CHARACTERIZATION OF SUPERCONDUCTING MULTILAYERS SAMPLES

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Summary:

Best RF bulk niobium accelerating cavities are now very close to their ultimate limits due to the transition of Nb to the normal state at the rf equatorial magnetic field H ≈ 200 mT close to the thermodynamic critical field Hc Attempts to use higher T_c and H_{C2} superconductors have failed up to now, probably due to their low H_{C1}, that allows early penetration of magnetic vortices resulting in high surface dissipation. In 2006 Gurevich proposed to use nano-scale layers of superconducting materials with high values of Hc > Hc^{Nb} for magnetic shielding of bulk niobium in order to increase the breakdown magnetic field (and accelerating field) inside SC RF cavities without reaching the transition field of Nb.

In regard to the difficulty of depositing good quality layers inside large curved surfaces like a whole cavity, we have decided to firstly prepare high quality samples with asserted techniques as the ones used for the preparation of superconducting electronics circuits and characterize these samples with standard measurements (PPMS, SQUID, X-ray reflectivity…). In particular it is important to estimate the first penetration field of layered samples as compared to the bulk niobium. Therefore dc magnetisation curves of 250 nm thick Nb film have been measured with and without a magnetron sputtered coating of a single or multiple stack of 15 nm MgO and 25 nm NbN layers. The Nb samples with or without the coating clearly exhibit different behaviours which will be presented. Since SQUID measurements are strongly influenced by edge and shape effects we propose to develop a specific local magnetic measurement of H_{C1} based on ac third harmonic analysis in order to reveal the screening effect of multilayer structures.

Theory : pioneering work [1,2]

Nanometric films : surface barrier

- Interaction with image vortices => ∃ **surface barrier**
- thin film with d< λ => higher H_{C1}

$$H_{C1}=\frac{\Phi_0}{4\pi\lambda}\left(\ln\frac{\lambda}{\xi}+0.5\right) \rightarrow H'_{C1}=\frac{2\Phi_0}{\pi d^2}\left(\ln\frac{d}{\xi}-0.07\right)$$

- Thermodynamic critical field Hc (surface barrier for vortices disappears):

$$H_S\approx H_C=\frac{\Phi_0}{2\sqrt{2}\pi\lambda\xi} \rightarrow H'_S\approx H'_C=\frac{\Phi_0}{2\pi d\xi}$$

- Example :
  - for NbN : ξ = 5 nm, H_{C1} = 0,02 T et H_C = 0,23 T, film 20 nm => H'_{C1} = 4,2 T et H_s = 6,37 T ;
  - for Nb_3Sn : ξ = 3 nm, H_{C1} = 0,05 T et H_C = 0,54 T, film 50 nm => H'_{C1} = 1,4 T.
  - N.B. Nb, ξ = 38 nm, H_{C1} = 0,17 T et H_C = 0,18 T

- Thin film on Nb :
  - Higher Tc thin layer provides magnetic screening of the bulk SC cavity (Nb, Pb) without → vortex penetration (H_{C1}<< H_{C1}^{Nb} but λ>> λ_{Nb}).
  - Bulk SC (Nb) prevents ↑ vortex penetration

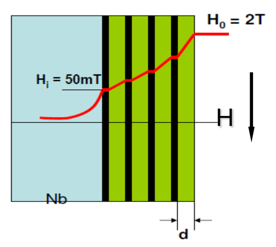
Multilayers : overcoming Nb monopoly

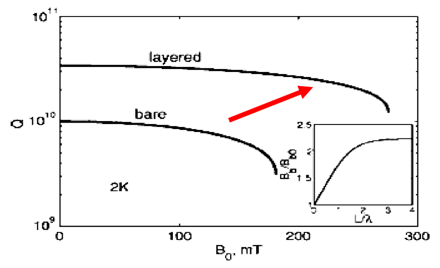
- Composite nanometric SC: supra/ insulating /supra:
  - Bulk Nb prevents ↑vortex presentation
  - Insulating layer ~ 15 nm : bulk/film Josephson decoupling
- High Tc SC ~ some 10 nm
  - High H_S
  - Magnetic screening for → vortex
  - Lower R_{BCS} Q_0 ↑↑
- Issues:
  - Building nanometric multi layer, conformational to the cavity surface, with sharp (clean) interfaces !?

