DE LA RECHERCHE À L'INDUSTRIE

THIN FILMS TECHNOLOGIES FOR SRF

EUCARD2 WP12.2 THIN FILMS PROSPECTIVES

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OUTLOOK

Today's thin films (vs bulk Niobium)

SRF limits

- Superheating
- Higher TC materials
- Vortex nucleation
- Multilayers

Thin films developments

- Characterization issues
- Line of sight techniques
- Chemical techniques

Focus on multilayers

- Characterization issues

Conclusion and perspectives

TODAYS'S THIN FILMS
(vs bulk niobium)

THIN FILMS 1

Nb : λ~50 nm => only a few 100s nm of SC necessary

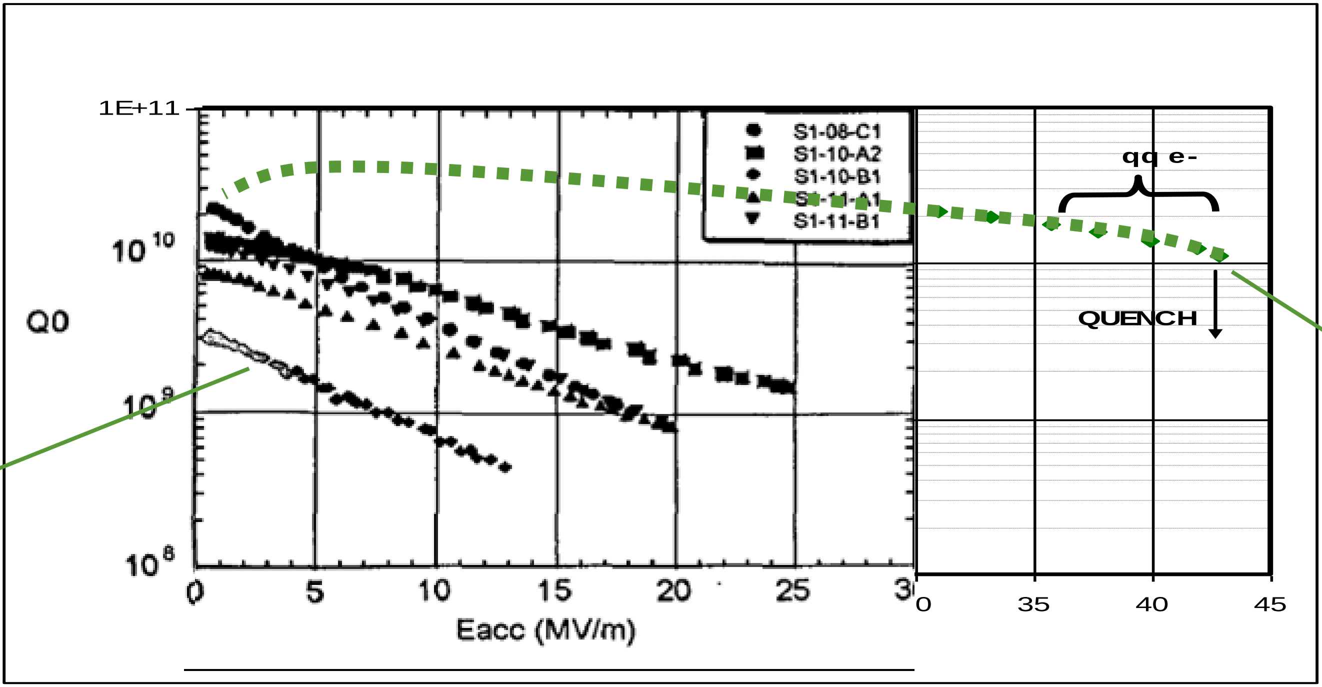
(the remaining thickness= mechanical support only) **=> Make thin films !**

- **Advantages**
  - Thermal stability (substrate cavity = copper)
  - Cost
  - Innovative materials
  - Optimization of R_{BCS} possible
- **Disadvantages**
  - Fabrication and surface preparation (at least) as difficult as for bulk
  - Superconductivity very sensitive to crystalline quality (lower in thin films for now)
  - Deposition of innovative (compound) materials is very difficult

