Enhancement of First Penetration Field in Superconducting Multi-layers Samples

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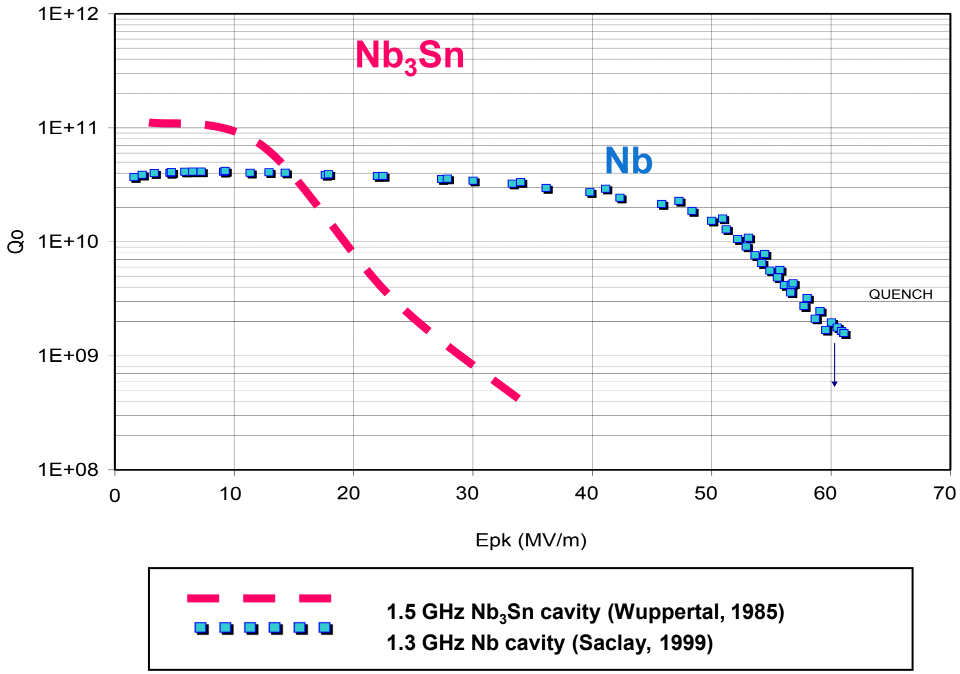
Limits in a RF cavity

Classical theory BCS + RF :

- Magnetic RF field limits E_{acc} : $E_{acc} \propto H^{RF}$
- Phase transition when magnetic H^{RF} ~> H_{SH} *(superheating field)*
- For Nb H_{SH} ~1,2.H_C *(thermodynamic)*
- Higher Tc => higher Hc => higher E_{acc}

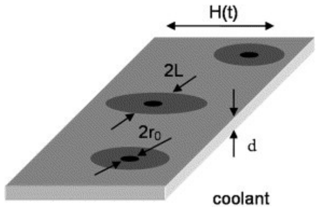
But…



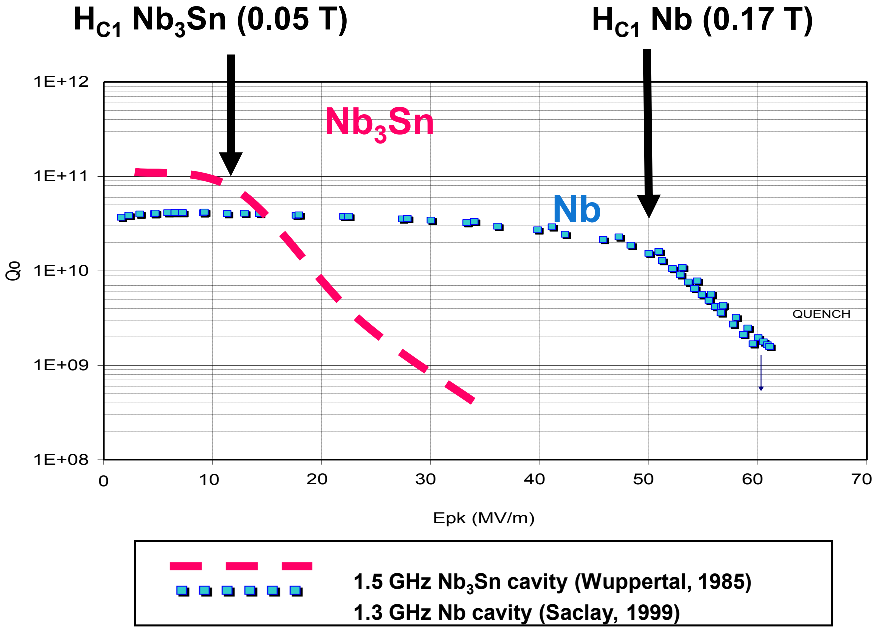
- **Bulk Nb_3Sn cavity : relative failure**
  - High Q_0 @ low field => low surface resistance => good quality material
  - Early Q slope !!!
- **Note :**
  - BCS valid only near T_C , clean limit
  - we work at 2 K + rather dirty limit.
- **BCS model needs to be completed**

High field dissipations : due to vortices ?

Theoretical Work from Gurevich : temperature correction



- Non linear BCS resistance at high field : quadratic variation of R_{BCS}
- Vortices : normal area ~ some nm can cause “hot spots” ~ 1 cm *(comparable to what is observed on cavities)*
- At high field vortices => thermal dissipation => Quench
- **Nb is the best for SRF because it has the highest H_{C1},** *(prevents vortex penetration)*



- **Nb is close to its ultimate limits**

(normal state transition)

- avoiding vortex penetration => keep below H_{C1}
- increasing the field => increase H_{C1}
- “invent” new superconductors with $H_{C1} > H_{C1}^{Nb}$

A. Gurevich, "Multiscale mechanisms of SRF breakdown". Physica C, 2006. 441(1-2): p. 38-43

A. Gurevich, "Enhancement of RF breakdown field of SC by multilayer coating". Appl. Phys.Lett., 2006. 88: p. 12511.

*P. Bauer, et al., "Evidence for non-linear BCS resistance in SRF cavities ". Physica C, 2006. **441**: p. 51–56*

Breaking Niobium monopoly

Overcoming niobium limits (A.Gurevich, 2006) :

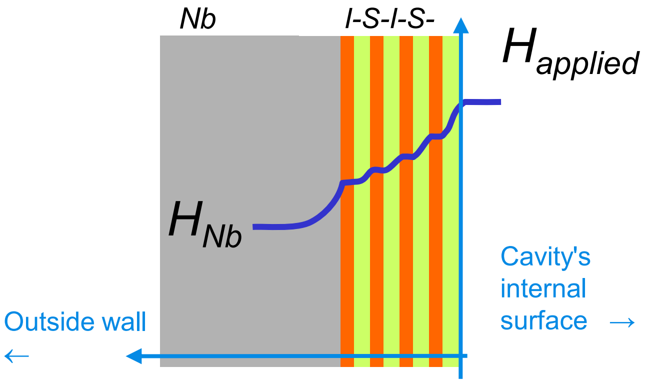
- **Keep niobium but shield its surface from RF field to prevent vortex penetration**
- Use nanometric films (w. $d < \lambda$) of higher Tc SC :
  => **H_{C1}** enhancement
- Example :

NbN , $\xi = 5$ nm, $\lambda = 200$ nm

(similar improvement expected with MgB_2 or Nb_3Sn)

$H_{C1} =$ **0,02 T**

20 nm film => $H'_{C1} =$ **4,2 T** **x 200**



$$H_{Nb} = H_{appl} e^{-\frac{Nd}{\lambda}}$$

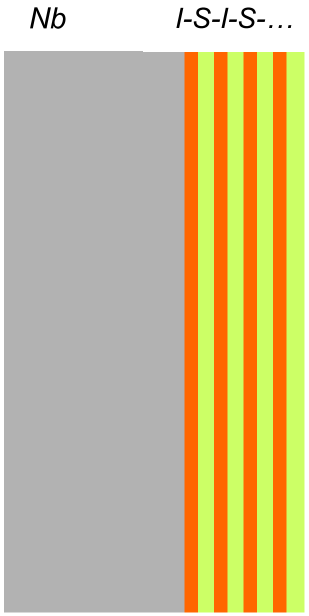
- high H_{C1} => no transition, no vortex in the layer
- applied field is damped by each layer
- insulating layer prevents Josephson coupling between layers
- applied field, i.e. accelerating field can be increased without **high field** dissipation
- thin film w. high Tc => low R_{BCS} at **low field** => higher Q_0

