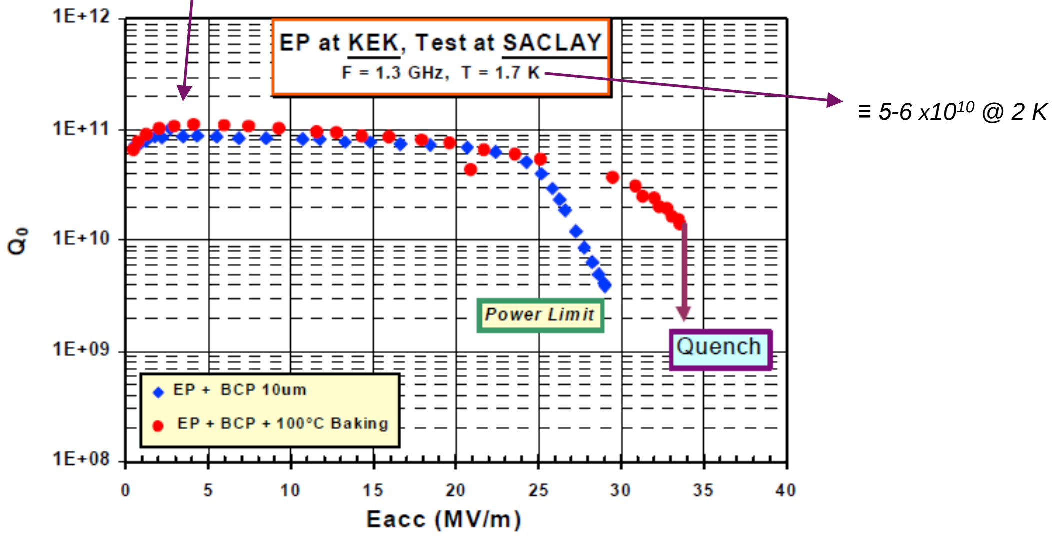
NITROGEN (OXYGEN ?)

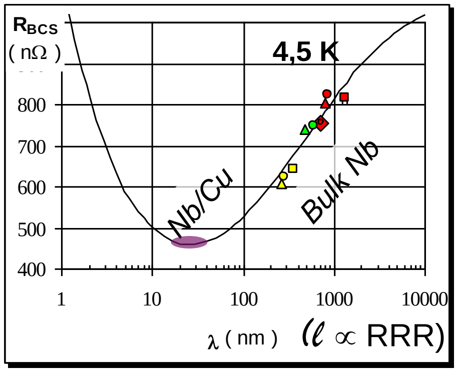
DOPING/INFUSION

BAKING/DOPING/INFUSION
WHAT IS THE DIFFERENCE?

- **N doping**
  - high temperature annealing (oxide disappears)
  - high temperature N_2 => degradation
  - EP (~80 µm) => very high Q_0, but E_{acc} ↓↓
  - At 1rst order : modification of *m.f.p*. ℓ
- **Not For ILC !!!**
  - Not necessarily related to N
  - Very well recrystallized material @ Saclay in 2001



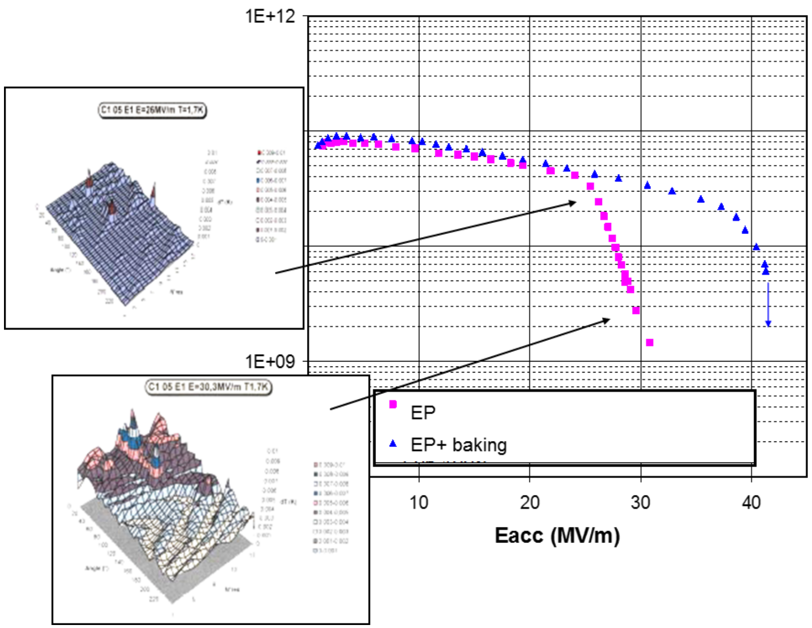


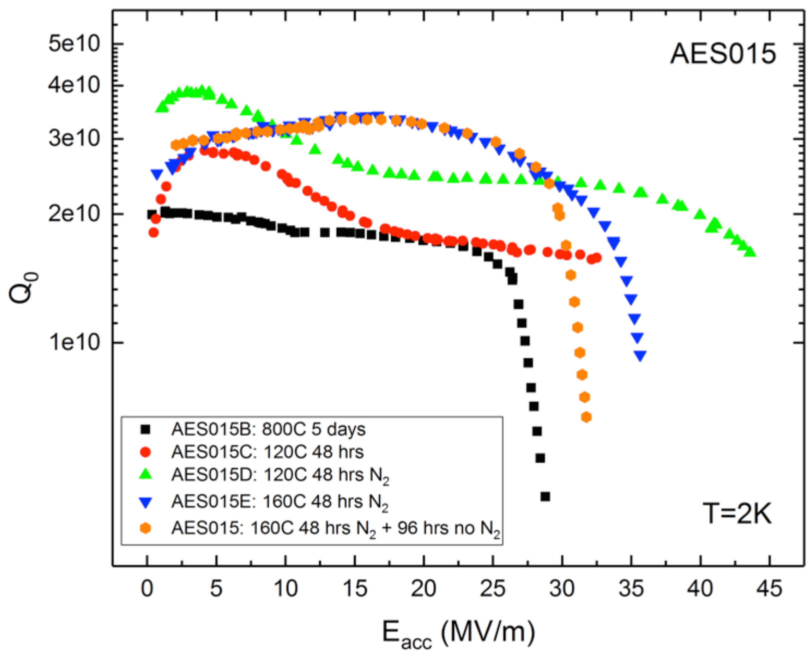


BAKING/DOPING/INFUSION WHAT IS THE DIFFERENCE?