or
  - Testing model, high quality samples

Nb-I-S-I-S… multilayers:

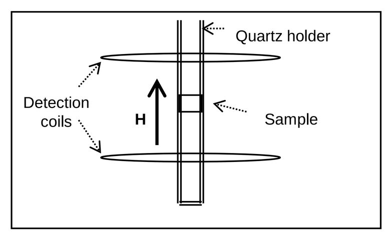
a composite solution to field penetration



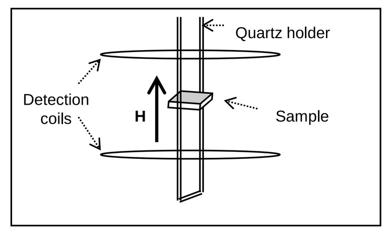


SQUID (1) :

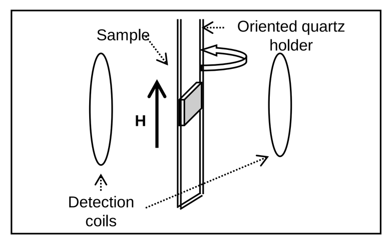
- Principle of measurement (5x5mm² samples)
  - H //, longitudinal moment



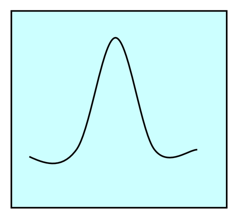
- H ⊥, longitudinal moment



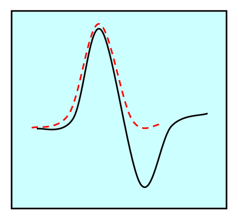
- H //, transverse moment



Measurement difficulties for SC thin films in H //:
- Strong ⊥ dipoles on edges => non purely dipolar signal => fits need to be reprocessed
- Very strong sensitivity to angle => intensity comparison = difficult



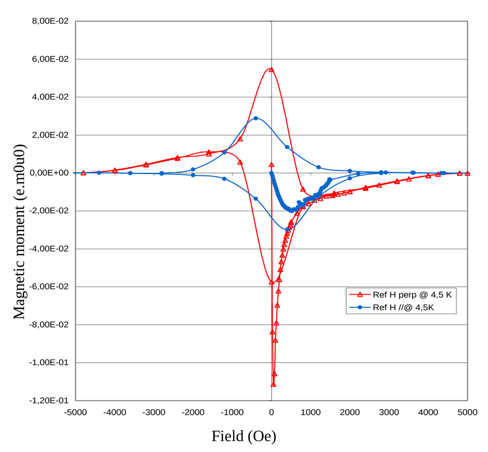
Usual dipolar signal



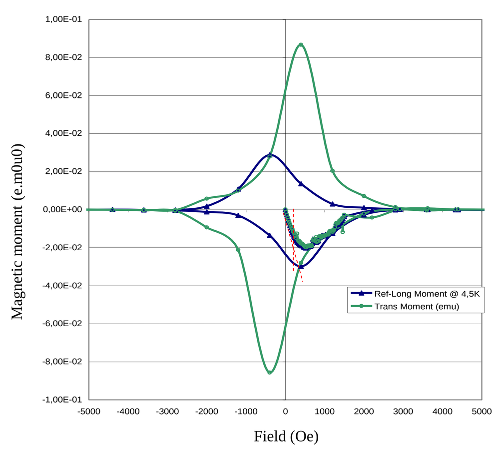
Fitting condition before fit reprocessing

SQUID (2) : Reference sample(250 nm Nb)