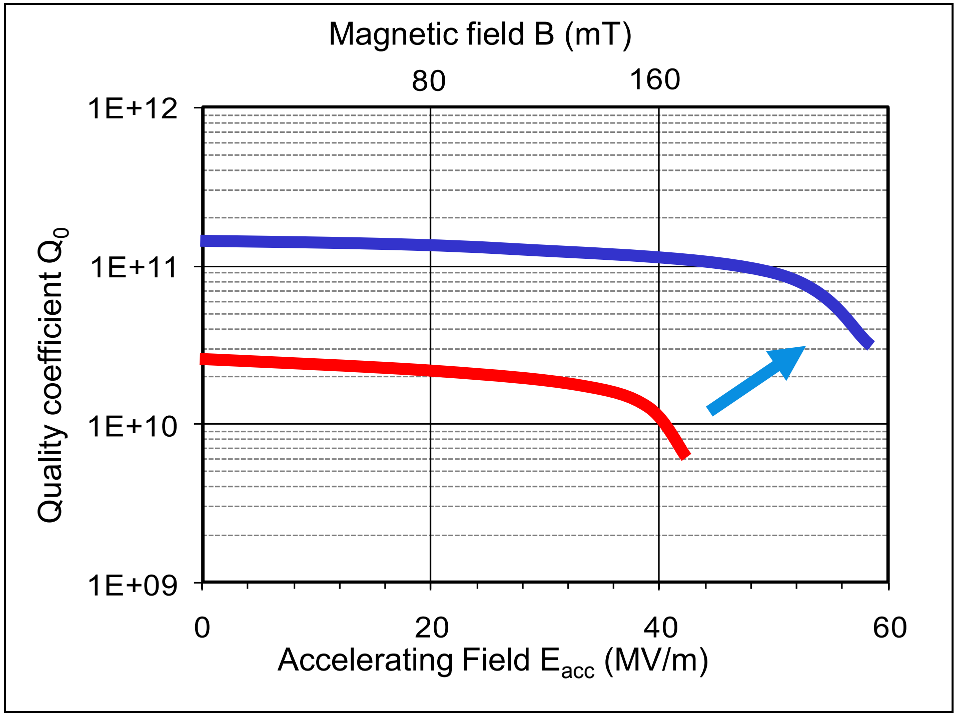
High Tc nanometric SC films : low R_S, high H_{C1}

- In summary : take a Nb cavity…
- deposit composite nanometric SC (multilayers) inside

Nb / insulator/ superconductor / insulator /superconductor…

(SC with higher Tc than Nb)

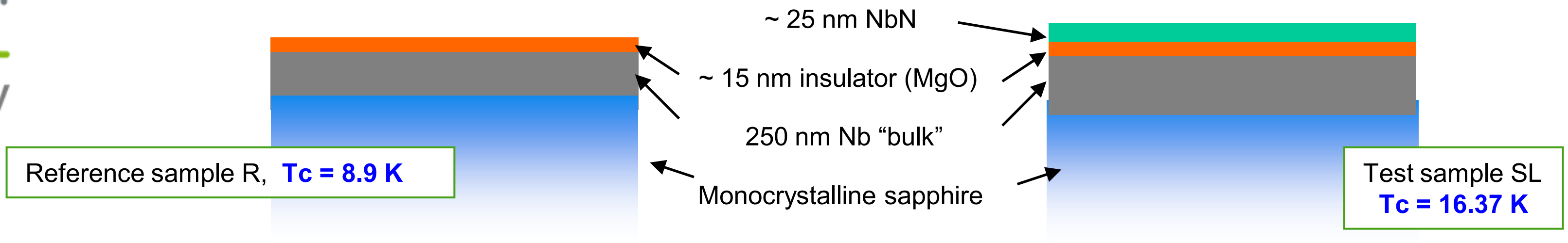




Increasing of E_{acc} AND Q_0 !!!

First exp. results on high quality model samples

- Choice of NbN:
  - ML structure = close to Josephson junction preparation (SC/insulator compatibility)
  - Use of asserted techniques for superconducting electronics circuits preparation:
    - Magnetron sputtering
    - Flat monocrystalline substrates



~ 25 nm NbN

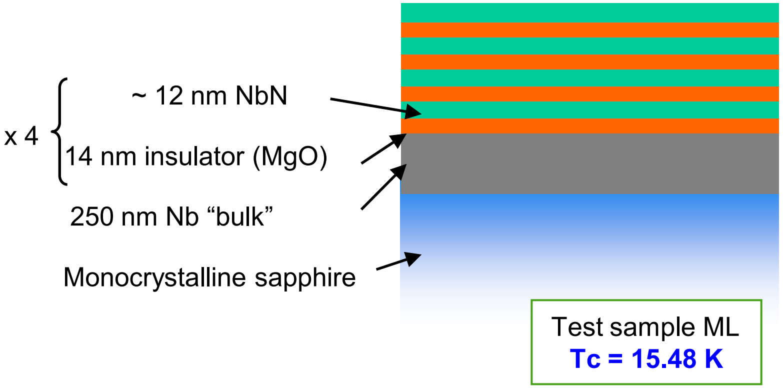
~ 15 nm insulator (MgO)

250 nm Nb “bulk”

Monocrystalline sapphire

Reference sample R, **Tc = 8.9 K**

Test sample SL
Tc = 16.37 K



x 4 { ~ 12 nm NbN
14 nm insulator (MgO) }

250 nm Nb “bulk”

Monocrystalline sapphire

Test sample ML
Tc = 15.48 K

Collaboration with J.C. Villégier, CEA-Inac / Grenoble

Samples and H_{C1} issues

Choice of model samples:

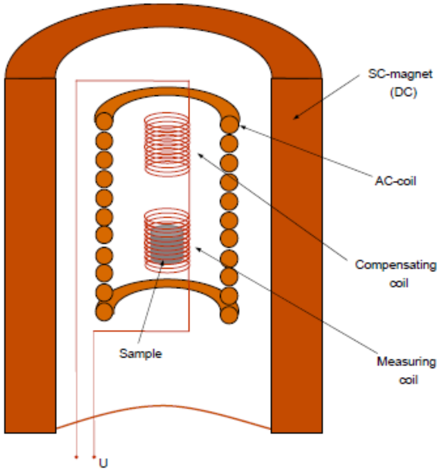
- It is easier to change parameters on samples than on cavities :
  - Easier to get good quality layers on small surfaces
  - Change of substrate nature : sapphire, monocrystalline Nb, polycrystalline Nb, surface preparation...
  - Optimization of SC thickness, number of layer, etc.
- But !
  - H_{C1} measurement is more difficult with classical means (DC).
  - Note that **$H_{C1}^{DC} \leq H_{C1}^{RF} \leq H_C \sim H_{SH}$** => any DC or low frequency measurement is conservative compare to what is expected if RF.
  - H_{C1} give an estimation of the maximum field achievable without dissipation : if I keep below H_{C1}, I don't really have to care about what exactly H_{SH} is, what the (complex!) behavior of vortices is, etc.
  - Still need RF test to estimate R_S/Q_0

Magnetic characterization : SQUID (1)

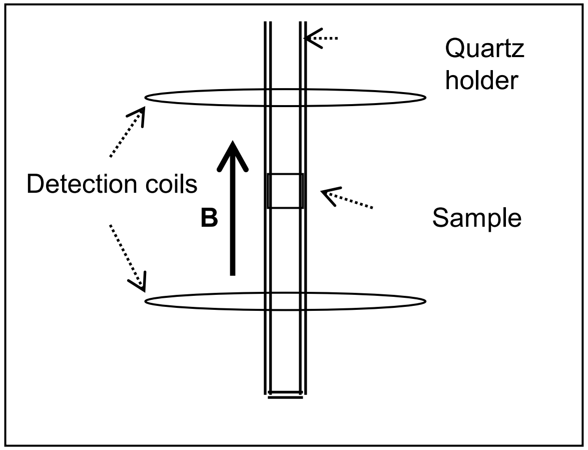
Principle of measurement (5x5mm^2 samples) :

- Parallel and perpendicular field tested
- Thin films in parallel configuration (**B**//):

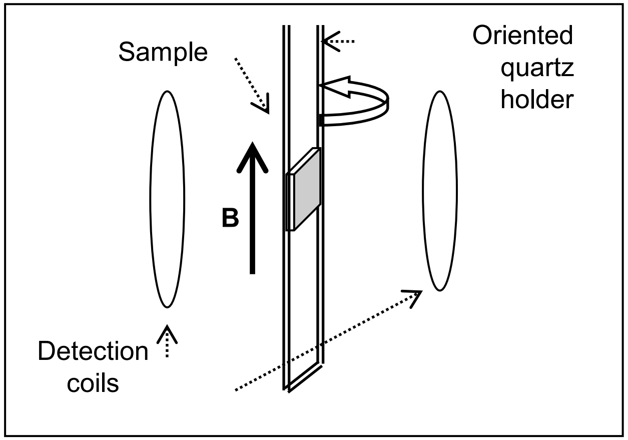
1. Strong sensitivity of **M** to applied field orientation (alignment should be better than 0.005°).
2. Strong transverse signal vs longitudinal => superposition of 2 signals => development of a dedicated fitting procedure was necessary