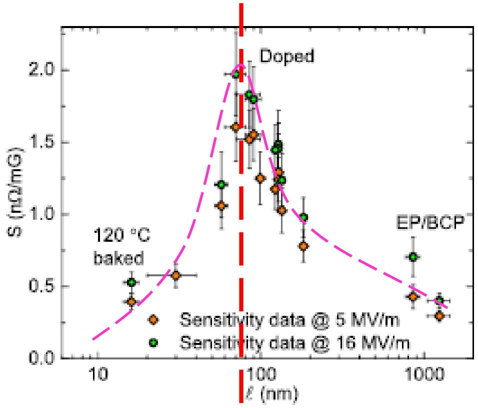
- **Baking**
  - 120 °C, 48 h => oxide degrades, O_i diffuses ~100 nm
  - Change in mean free path => better R_S
  - prevents hydride precipitation ?

- **N infusion**
  - 800°C annealing (oxide disappears)
  - 120 °C, 48 h in presence of N_2 => N_i diffuses ~10 nm
  - Change in mean free path => better R_S
  - prevents hydride precipitation ?



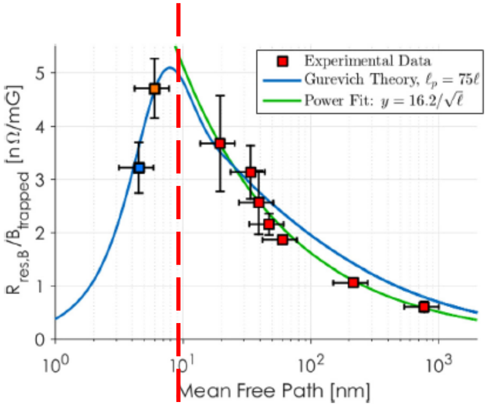


- **Variability lab to lab**
  - Same recipe, but not same results,
  - Needs adaptation : high temperature treatment ≠
- **Higher sensitivity to trap flux**
  - Upon cooldown if ∃ defects, magnetic remnant flux gets trapped
  - very high surf resistance in RF !



~100 nm =>
dislocation cells

Martinello et al, FNAL



~10 nm =>
interstitials

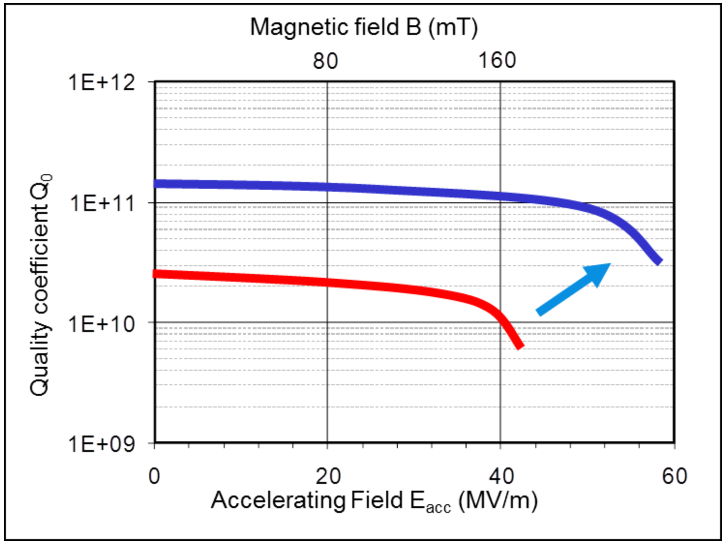
Gonella et al, CORNELL U.

Related to crystalline sub-structure, not specified/monitored yet

MULTILAYERS

AFTER NIOBIUM : NANOCOMPOSITES MULTILAYERS

Structures proposed by A. Gurevich in 2006, SRF tailored

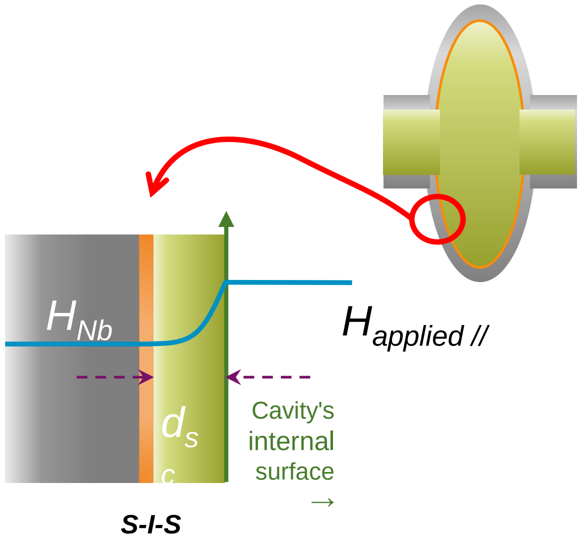


- **Dielectric layer**
  - Small ⊥ vortex (short -> low dissipation)
  - Quickly coalesce (w. RF)
  - Blocks avalanche penetration

  => **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): $R_s^{NbN} \approx \frac{1}{10} R_s^{Nb}$