BULK NIOBIUM MONOPOLY

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

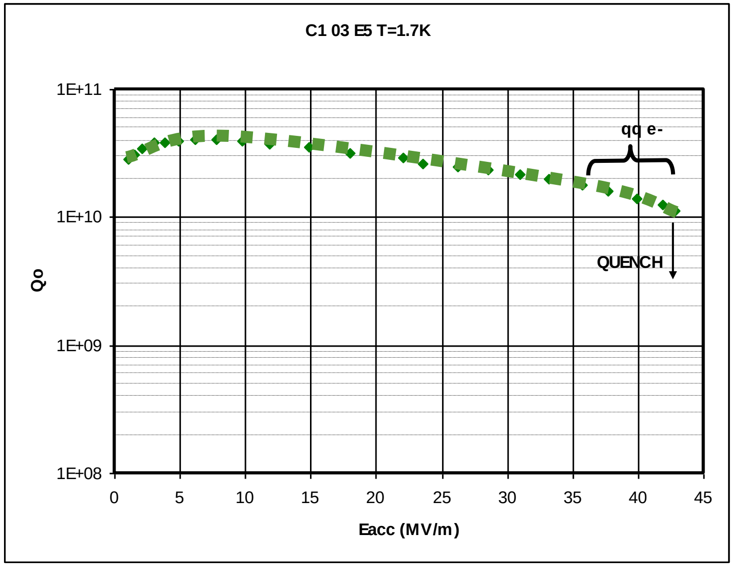
Typical sputtered Nb cavities 1.5 GHz



Typical bulk Nb cavity 1.3 GHz

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

NIOBIUM CAVITIES



Typical performances

(CEA/Saclay- CARE-SRF project Cavity):

40-45 MV/m (~170MT) !

Niobium: **bulk, electropolished** and **baked**

…and **cleanroom** assembled

Practical issues

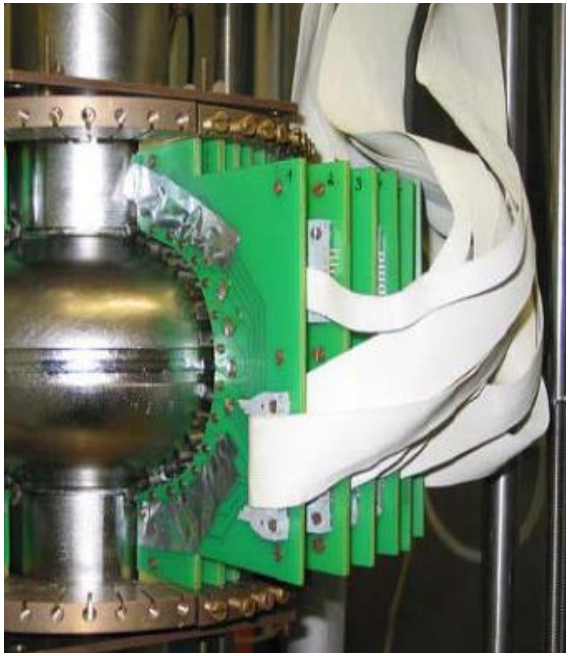
- we do not know the exact origin of the limitation: *classical theory (BCS) is not enough to fully predict RF observations,*
- reproducibility not good

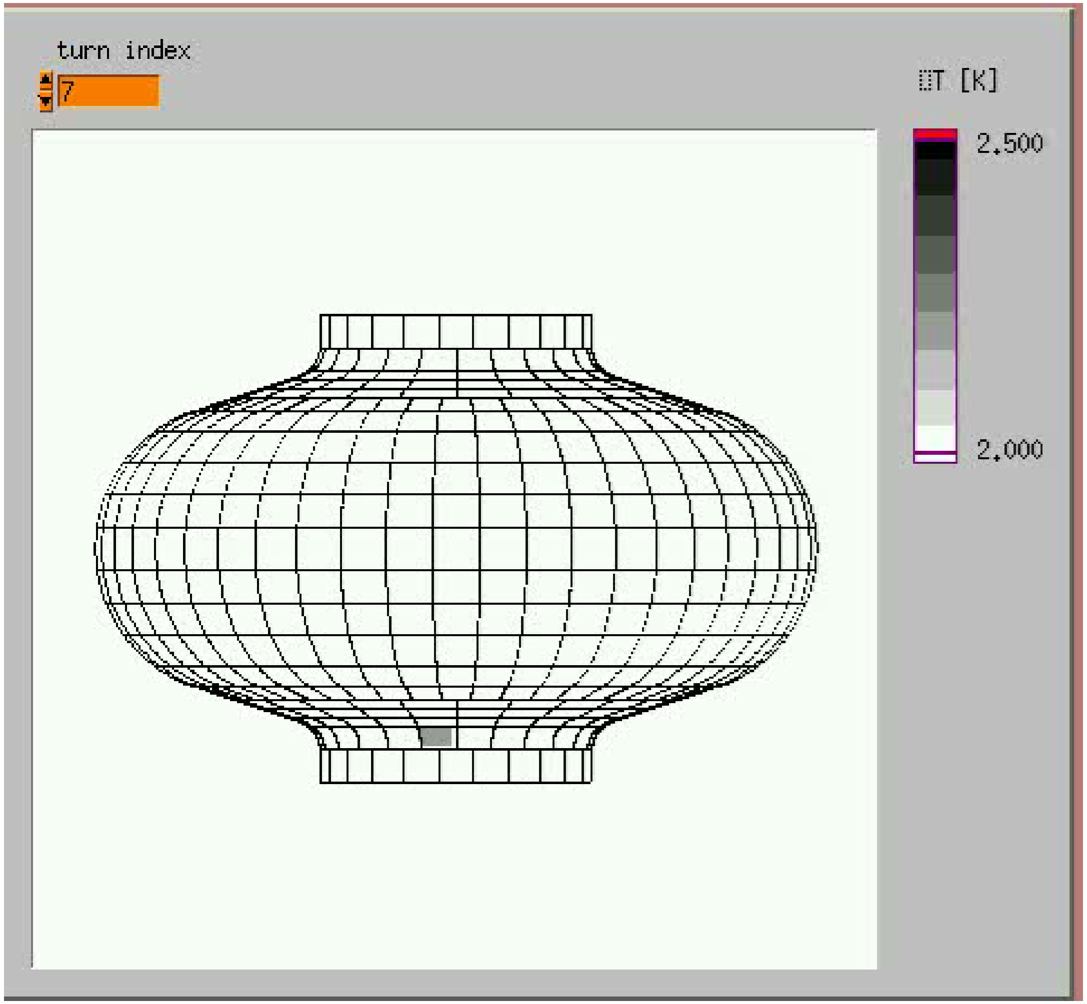
RF superconductivity: a surface phenomenon