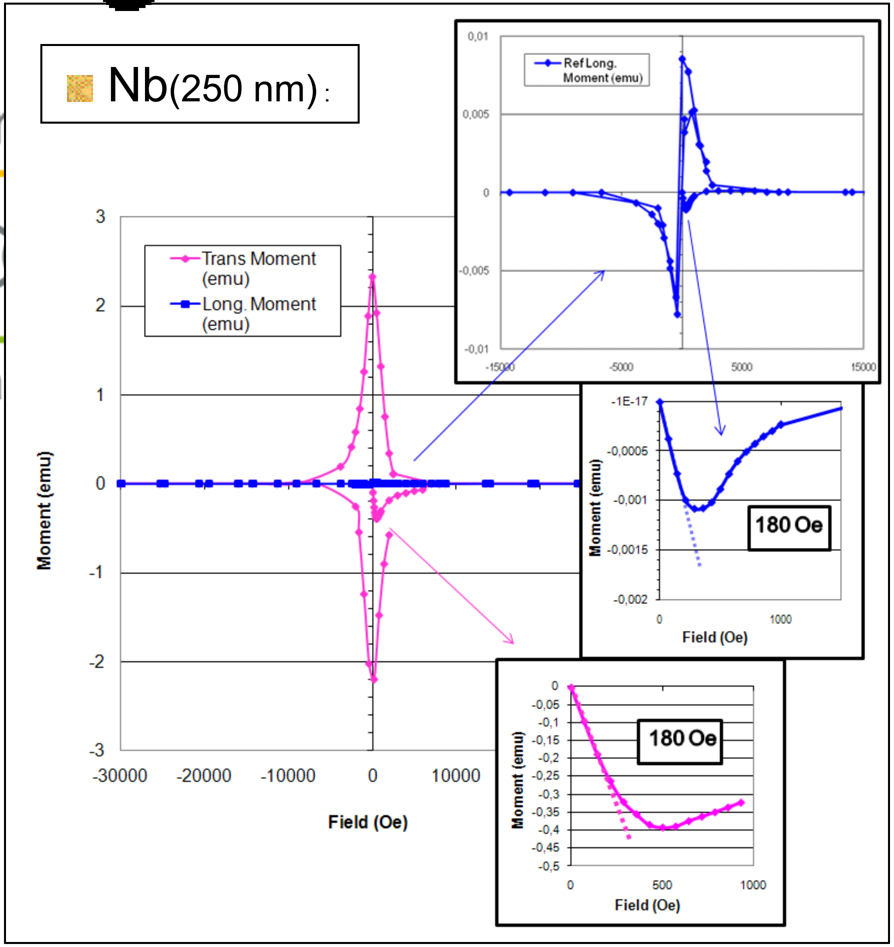
- B //, longitudinal moment

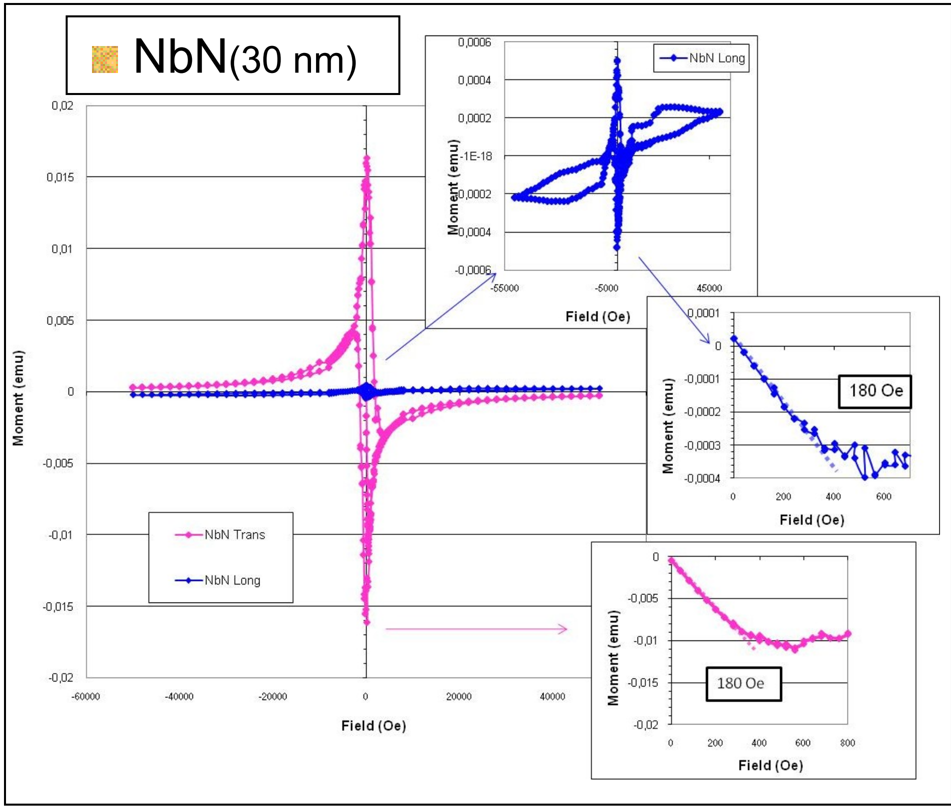


- B //, transverse moment



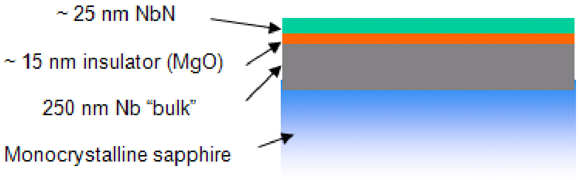
SQUID (2) : references @ 4.5 K





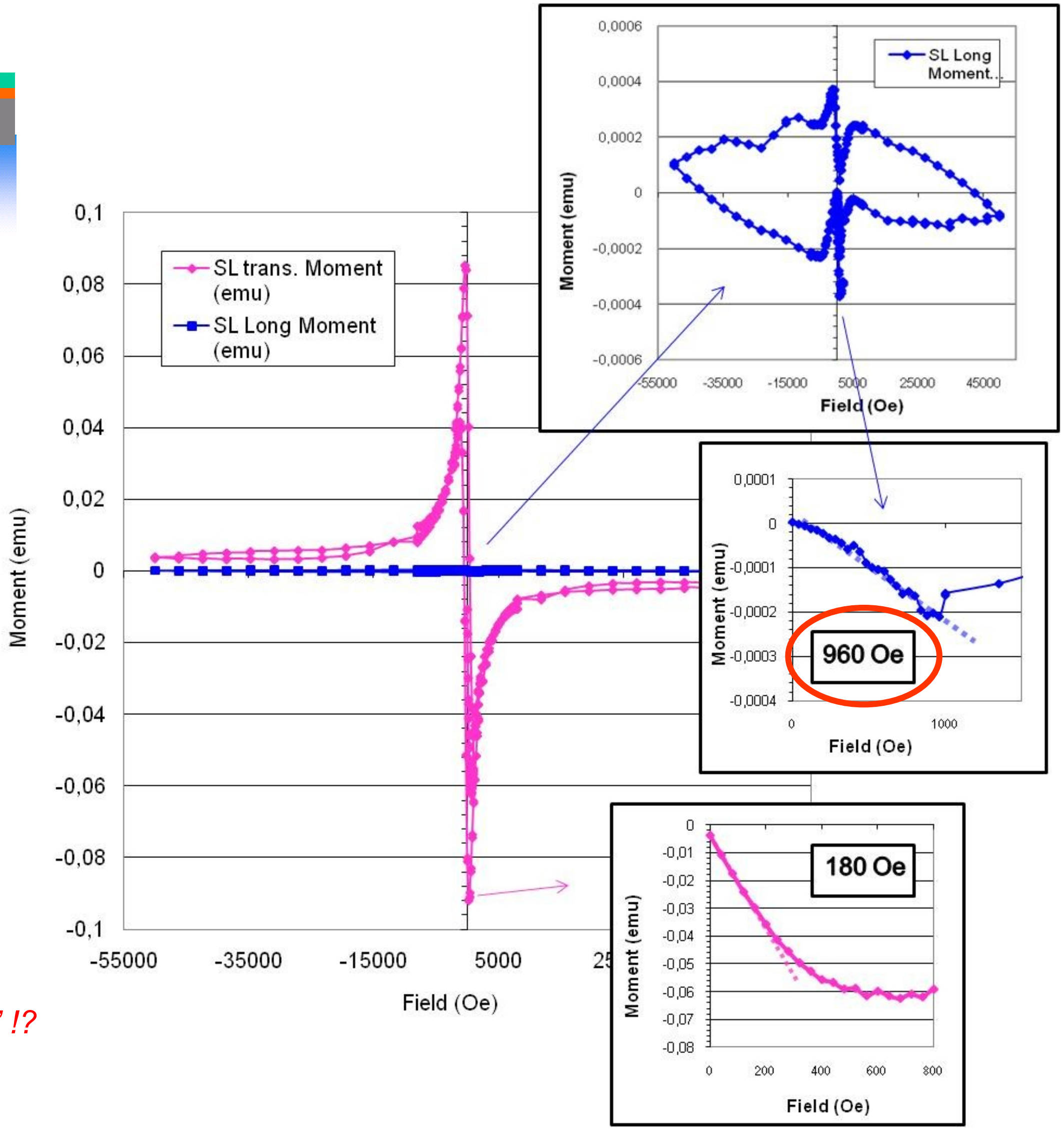
- "Elemental" layers : isotropic.
- H_P ~ 18 mT = compatible with magnetron sputtered films
- No field enhancement on 30 nm NbN layer !?