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



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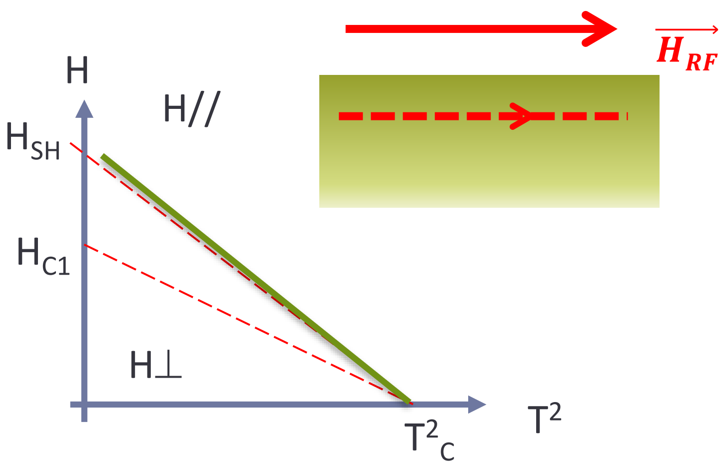
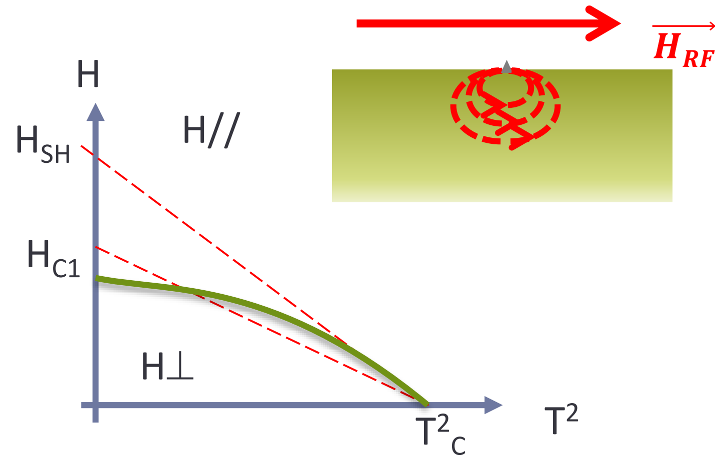
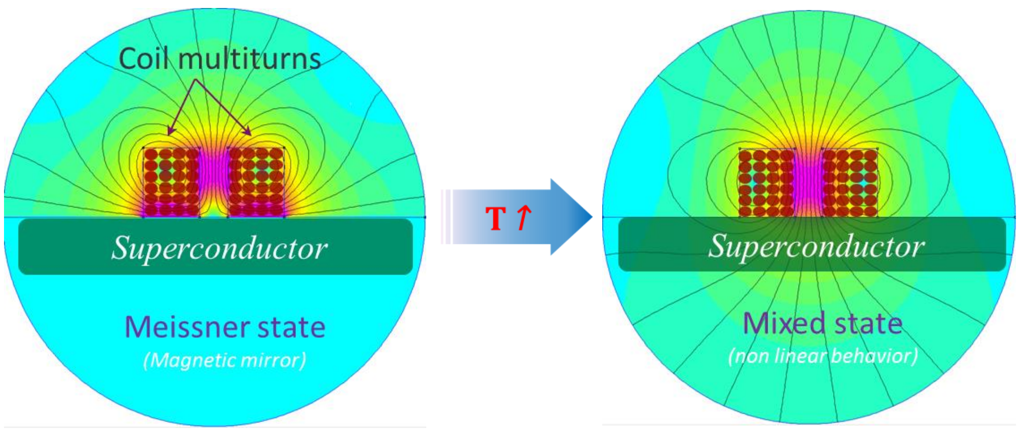
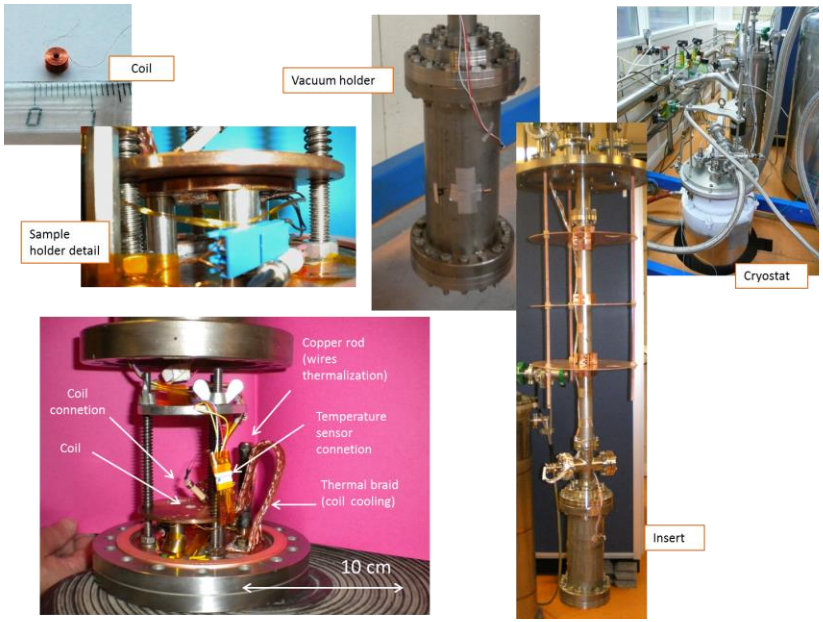


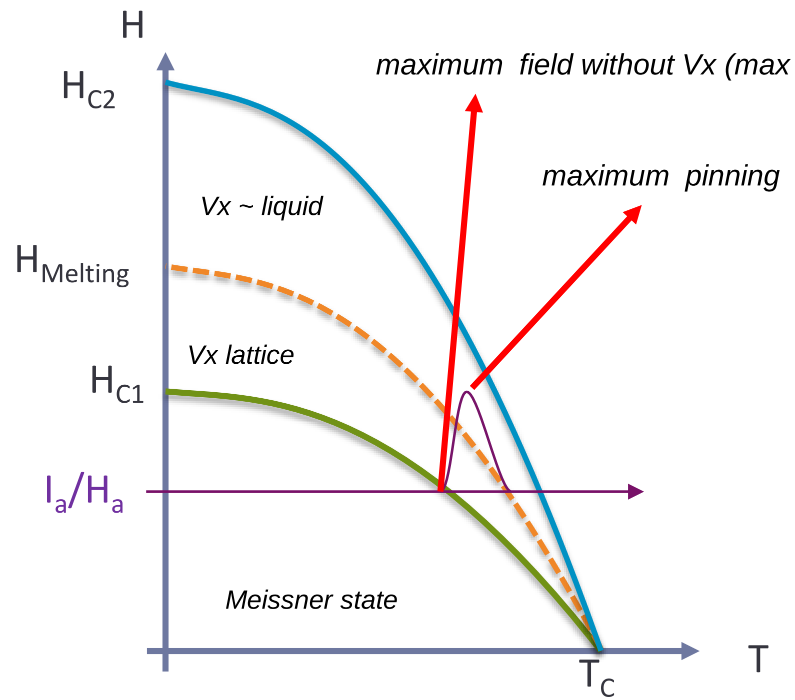


- Local magnetometry
  - ~ Same geometry as cavities
  - No shape/edge effect (vs DC/ Squid magnetometry)
  - No demagnetization effect
  - Measures actual penetration field wherever it is $H_P/H_{C1}/H_{SH}$

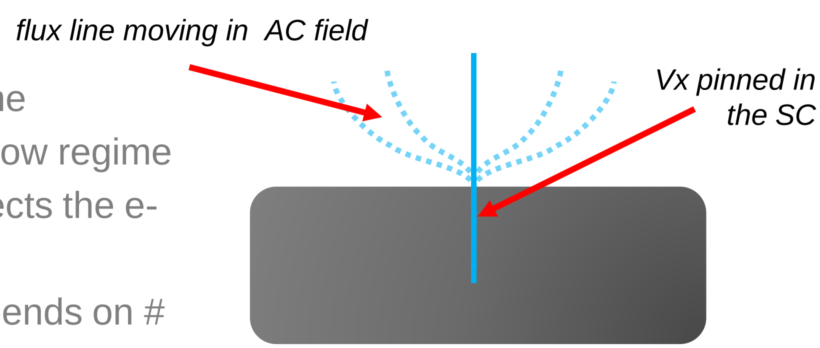


EXPERIMENTAL DETAILS





- **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).