λ_L = field penetration depth
= where **thermal dissipation** occurs

Nb : **~ 50 nm**

HAS NIOBIUM REACHED ITS ULTIMATE LIMITS?





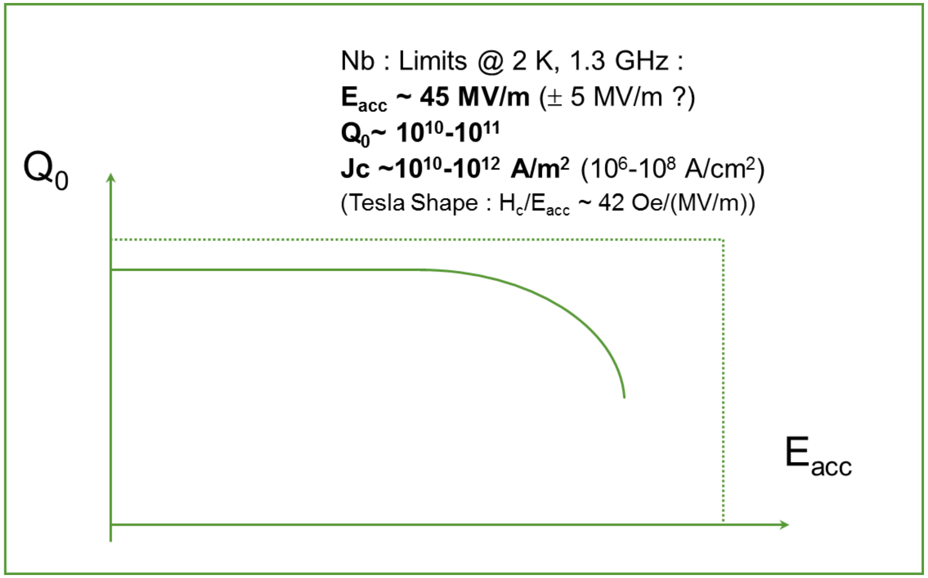
Cavity 1DE3 :
EP @ Saclay
T- map @ DESY
Film : curtesy
A. Gössel +
D. Reschke
(DESY, 2008)