SQUID (3) : SL Sample @ 4.5 K



- High quality NbN film (Tc =16.37K)
- Strong anisotropic behavior
- Longitudinal moment : Fishtail shape characteristic of layered SC
- H_P ~ 96 mT (+ 78 mT /Nb alone) !!!
- Similar behavior with ML

~ "20 MV/m" !?



SQUID : ISSUES

- Strong screening effect observed although sample is in uniform field (!?)
- Edge, shape, alignment issues => is $B_P \sim B_{C1}$?
- Perpendicular remnant moment => what is the exact local field ?
- DC instead of RF : not a problem; B_{C1} is expected to be higher in RF

=> need to get rid of edge/orientation effects

=> need to get local measurement !

Local magnetometry (1)

- 3^{rd} harmonic measurement, coll. INFM Napoli

  M. Aurino, et al., Journal of Applied Physics, 2005. ***98: p. 123901.***

  Perpendicular field : field distribution can be determined analytically.

  - If $r_{sample} > 4\ r_{coil}$: Sample ≡ infinite plate
  - Applied field : perpendicular, induction (B) // surface

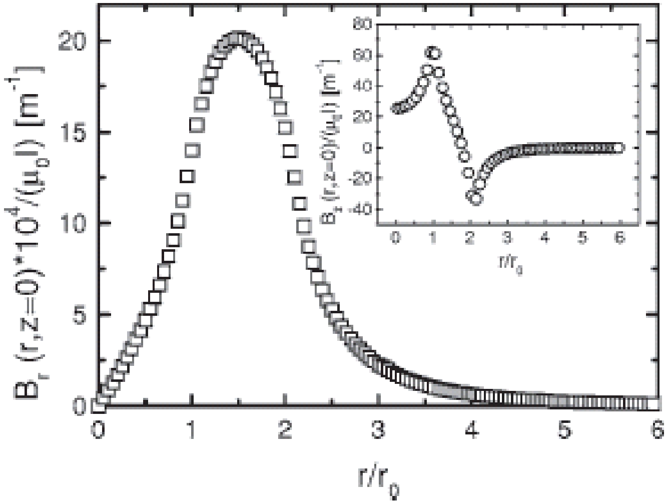
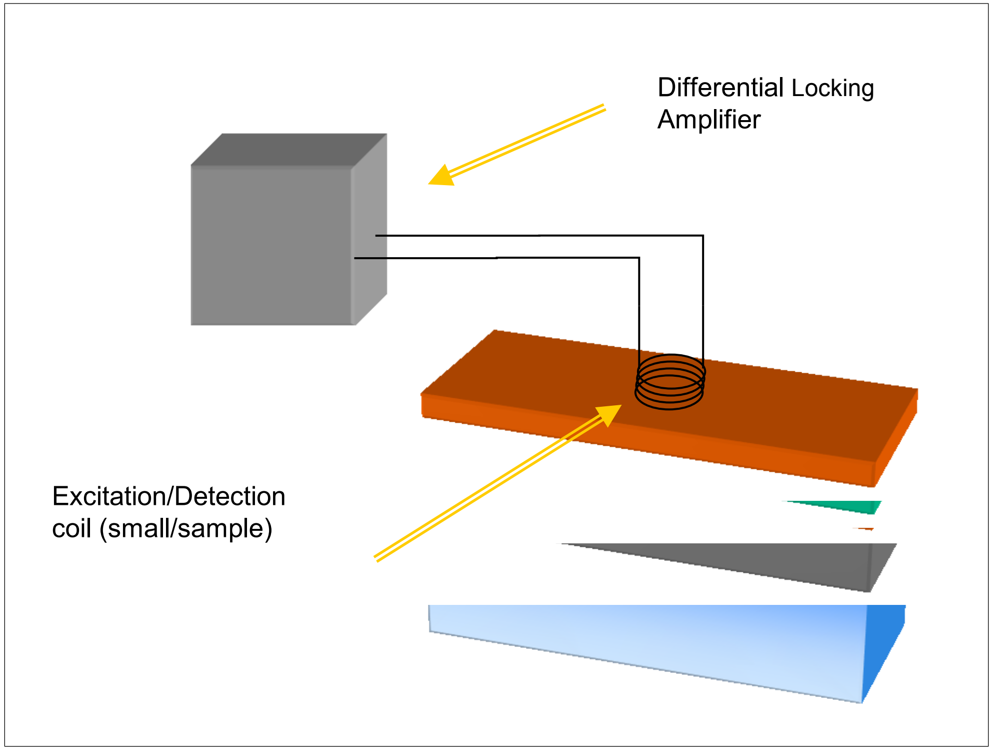


FIG. 4. Radial component of the total induction field (open squares) for a multiturn coil. In the inset the result for the normal component (open circles) is shown. Both components have been calculated at the sample surface as a function of r/r_0.

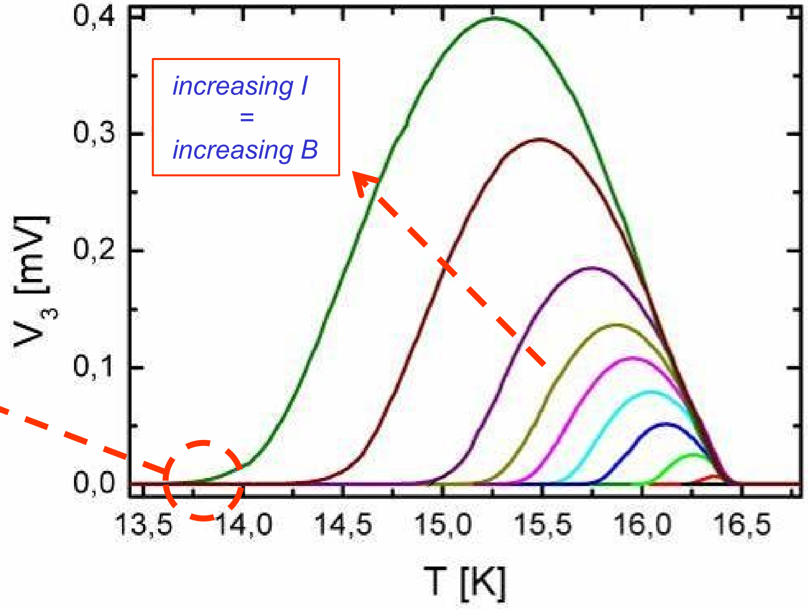


Differential Locking Amplifier

Excitation/Detection coil (small/sample)

Local magnetometry (2)

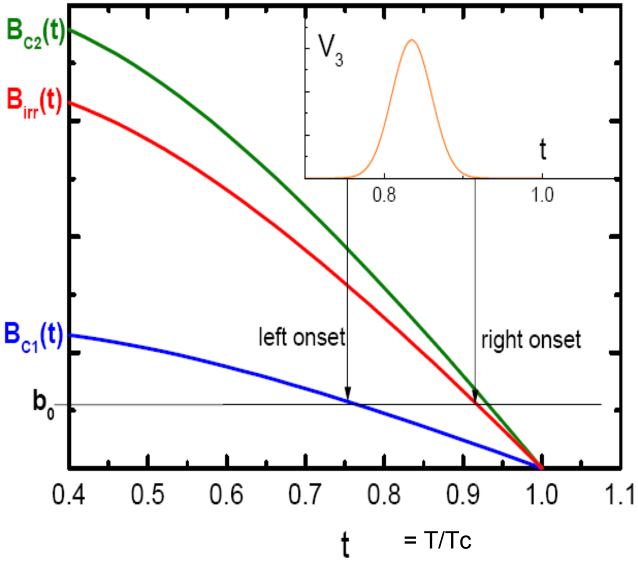
- 3^{rd} harmonic measurement, coll. INFM Napoli
  - $b_0 \cos(\omega\tau)$ applied in the coil
  - temperature ramp
  - third harmonic signal appears @ T^{b0} , when b0 reaches $B_{C1}(T^{b0})$
  - series of b0 => series of transition temperature => $B_{C1}(T)$)