Nb – INSULATOR – NbN MODEL

NbN coating by Magnetron Sputtering

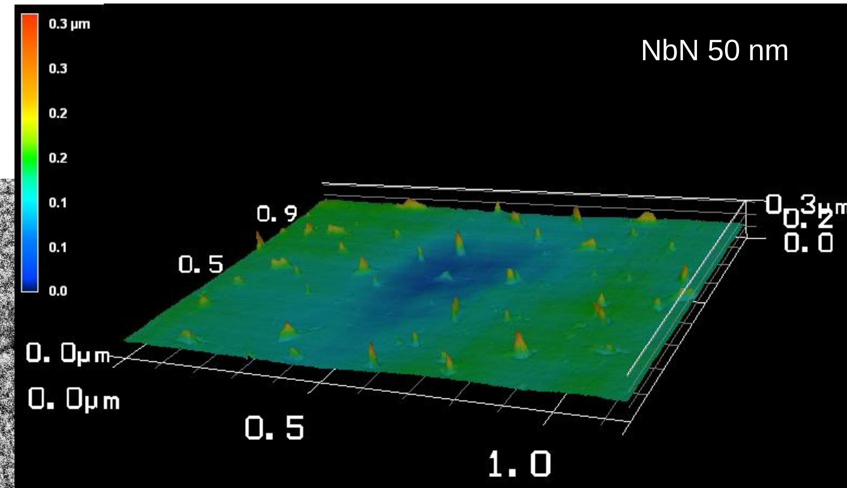
- **NbN single layers series**
  - NbN SL / “thick” Nb layer
    - Magnetron sputtered
    - MgO as dielectric layer
  - Far from perfect…

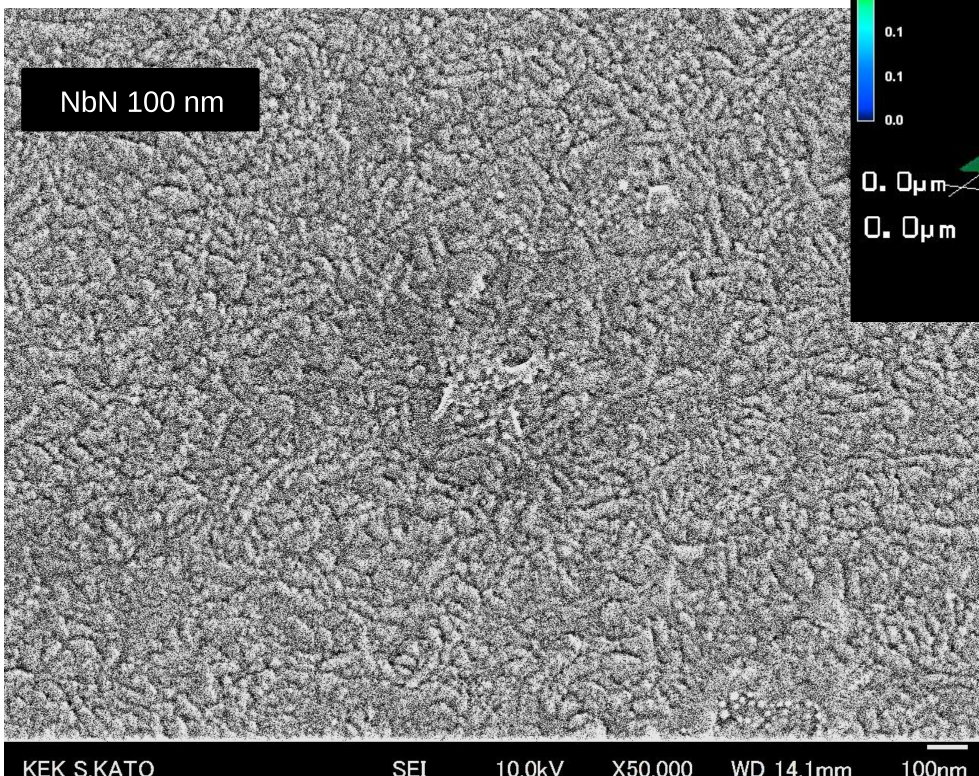
Nb (nm)	MgO (nm) Calc(actual)	NbN (nm) Calc(actual)	T_C (K)
250†	14	0	8.9
250†	14	25	15.5
500	10 (10.3)	50 (65)	15*
500	10 (8.4)	75 (72)	14.1*
500	10 (9.8)	100 (94)	14*
500	10	125	14.3*
500	10 (6.7)	150 (132)	15.9*
500	10 (10.4)	200 (164)	15*

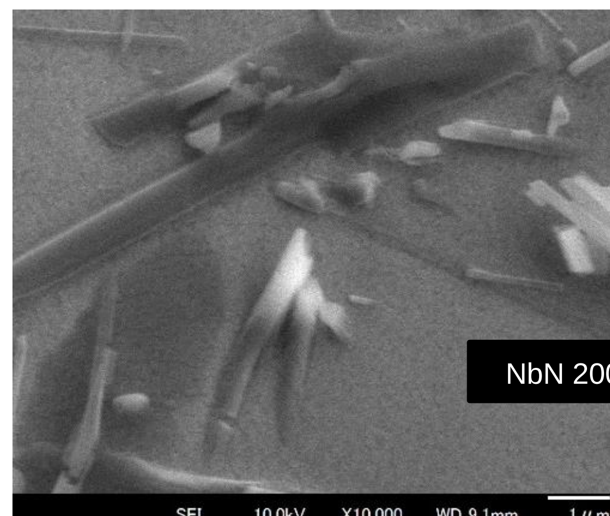
† Not same batch, deposited on the same conditions, but substrate = sapphire
*As determined with magnetometry, see below.