SRF LIMITS

2013-06-12

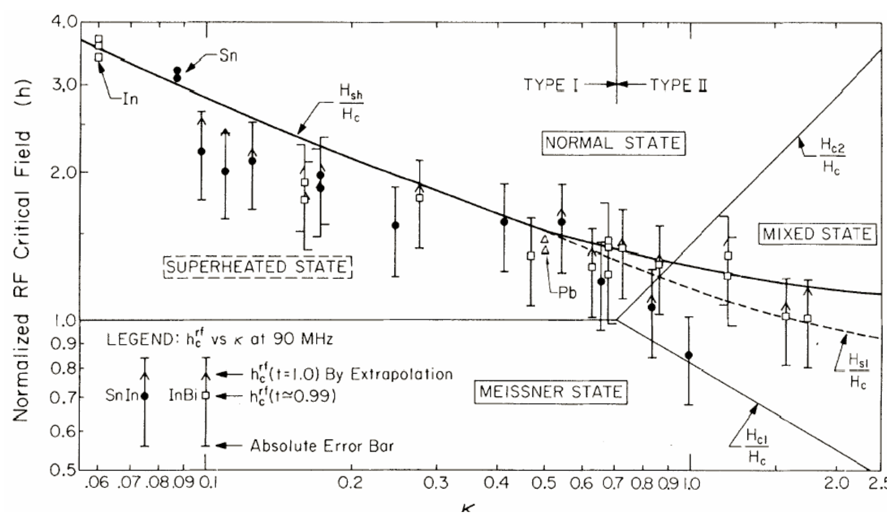
SRF LIMITS : BACK TO BASICS

- **Q_0 ($\propto$1/Thermal dissipations)**
  - depends on surface resistance … which depends on Tc
  - Higher Tc => higher Q_0 => lower operation cost
- **Ultimate limit in E_{acc}: when the SC becomes normal conducting !**
  - Transition : when T and/or B↑
  - Cavity is not tuned anymore
- **At ω < 3 GHz: we are limited by B^{RF} !!!**



SRF LIMITS: TRANSITION FIELD

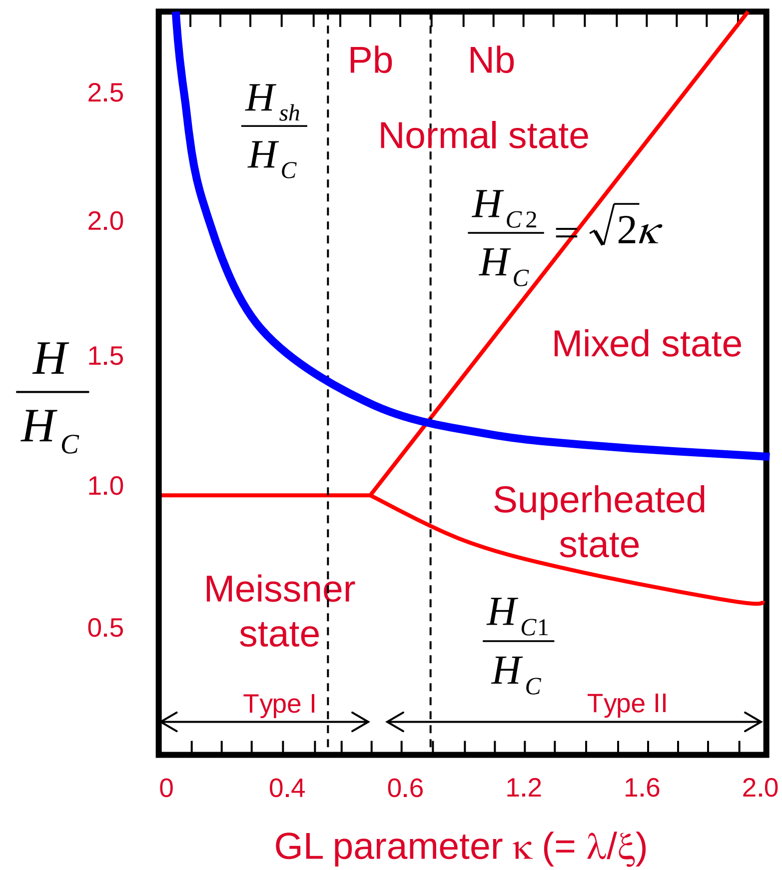
- **What is the proper transition field in RF?**



- **Superheating field ?**
  - normal zone nucleation ~10^{-6} s
  - RF ~10^{-9} s *

BUT

  - 1! vortex penetration ~10^{-13} s **



H_{SH} ~1,2.H_C pour κ~1

H_{SH} ~0,75.H_C pour κ>>1

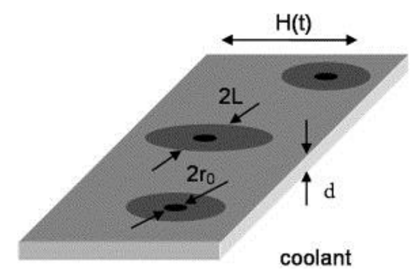
** H. Padamsee, et al, "RF superconductivity for accelerators". 1998: J. Willey & son.*
*** Gurevich, Brandt, Smethna…*