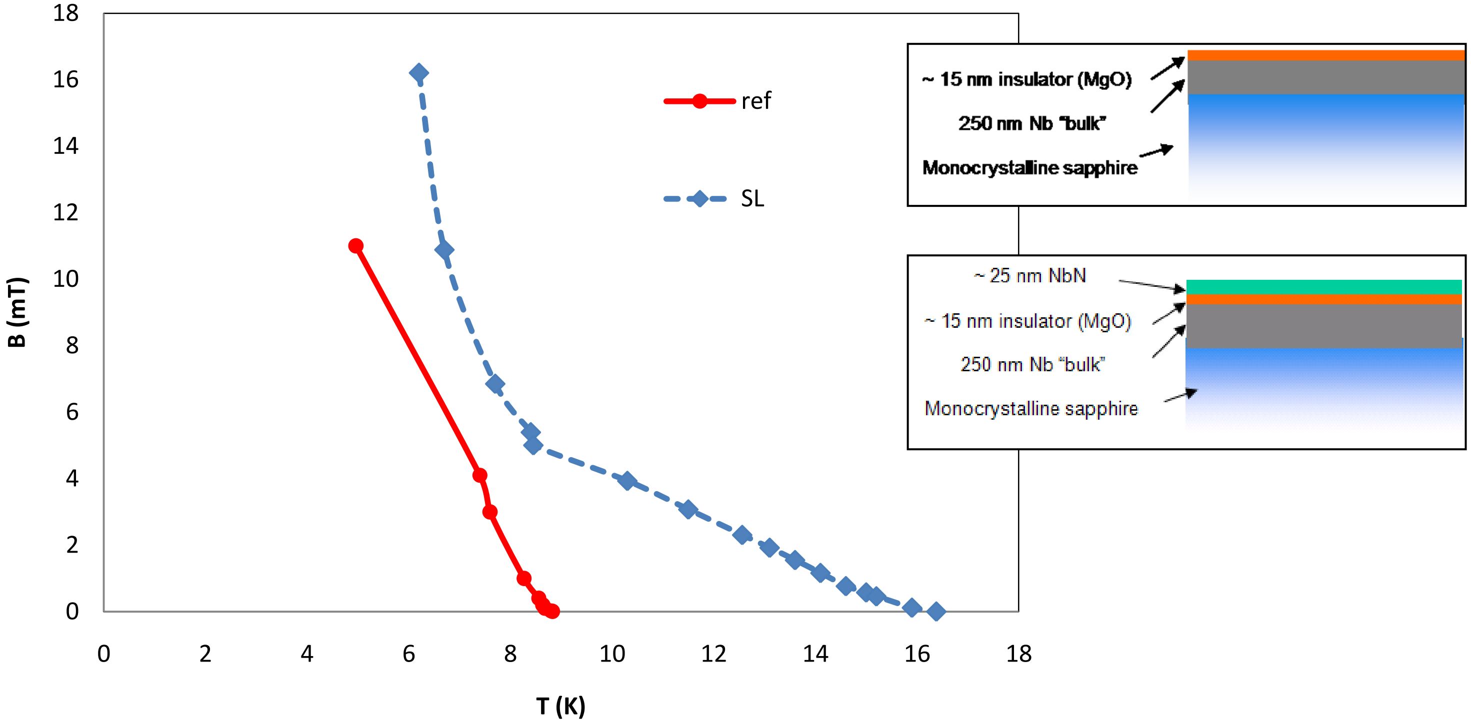
increasing I = increasing B

T_{Ci} at B_i

Sample SL : third harmonic signal for various b0



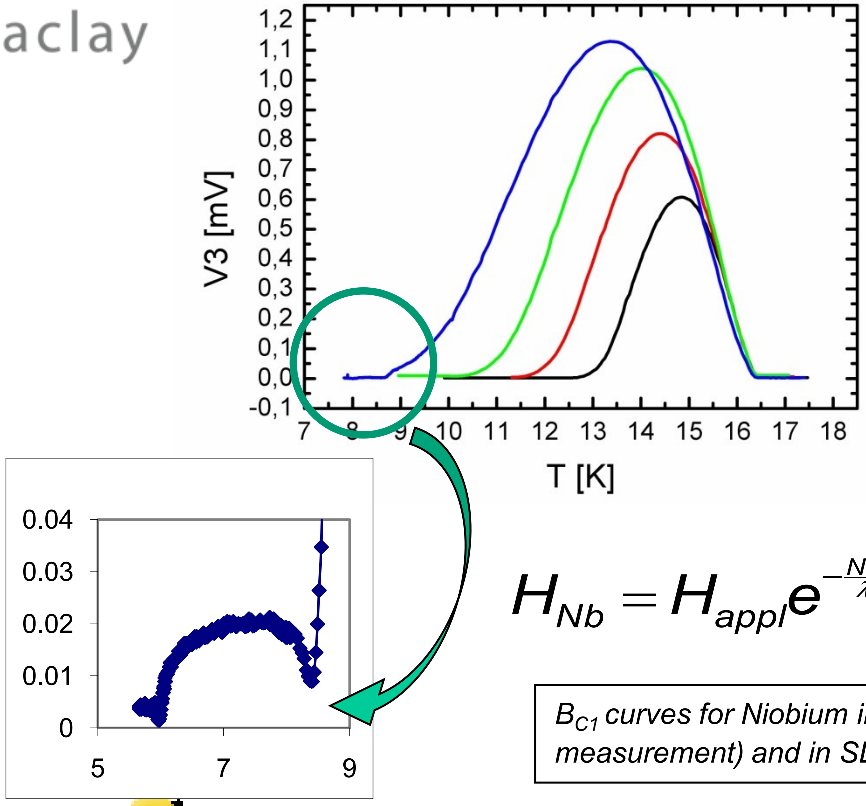
Local magnetometry (3)



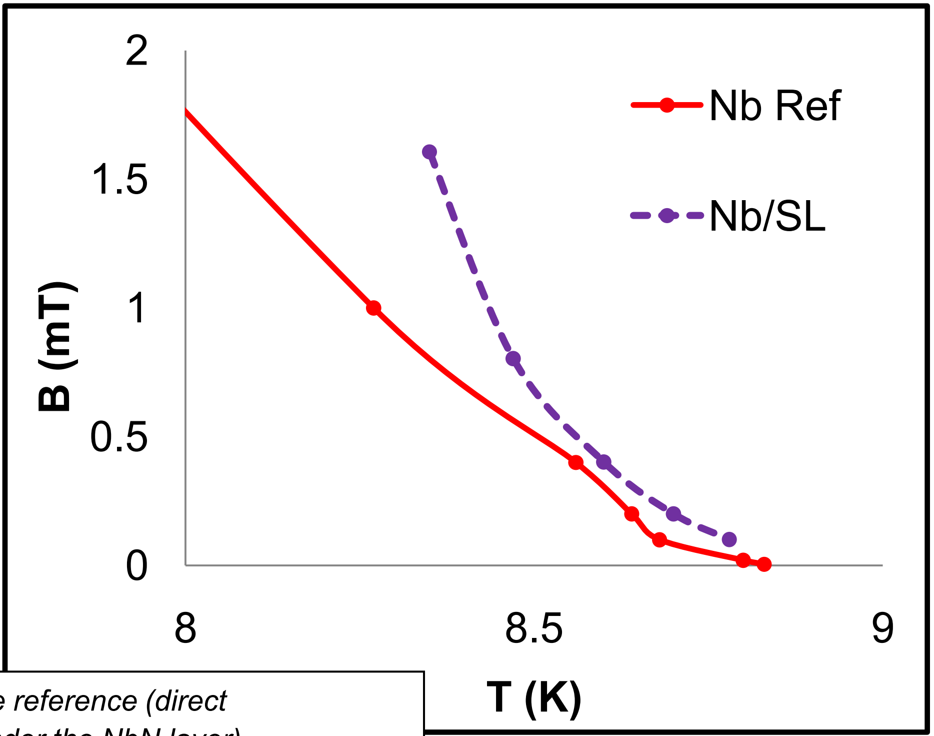
- **SL sample :** 250 nm Nb + 14 nm MgO + 25 nm NbN
- 8.90K < Tp° < 16K : behavior ~ NbN alone
- Tp°< 8.90K, i.e. when Nb substrate is SC , => $B_{C1}^{SL} >> B_{C1}^{Nb}$

Local magnetometry (4)

- Sample SL : small Nb signal @ ~Tc^{Nb} : Nb is sensed through the NbN layer !
- Since the Nb layer feels a field attenuated by the NbN layer, the apparent transition field is higher.
- This curve provides a direct measurement of the attenuation of the field due to the NbN layer