Morphology

- Rough surface





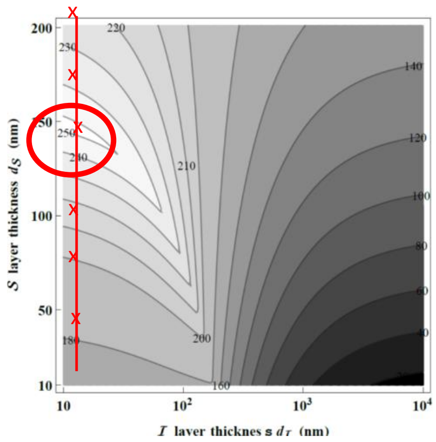


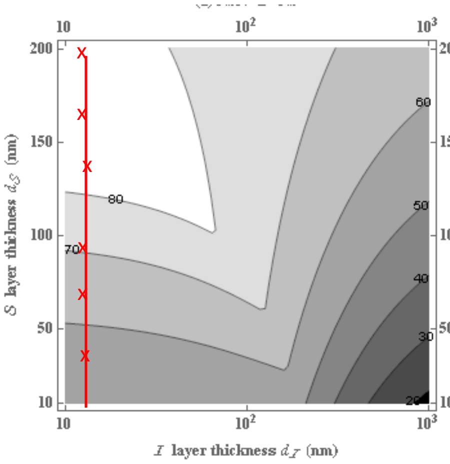
MgO needle ?
(capping material)

COMPARAISON WITH THEORY

Theoritical predictions from T. Kubo (KEK)

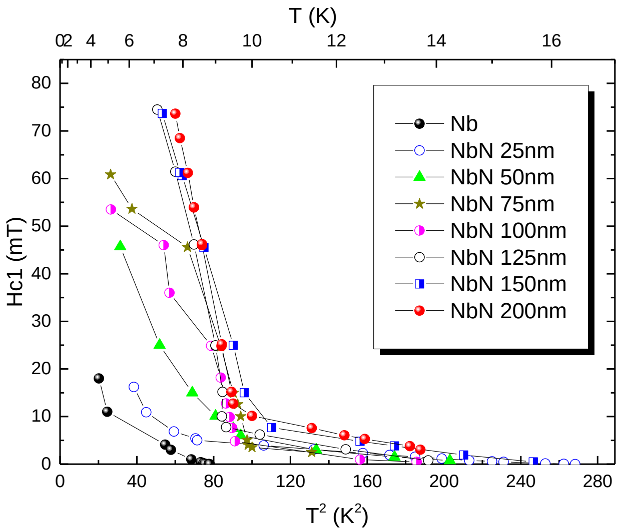
Ideal Nb substrate with B_{C1}=170 mT





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

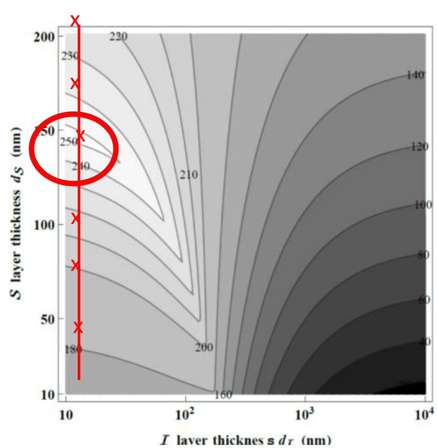
** e.g. morphologic defects that allow earlier vortex penetration See SST paper cited earlier*

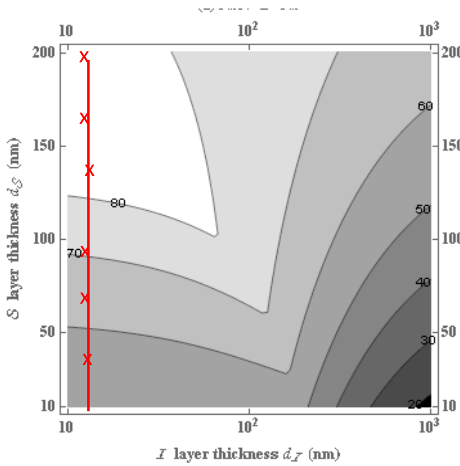


- The enhancement of the field penetration increases with thickness of NbN
- It reaches a saturation at thicknesses > 100 nm

Theoritical predictions from T. Kubo (KEK)

Ideal Nb substrate with B_{C1}=170 mT

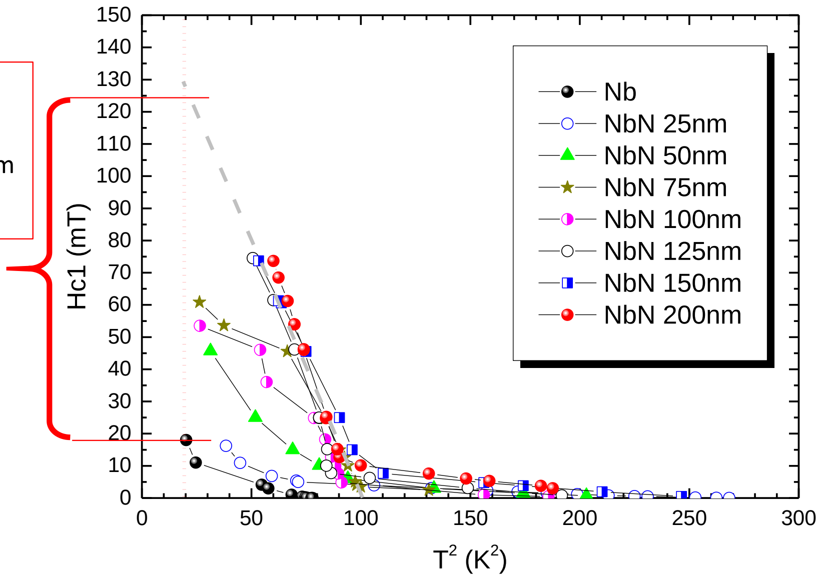




Nb with defects, with B_{C1}=50 mT*

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

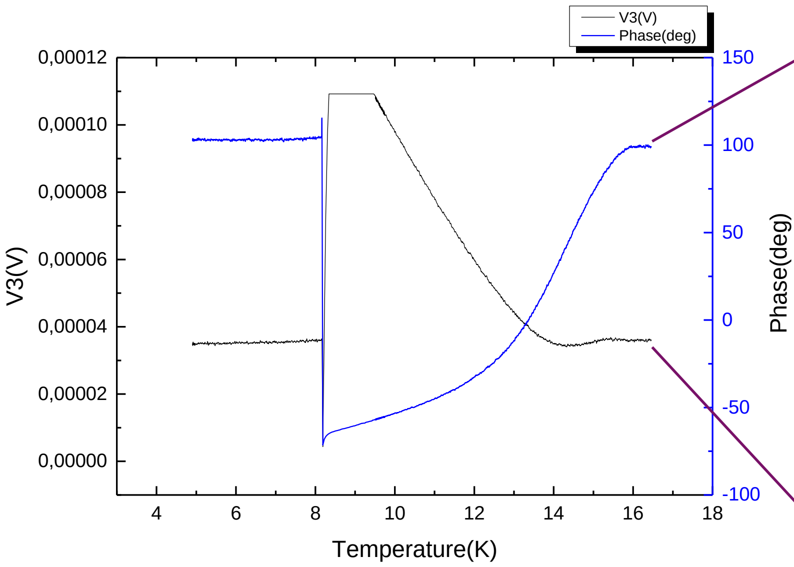
@ 4.5 K
~ + 110 mT?
~25-30 MV/m
ILC shape