HIGHER T_C MATERIALS

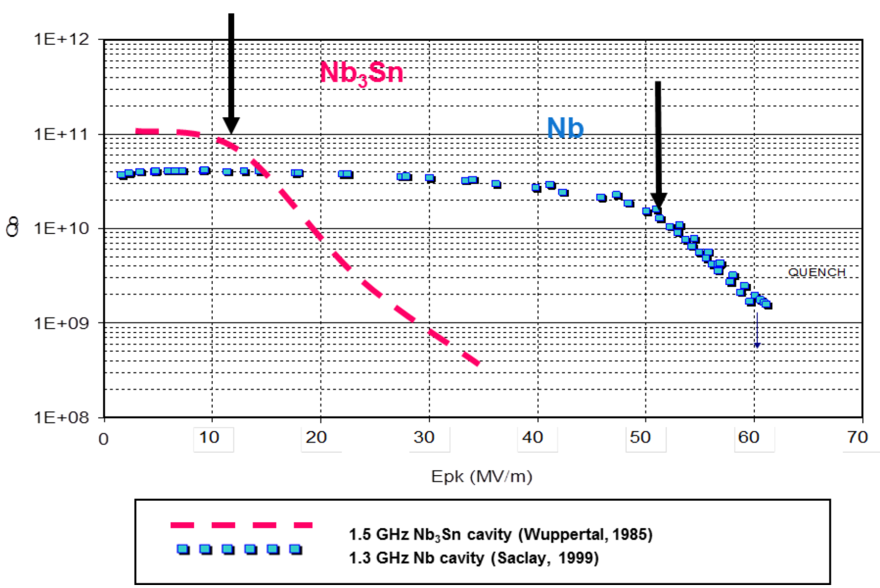
$T_C\uparrow$
et
$H_C\uparrow$

Matériau	Operation temperature (K)	E_{acc} : expected limit (MV/m) forH_{pic}/E_{acc} ~40 Oe/(MV/m)
Nb	2	55
Nb	4	49
Nb_3Sn	4	95
MgB_2	4	80
MgB_2	4	52

H_{SH} ~1,2.H_C pour κ ~1
&
H_{SH} ~0,75.H_C pour κ>>1



H_P **Nb_3Sn 0.03T** ($H°_{C1}$=0.05 T) H_P **Nb 0.12 T** ($H°_{C1}$=0.17 T)



G. Muller, et al. in EPAC 96. 1996. Sitges, Spain

- Dissipation due to early vortex penetration ?
- Recent theoretical work :
  - 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 because of its high H_{C1}?

AFTER NIOBIUM: MULTILAYERS

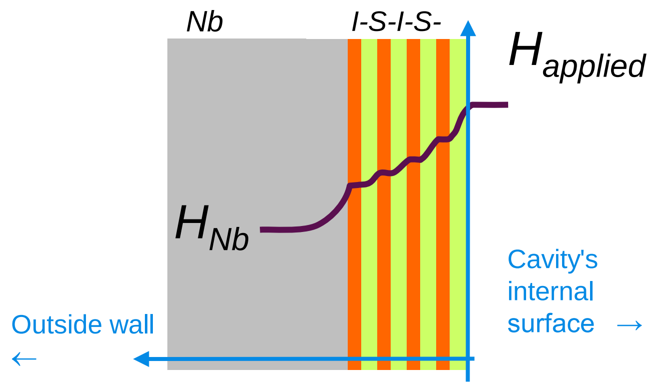
(Proposed by A.Gurevich, 2006) :

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

NbN , ξ = 5 nm, λ = 200 nm

(similar improvement expected with MgB_2 or Nb_3Sn)

20 nm film => H_{C1} = **0,02 T** ; H'_{C1} = **4,2 T** **x 200**



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

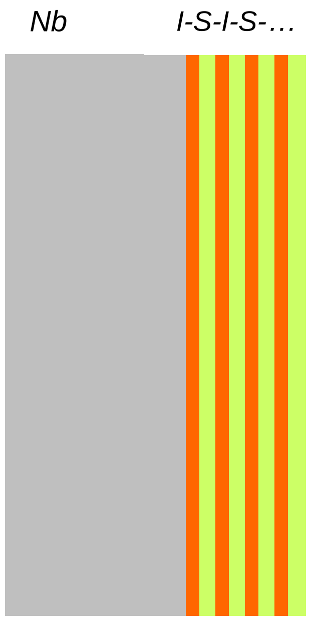
- high H_{C1} => no transition, no vortex in the layer
- applied field is damped by each layer
- insulating layer prevents Josephson coupling between layers
- applied field, i.e. accelerating field can be increased without high field dissipation
- thin film w. high T_C => low R_{BCS} => higher Q_0