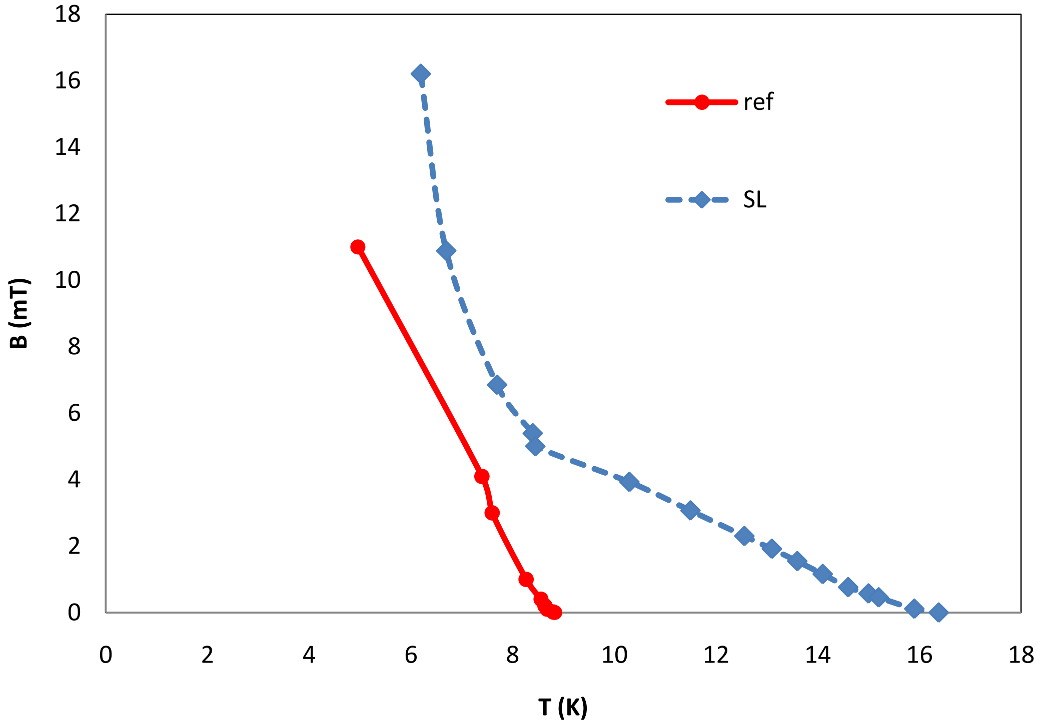


$$H_{Nb} = H_{appl} e^{-\frac{Nd}{\lambda}}$$



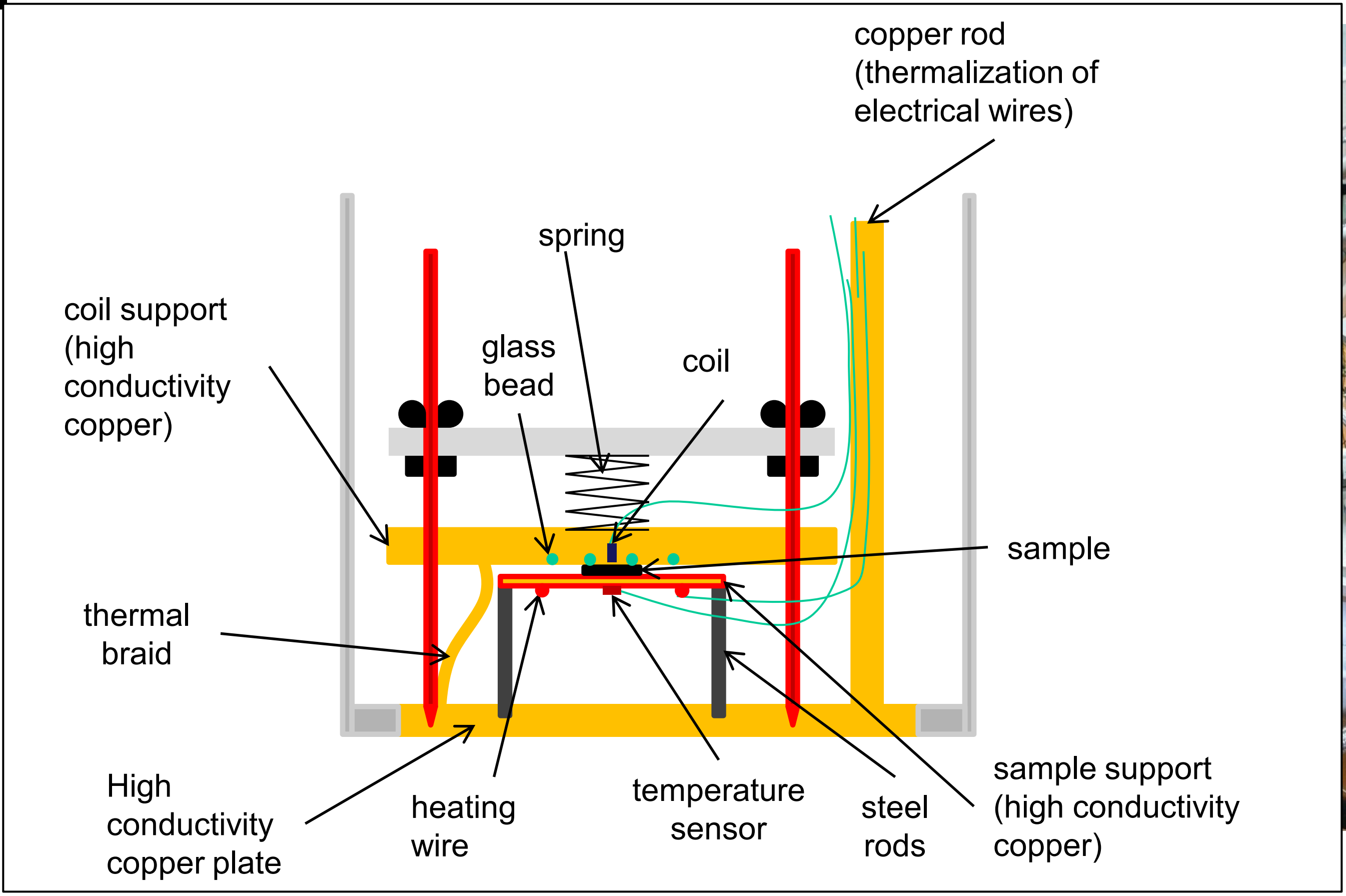
B_{C1} curves for Niobium in the reference (direct measurement) and in SL (under the NbN layer).

Local magnetometry (5)



- **SL sample :** 250 nm Nb + 14 nm MgO + 25 nm NbN
- Tp°< 8.90K, i.e. when Nb substrate is SC , **=> B_{C1}^{SL} >> B_{C1}^{Nb}**
- **Need to extend measure @ higher field and lower temperature**

Local magnetometry (4)



- coil with ext. Ø : 5 mm => samples with Ø> 13 mm ≡ infinite plane
- thermal regulation : 1.6 K <Tp°< 40K, automated
- 100 to 200 mT available soon

Conclusions for local magnetometry:

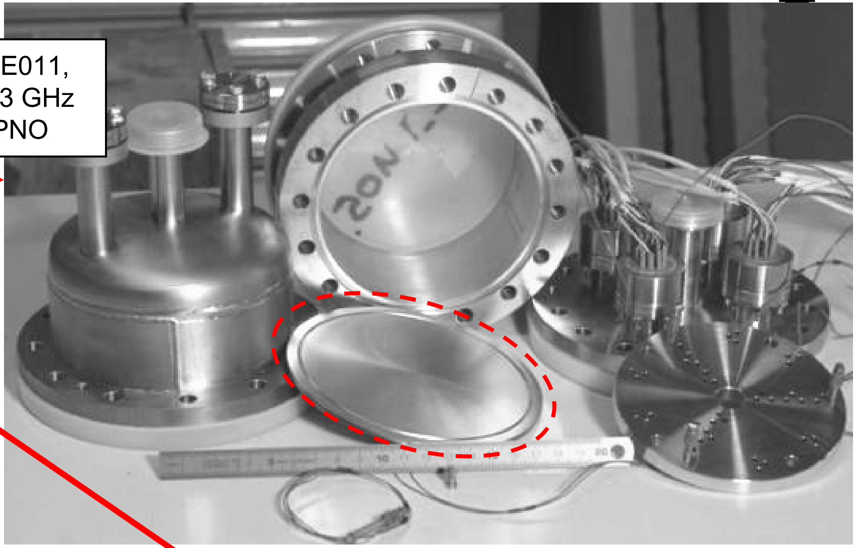
- Local magnetometry is a convenient tool for sample characterization :
  - *ML structure optimization (SC, thickness, number of layers, substrate preparation…)*
  - *Evaluation of various deposition techniques*
- When no edge effect (i.e. demagnetization factor) is involved, magnetic screening of NbN is effective even in perpendicular field
- Similar increase of B_{C1} has been observed @ Napoli on Nb multilayers (80 nm)
- This result is very encouraging regarding cavities situation

Future : Depositing and testing RF cavities

- depositing and testing RF Cavities:
  - *IPN (Orsay) : 3GHz,*
  - *LKB (Paris) : 50GHz*
  - *Cavités 1.3 GHz @ Saclay*

(what deposition technique?!)