- Longitudinal moment: comparison H//-H⊥

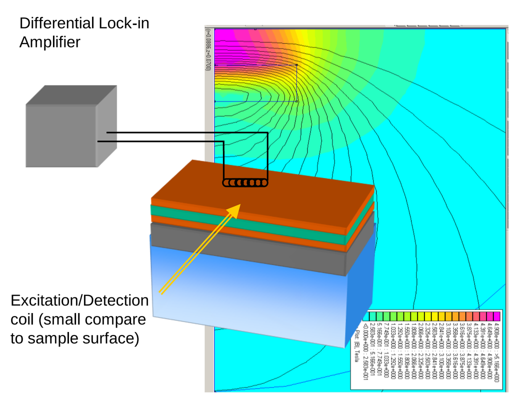


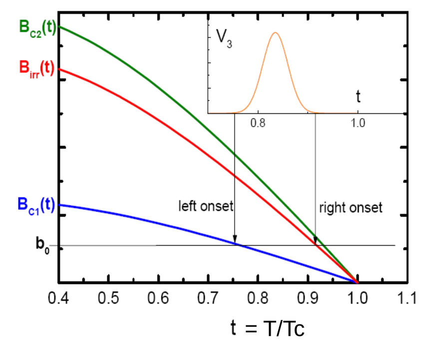
- H // : Comparison longitudinal/transverse moment



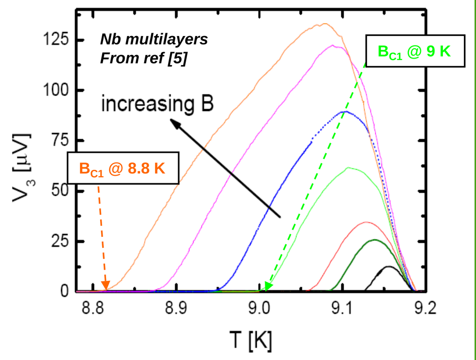
- The first transition appears at lower field when H is ⊥ (demagnetization factor ~20 000!)
- Transverse signal appears only in the SC state (edge currents confined inside the SC layer)
- Transverse and longitudinal behavior are similar at low field (same H_{C1})

Outlook: local B_{C1} measurement





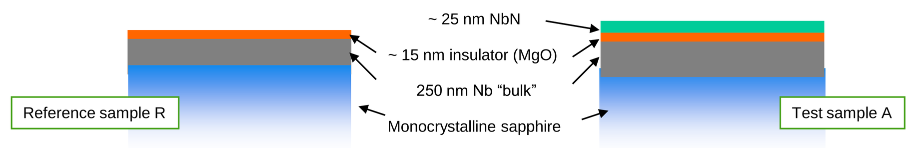
Third harmonic analysis [4]
- Sample is 0-field cooled
- Low frequency $b_0$cos (ωt) applied in the excitation/measurement coil
- Tp° : some Ks => room Tp°
- Non linear signal (3rd harm.) appears between B_{C1} and B_{irr}
- Various b_0 => various onset Tp°
- => B_{C1} = f(Tp°)

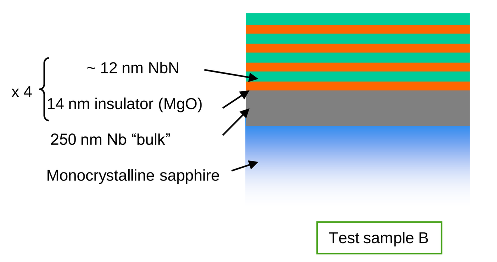


Experimental:

High quality Model samples :