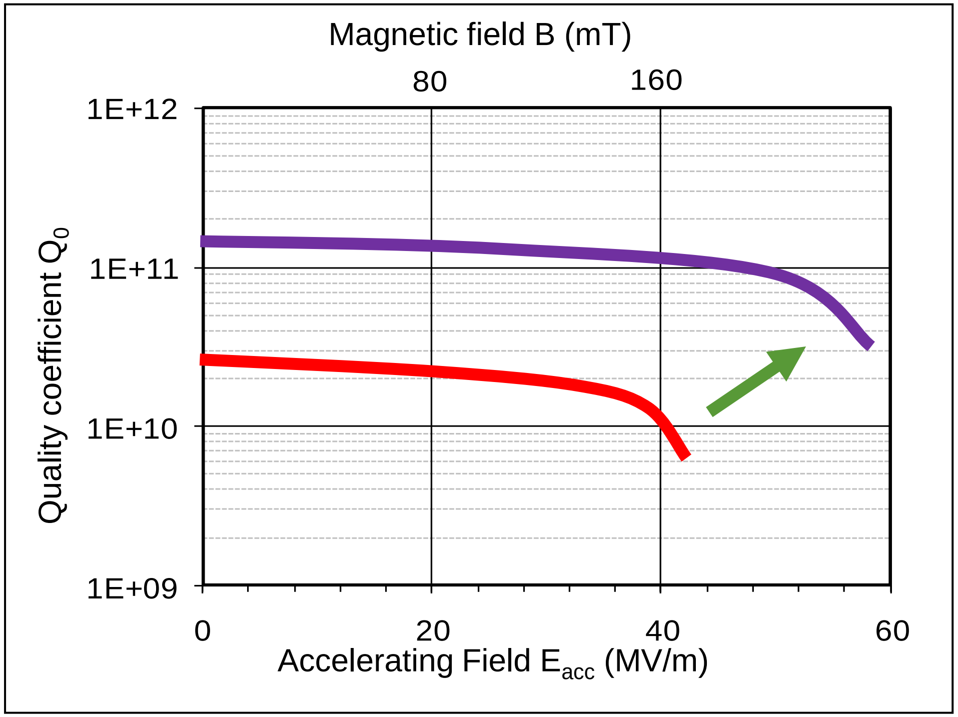
HIGH TC NANOMETRIC SC FILMS : LOW R_S, HIGH H_{C1}

- 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 !!!

Superheating field vs Vortex nucleation

Nb~ 55 MV/m
Nb_3Sn ~ 95 MV/m

Nb<50 MV/m
+ magn. screening

- Superheating field limitation observed principally
  - close toT_C
  - "perfect material" (few surface defects)
  - and/or short pulses
- In real life :
  - early/fast penetration of vortex possible @ surface defects
  - penetration of vortex seem faster @ low temperature (why !? λ small ?)
- Why is Nb the best for SRF ?
  - because we master its quality ? Then good Nb_3Sn would be even better
  - because of its high H_{C1}? Then only ML can do better….
- **More theoretical and exp. work needed**

THIN FILMS DEVELOPMENTS

2013-06-12

THIN FILMS

There are two categories of films

Films: Many techniques, not possible mention all

- **Films which are intrinsically “*films*”**
  - Thin, small grains, under stress
  - Problems: defects & microstructure, impurities, surface state
  - Examples: magnetron sputtered films on oxidized copper
- **The general trend is to move towards bulk-like films :**
  - Dense, large grain material, e.g.:
    - high-energy deposition techniques
    - Thermal diffusion films
    - CVD, ALD (chemical techniques)

CHARACTERIZATION ISSUES

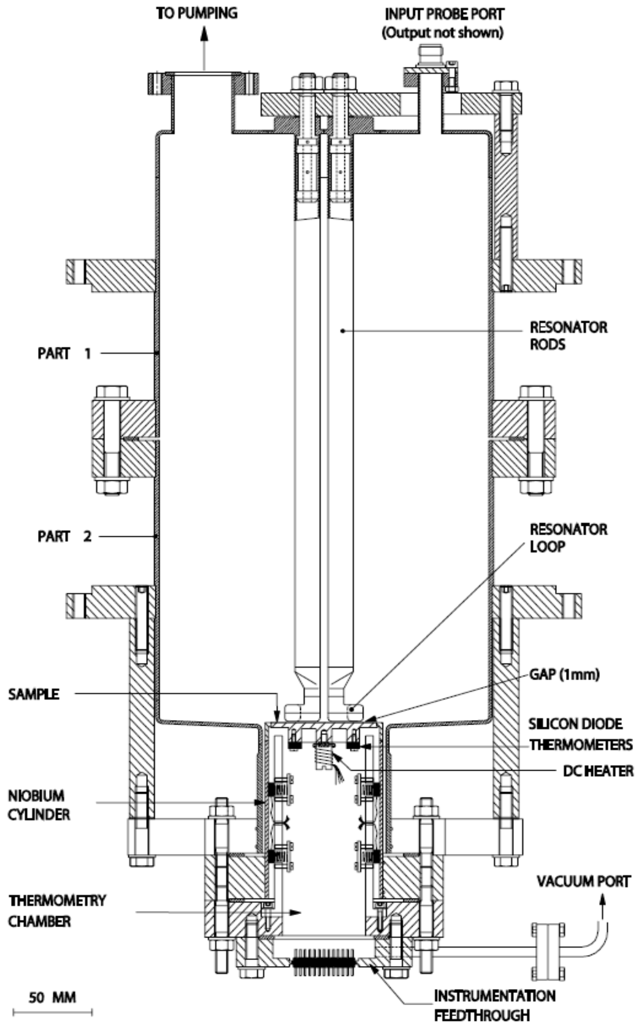
Films: Many techniques, not possible mention all