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

CLOSEUP OF 3rd HARMONIC SIGNAL

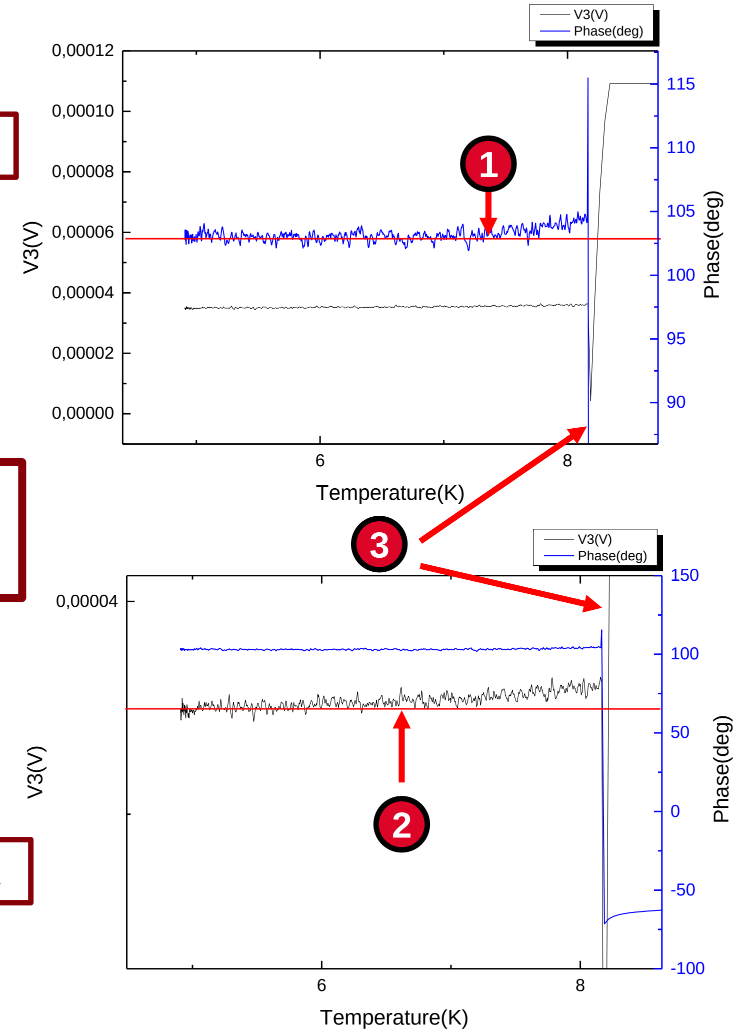
- For a given H_{appl}, we observe 3 ≠ transition temperatures