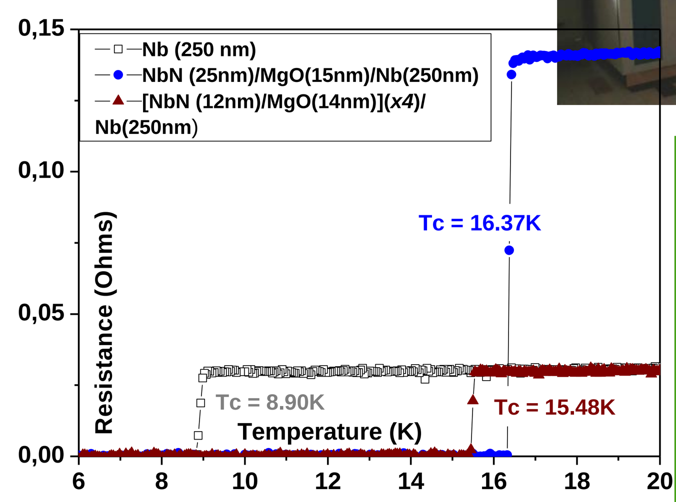
- Asserted techniques for superconducting electronics circuits preparation [3] :
  - Magnetron sputtering
  - Flat monocrystalline substrates
  - Same as Josephson junction preparation





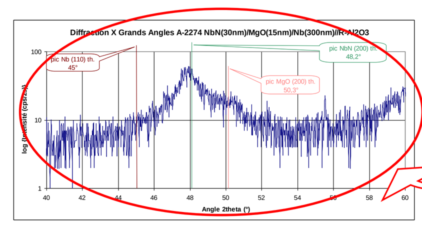
Characterization 1:

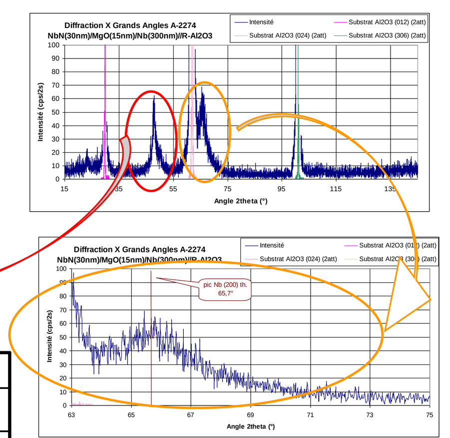
- Quantum design physical properties measurement system (PPMS):



Xray Characterization :

- 1) Large angle diffusion:
  - Peak/phase identification
  - Distortions

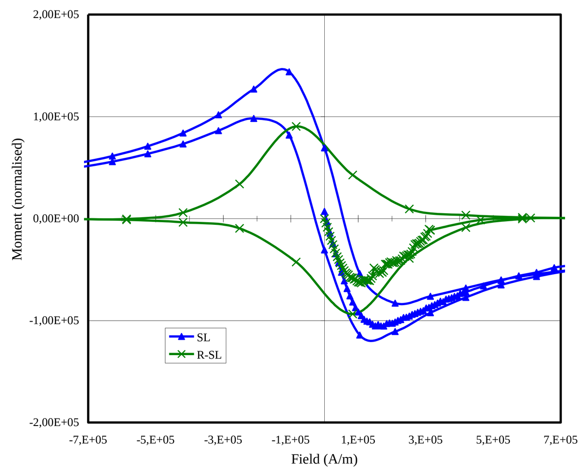




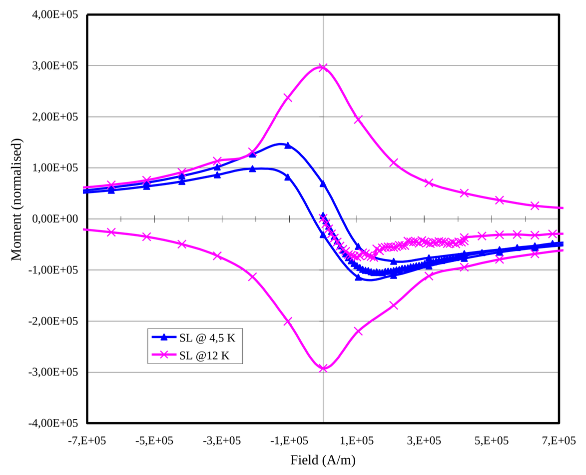
Sample	A	
Layer sequence	NbN / MgO/ Nb// R-$A_{l2}O_3$	
Xrays Wide angle scattering	• Monocrystalline or highly (200) textured layers • d(200) on NbN expanded: ~ 0,5 %	
	Nb :peak **(200)**	Th. : 65,7° Exp. : **65,8°**
	NbN : peak **(200)**	Th. : 48,2° Exp. : **47,9°**
	MgO : peak **(200)**	Th. : 50,3° Exp. : **50,3°**