TE011,
~3 GHz
IPNO



1.3 GHz
Irfu

50 GHz
LKB

Miroirs de la boîte à photons de l'ENS
© Michel Brune / LKB

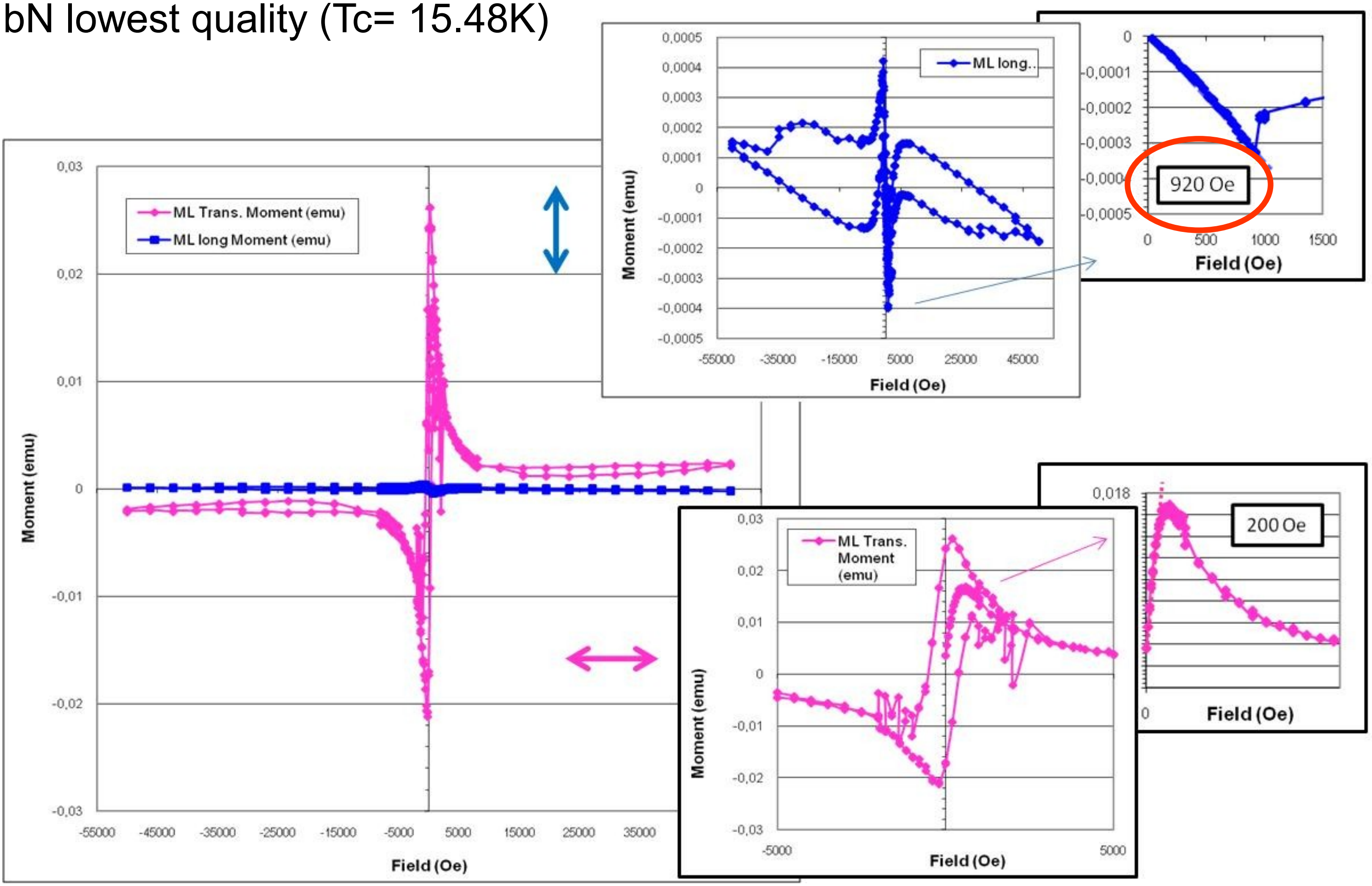
Conclusions and perspectives

- If Gurevich approach is correct, ML structures are the only way to go beyond Nb
- Magnetic screening of nanometric layers seems effective even in perpendicular field
- An increase of first penetration field ~ 80 mT has been observed with only one 25 nm NbN layer !!!
- next challenges :
  - confirm the squid data with local magnetometry @ 2-4 K
  - deposit sample RF cavity (conventional techniques)
  - develop deposition techniques for “real” cavities

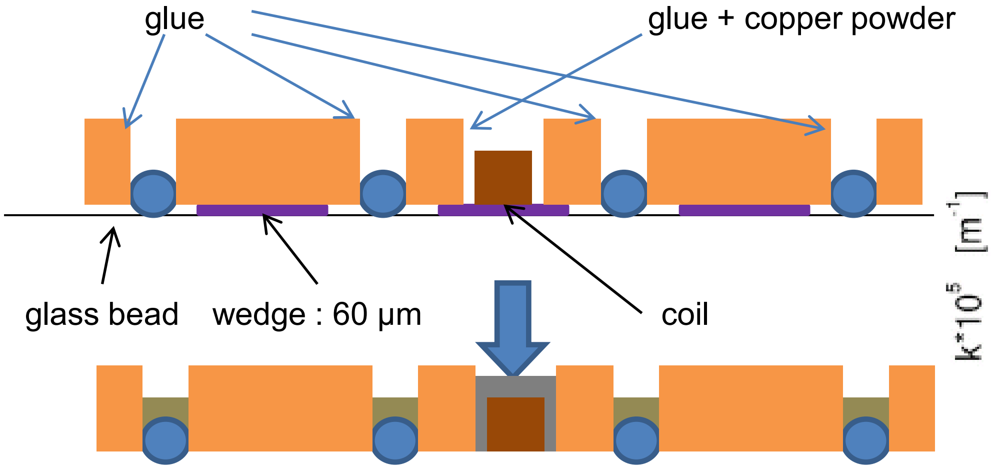
Compléments

SQUID (4) : ML Sample @ 4.5 K

- **ML sample :** 250 nm Nb + 4 x (14 nm MgO + 12 nm NbN)
- Similar behavior as SL
- Instabilities in 1rst and 3rd quadrant (vortices jumps ?)
- NbN lowest quality (Tc= 15.48K)



Adjustment of coil distance



glue

glue + copper powder

glass bead

wedge : 60 µm

coil

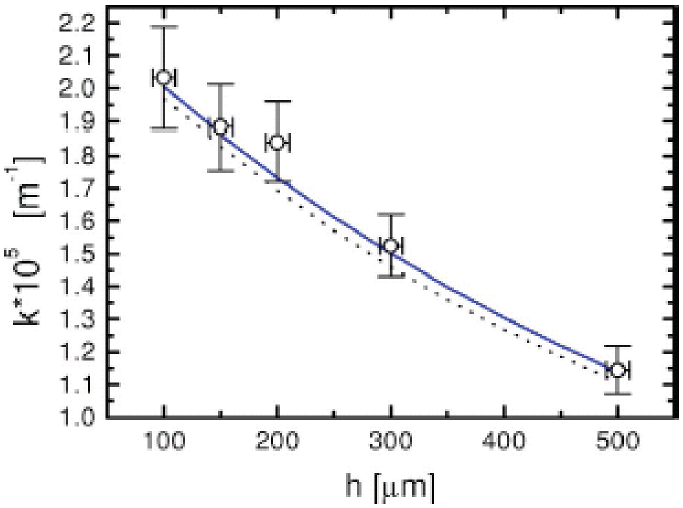


FIG. 5. Determination of the scaling factor k vs the sample-coil distance h. The continuous and the dashed lines represent the behavior expected for the discrete and the continuous models, respectively. The open circles represent the k values experimentally evaluated.

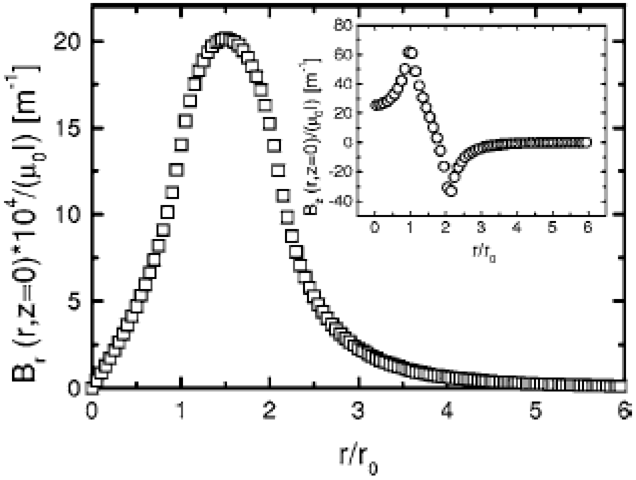


FIG. 4. Radial component of the total induction field (open squares) for a multiturn coil. In the inset the result for the normal component (open circles) is shown. Both components have been calculated at the sample surface as a function of r/r_0.