Characterization must be done on samples (flat, small)

- **Use existing deposition set-ups to find the proper technique**
  - Optimization of the material deposition conditions
  - Classical characterization (T_C, composition, crystal structure…)
  - Specific SRF properties :
    - Complete RF characterization not possible on samples
    - RF surface resistance (Q_0) =>"sample cavities"
    - Maximum achievable field (E_{acc}) => local magnetometry
- **Then develop a deposition set-up dedicated to cavities**

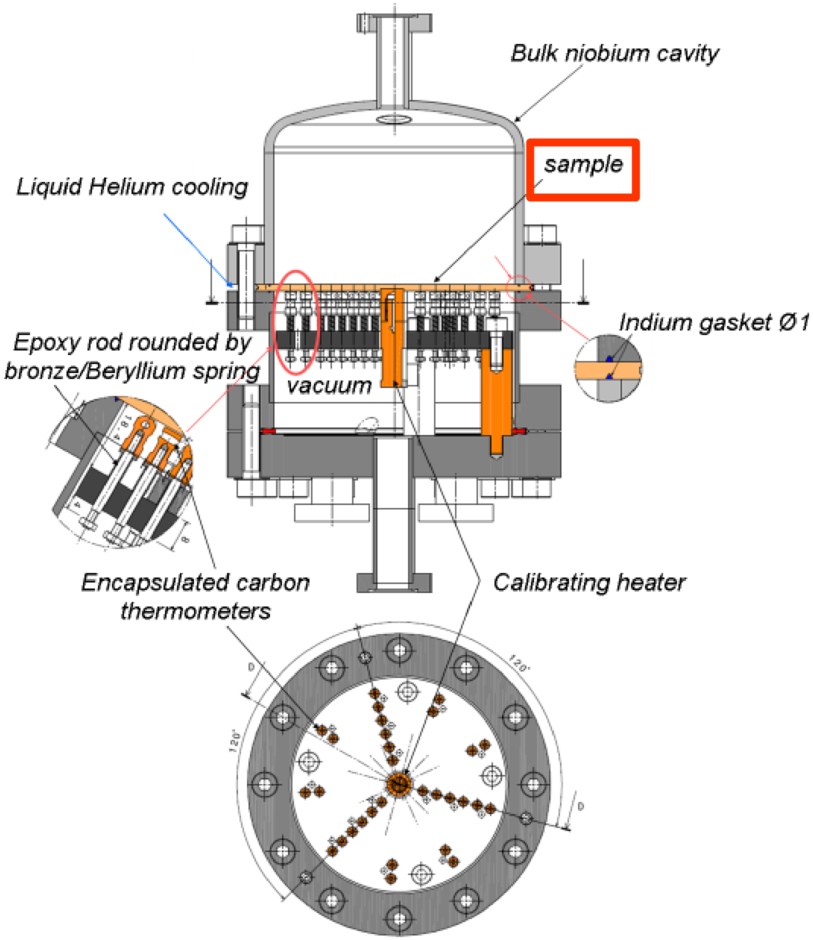
„SAMPLE CAVITY“ @ HZB

- **Build an optimized thin films RF testing resonator**
  - Magnet field generation based on the CERN quadrupole principle
  - Thermometric measurement of Rs vs B
  - Operating frequencies:
    - 433 MHz (70cm band, cheap components)
    - 866 MHz and
    - 1.3 GHz (relevance for TESLA)
- **Optimization :**
  - Optimize external coupling
  - Improve resolution of surface resistance
  - Modify thermometry chamber to accommodate samples on wafers
  - Improve magnetic shielding
- **Goal**
  - Investigate samples under external magnetic fields (flux pinning behavior)
  - Provide high sample throughput by procuring dedicated cryostat