SQUID (3) : H // sample plane; longitudinal moment

- Sample A (one layer MgO/NbN) at 4.5 K (blue) compared with reference sample ("bulk" Nb). Large hysteresis on "bulk" Nb => a lot of vortex penetration



- Sample A (one layer MgO/NbN) at 4.5 K (blue) and 12 K where only NbN is superconducting (pink). The combination NbN over "bulk" Nb seems to prevent effectively field penetration.



1rst penetration field B_P:
note : B_P ~ B_{C1} x demagnetisation factor x surface barrier factor x…

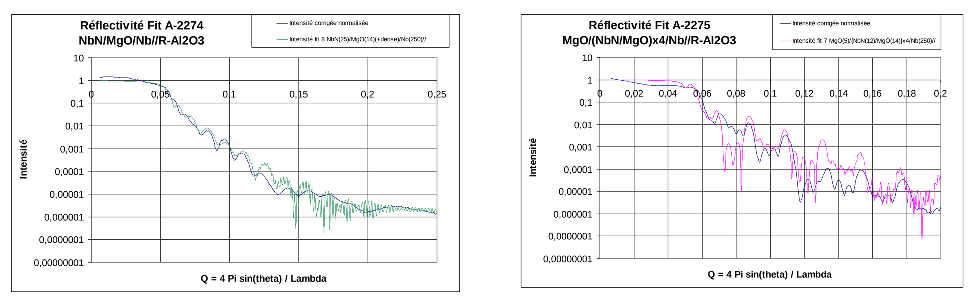
Orientation/ temperature	4.5 K, ⊥	12 K, ⊥	4.5 K, // long	4.5 K, // trans	12 K, // long	12 K , // trans
Ref	5 mT	na	20 mT	18 mT	na	na
SL	10 mT	2.5 mT	36 mT	55 mT	20 mT	40 mT
ML	5 mT	?	90 mT (ne?)	ne	ne	ne

na : non applicable ; ne : needs rework of the fitting

There is a striking difference in the hysteresis behavior: the combination of an NbN layer on Nb obviously prevents field penetration compare to Nb or NbN alone!

Xray Characterization :

- 2) Reflectivity:
  - Thickness and roughness of layers



Sample	A			B		
Layer sequence	NbN / MgO/ Nb// R-$A_{l2}O_3$			MgO / {NbN / MgO} **x4** / Nb // R-Al_2O_3		
X-ray reflectivity	Layer	Thickness	Roughness	Layer	Thickness	Roughness
	NbN	**25** nm	1,5 nm	MgO	**5** nm	1,5 nm
				NbN	**12** nm	1 nm
	MgO *Density close to NbN's*	**14** nm	1nm	MgO *Slightly denser than bulk*	**14** nm	1nm
	Nb	**250** nm	1nm	Nb	**250** nm	1nm

Conclusions:

- We have presented the superconducting properties of composite structures specifically designed for RF accelerating applications. In particular we have analyzed Nb/MgO/NbN and Nb/[MgO/NbN]x4 multilayer by DC SQUID magnetization measurement in a parallel field configuration.
- We have put in evidence a very promising behavior of these composite structures:
  - the first penetration field is enhanced in the multilayers
  - the vortex penetration is prevented as can be inferred by the reduction of the area enclosed in the hysteresis magnetization cycles.

References:

[1] Gurevich, "Enhancement of RF breakdown field of SC by multilayer coating". Appl. Phys.Lett., 2006. 88: p. 12511.
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[4] G. Lamura, et al., "First critical field measurements by third harmonic analysis". Journal of Applied Physics, 2009. 106: p. 053903
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Keywords:
Particle accelerators, niobium, niobium nitride, RF cavities, thin films, superconducting multi-layers