Characterization:

- Standard characterization : material quality (collab^n CEA/INAC-Grenoble)
  - Quantum design PPMS:
    - Tc, conductivity
  - X Rays : low angle diffusion :
    - Peaks/phases Identification : Monocrystalline or highly (200) textured layers
    - Distortions :d(200) on NbN expanded: ~ 0,5 %
  - X Rays : reflectivity:
    - thickness and interface roughness

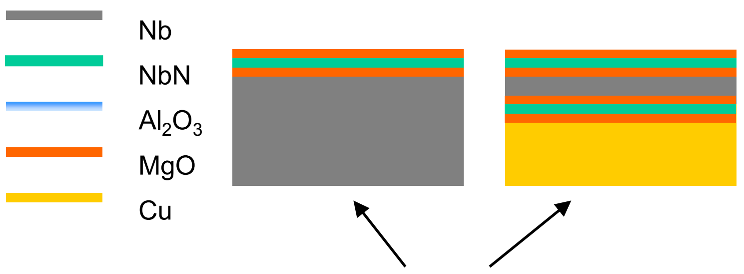
Quantum design physical properties measurement system (PPMS):

Reference Sample **R*** **Tc = 8.9 K**	Thickness (nm)	Roughness (nm)	Sample **SL** **Tc = 16.37 K**	Thickness (nm)	Roughness (nm)	Sample **ML**** **Tc = 15.48 K**	Thickness (nm)	Roughness (nm)
Nb	250	1	**Nb**	250	1	**Nb**	250	1
MgO	14	1	**MgO**	14	1	**MgO *** **	14	1
NbN	0	0	**NbN**	25	1.5	**NbN**	12	1.5

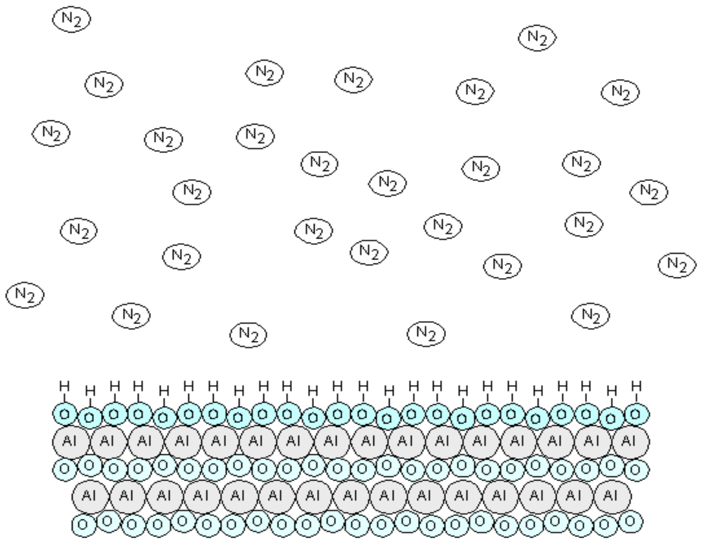
* Sample R contains only Nb capped with a layer of NbO. Obtained by RIE etching of sample SL.
** In ML the motive MgO/NbN is repeated 4 times.
*** except the external, capping layer which is 5 nm

Multilayers optimization

- SC structure optimization
- Deposition techniques optimization
  - Magnetron sputtering *Inac (Grenoble)*,
  - Atomic Layer Deposition *INP (Grenoble)*



Metallic substrates more realistic):

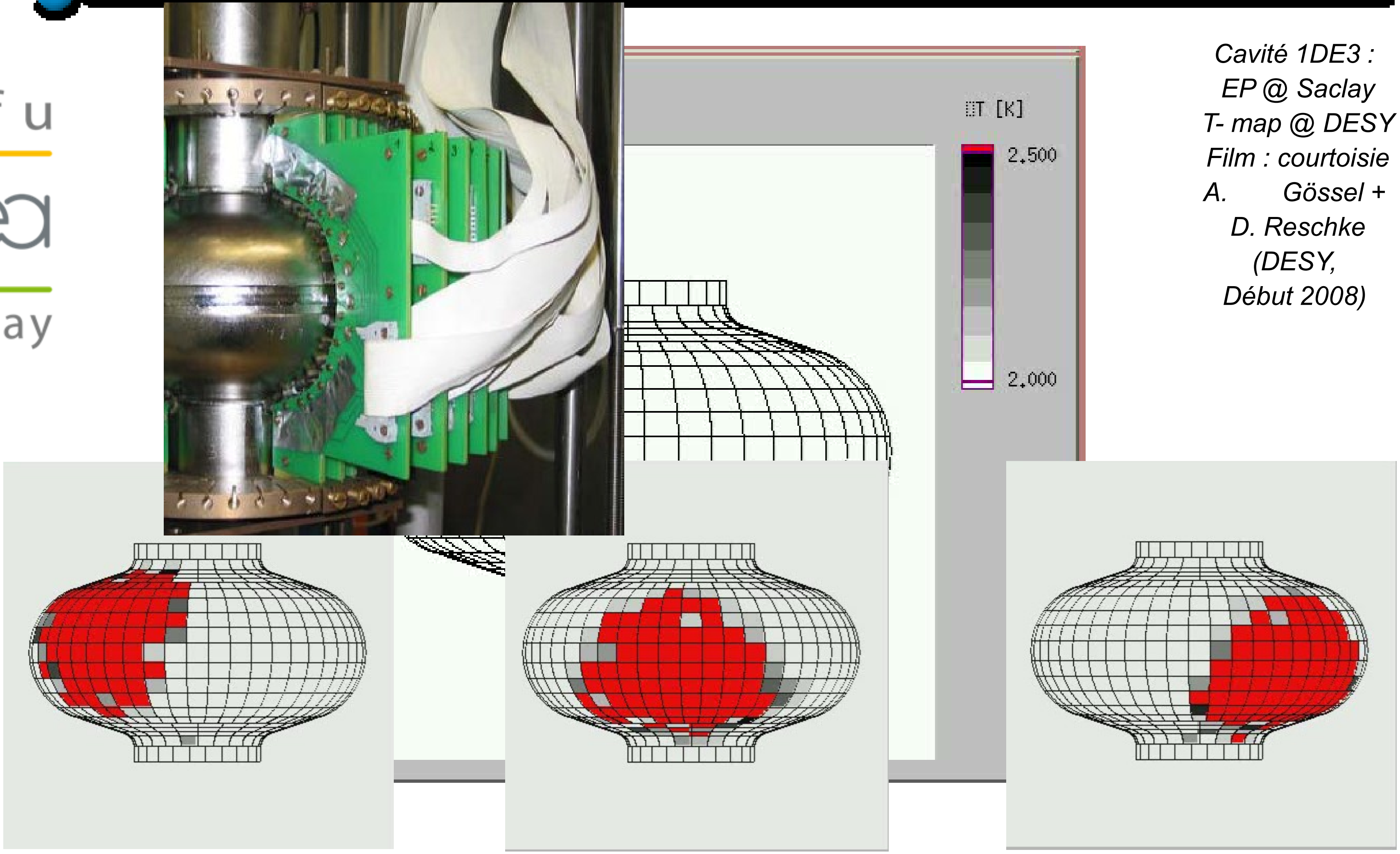


From samples to cavities :

- ALD involves the use of a pair of reagents
- Application of this AB Scheme
  - Reforms a new surface
  - Adds precisely 1 monolayer
- Viscous flow (~1 Torr) allows rapid growth
- No line of site requirements

- **=> uniform layers, larges surfaces, well adapted to complex shapes : cavities!**
- **up grade of existing cavities ?**

Bulk Nb ultimate limits : not far from here !



Cavité 1DE3 :
EP @ Saclay
T- map @ DESY
Film : courtoisie
A. Gössel +
D. Reschke
(DESY,
Début 2008)

The hot spot is not localized : the material is ~ equivalent at each location => cavity not limited /local defect, but by material properties ?

Rappels sur les principaux supras

Matériau	T_C (K)	ρ_n (µWcm)	H_C (Tesla)*	H_{C1} (Tesla)*	H_{C2} (Tesla)*	λ_L (nm)*	Type
Pb	7,1		0,08	n.a.	n.a.	48	I
Nb	**9,22**	**2**	**0,2**	**0,17**	**0,4**	**40**	**II**
Mo_3Re	15		0,43	0,03	3,5	140	II
NbN	17	70	0,23	0,02	15	200	II
V_3Si	17						II
NbTiN	17,5	35		0,03		151	II
Nb_3Sn	18,3	20	0,54	0,05	30	85	II
Mg_2B_2	40		0,43	0,03	3,5	140	II-2gaps
YBCO	93		1,4	0,01	100	150	d-wave