Phase signal

T❶~T❷
T ❸>>T❷

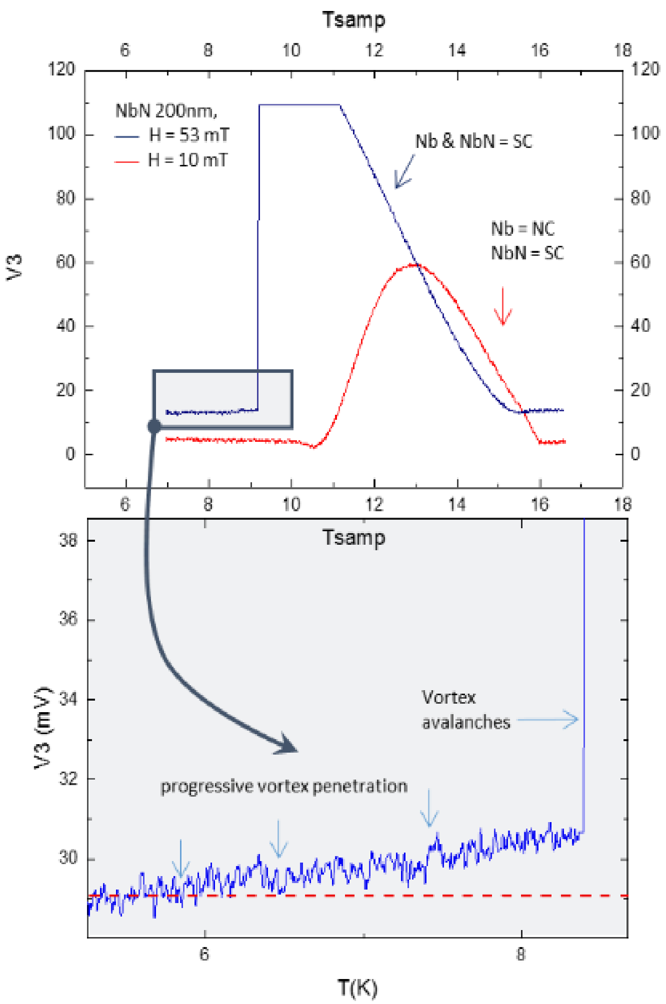
Voltage signal

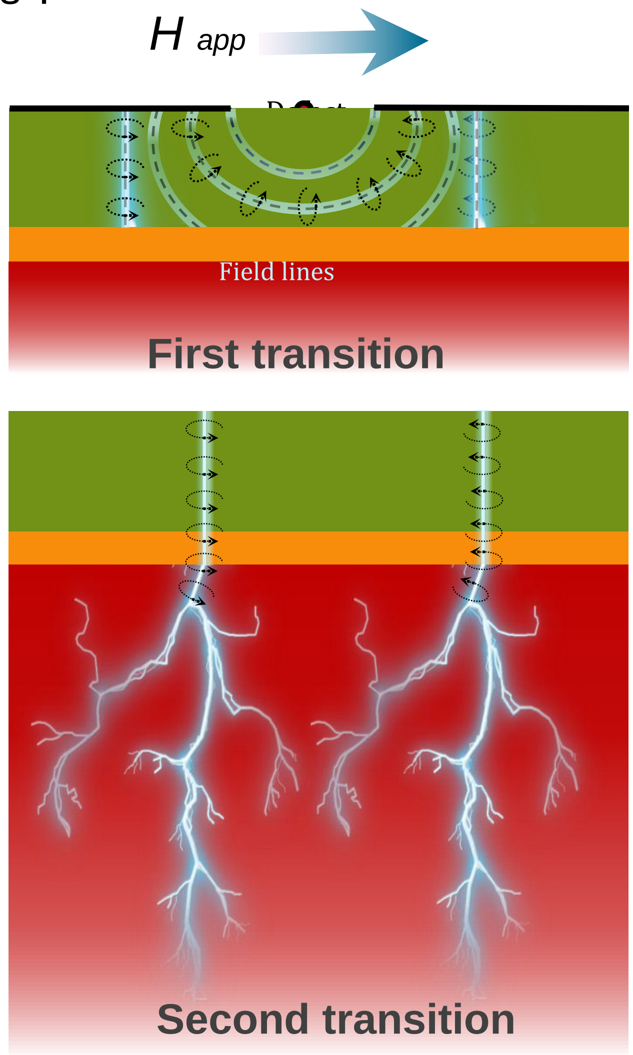


- T❶~T❷: within noise level
- T ❸>>T❷: dramatic transition

ROLE OF THE DIELECTRIC LAYER !

- Why do we have two transitions ?





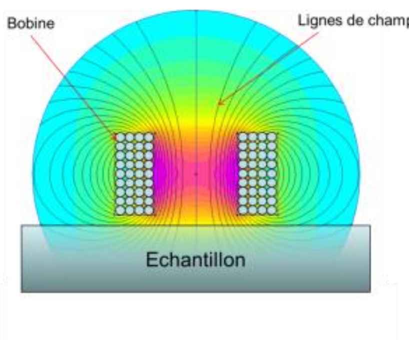
- Thin SC layer NbN
- Insulator MgO
- Thick SC layer Nb

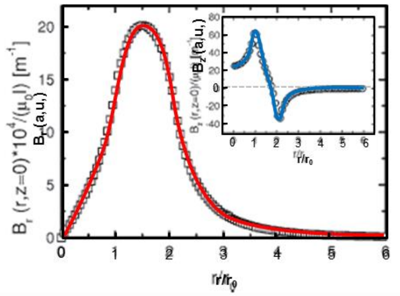
- H // surface => surface barrier†
- A defect locally weakens the surface barrier
- 1st transition, vortex blocked by the insulator ~100 nm => low dissipation.
- 2nd transition, propagation of vortex avalanches (~100 µm) => high dissipation.
- **Dielectric layer = efficient protection !!!**

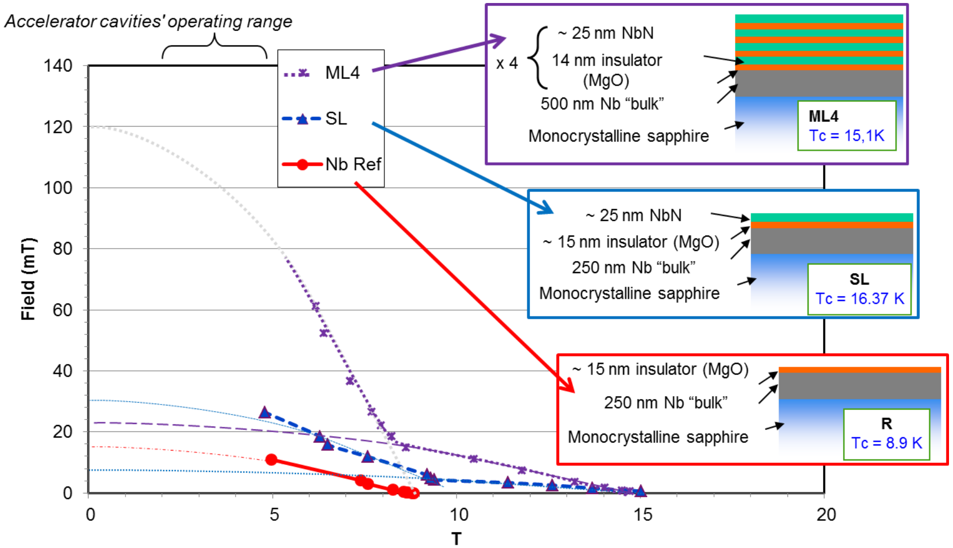
†*B. Bean and J. D. Livingston, Phys. Rev. Lett. 12, 14 (1964).*

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

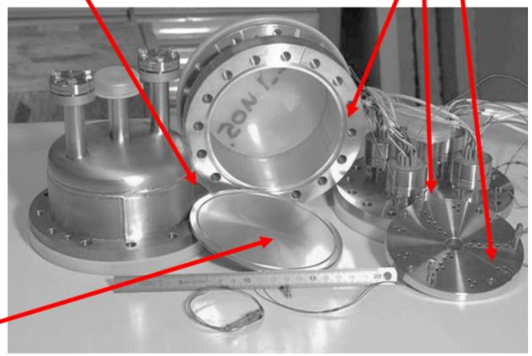
Local magnetometry:

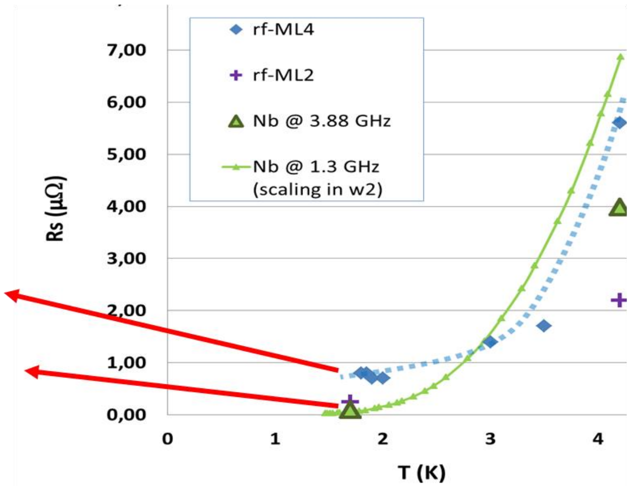






RF test (collaboration IPNO)



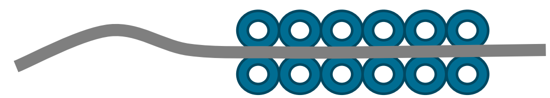


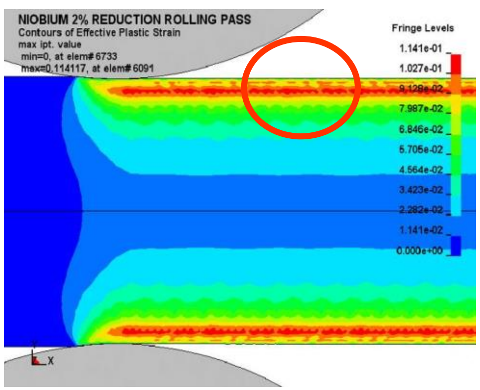
DAMMAGE LAYER

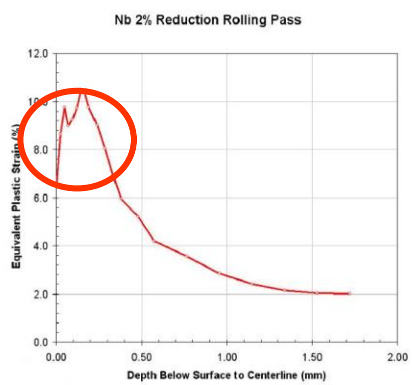
DAMAGE LAYER / ROLLING

- **High dislocation density (damage) incriminated in:**
  - Apparition of hot spots on operating cavities
  - High density of hydride precipitates
  - High sensitivity to trapped flux
- **Damage layer seems to essentially originate from rolling**
  - Surface texture resistant to recrystallization
  - Not fully eliminated after 150µm removal (patchy nature)

NB : in case of billet slicing damage layer is ≠ and needs to be assessed





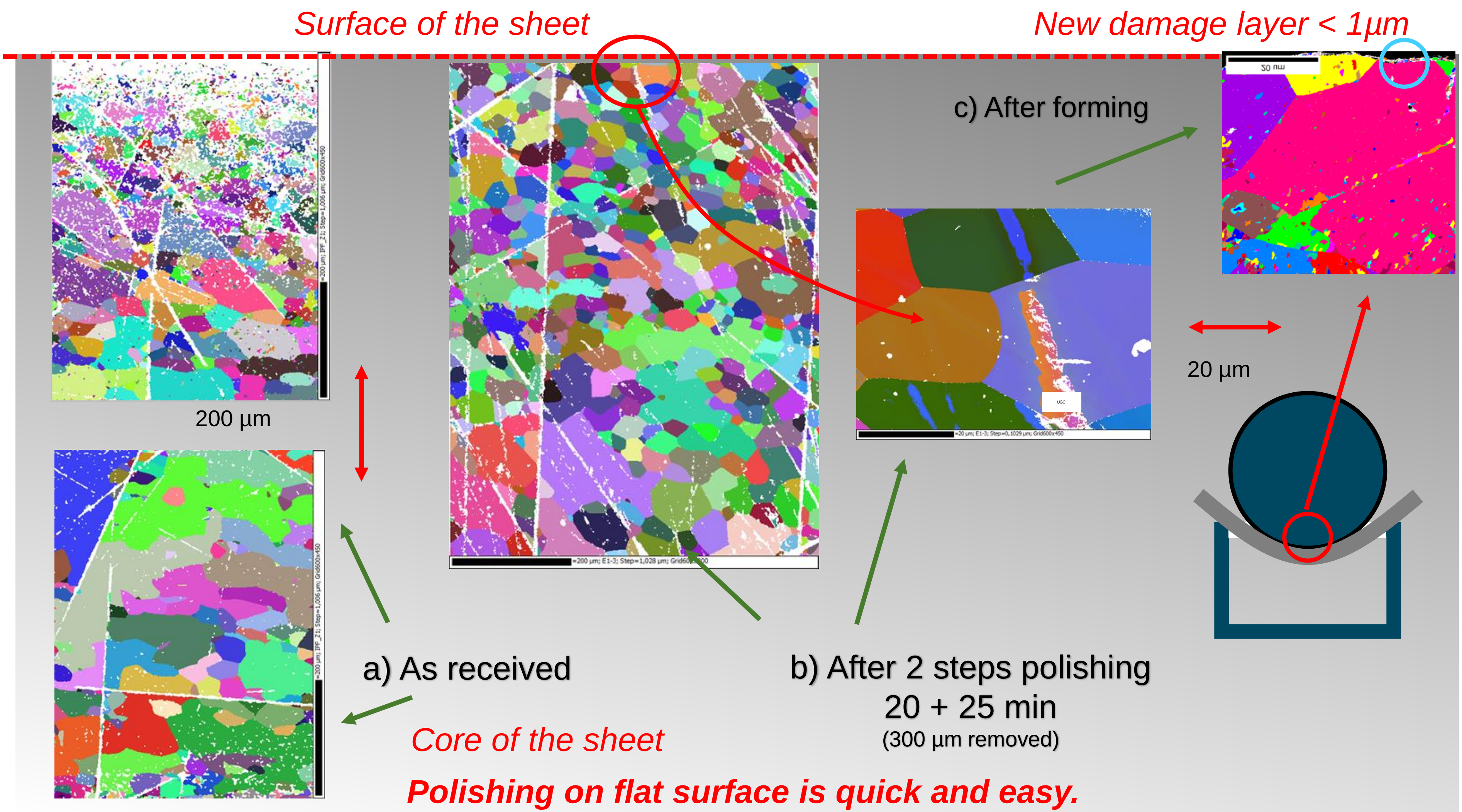


Finite element simulation of 2% reduction of 3.5 mm sheet with 1 cm diameter rolls (Courtesy Non-Linear Engineering, L.L.C.).

[R. Crook et al, Black Laboratory] & http://accelconf.web.cern.ch/AccelConf/srf2009/posters/tuppo071_poster.pdf

- **Postulate :**
  - Strain left by forming and welding can be easily removed by recrystallization treatment
  - => **mechanical polishing of flat sheet easy and inexpensive !!!**

DAMAGE AS SEEN BY ELECTRON DIFFRACTION



Polishing on flat surface is quick and easy.
Mechanical chemical preparation inspired from metallographic polishing can produce damage layer ≤100 nm

CONCLUSION AND OUTLOOK

- **Production already asserted to produce specification**
- **Reducing cost R&D :**
  - Today limited to only 2 directions : large grain and N infusion
  - Already promising
  - Physics not fully understood => risks
- **Longer term R&D**
  - Promising trails for improvement also exist
  - better control of the material production is required

THANK YOU FOR YOUR ATTENTION

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
- Why do we have two transitions ?