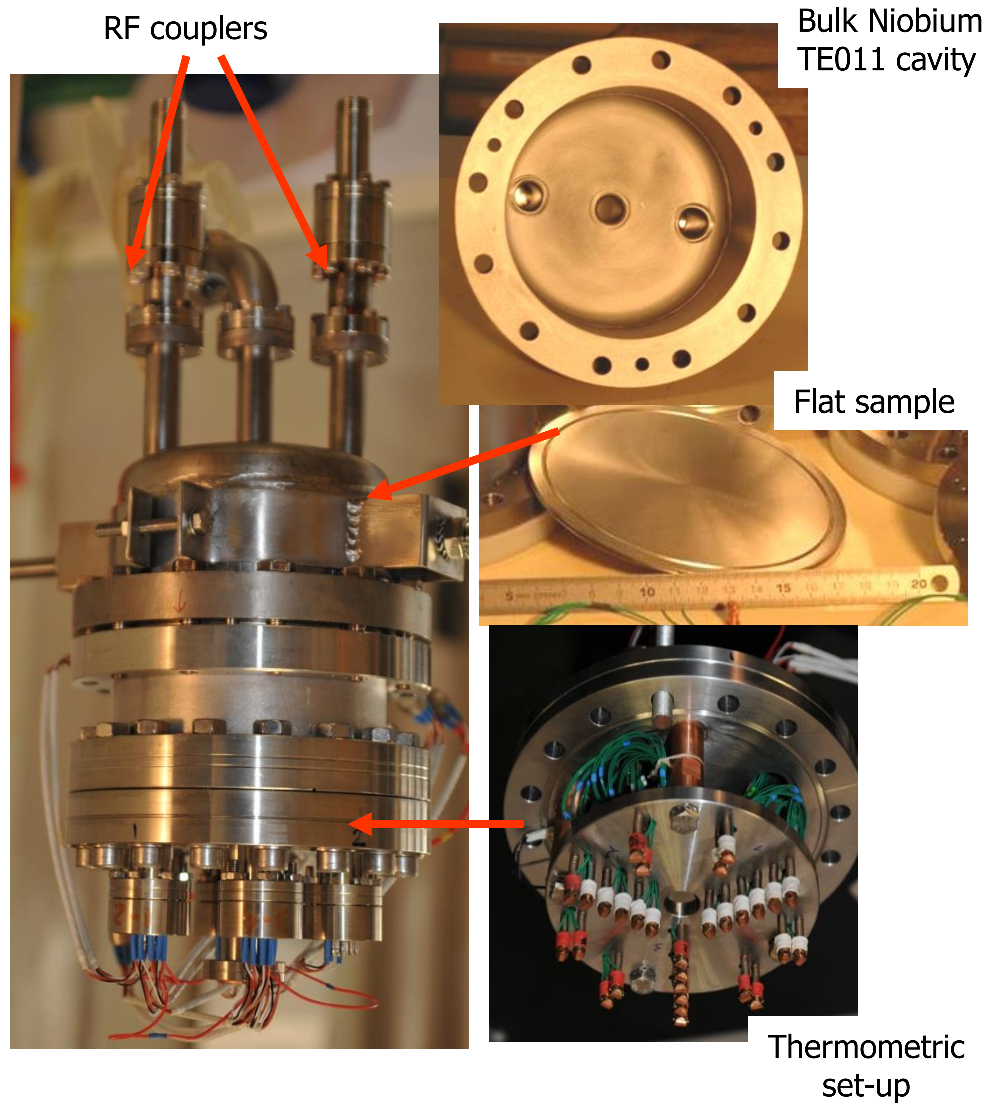


TE011 CAVITY AT IPNO

3.88 GHz => R_{BCS}~ 9 x R (1.3 GHz)

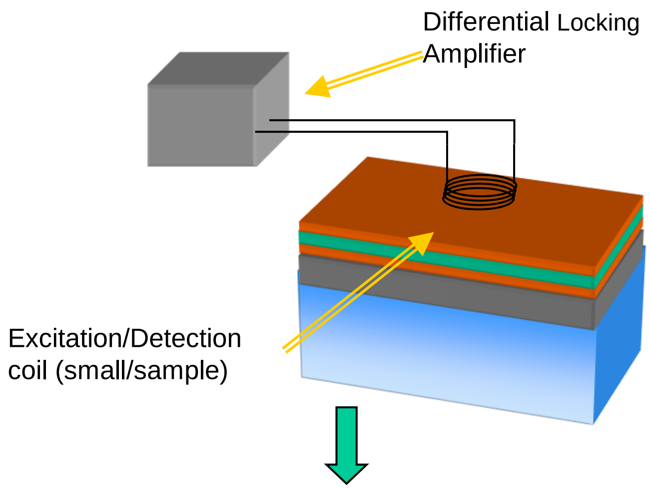


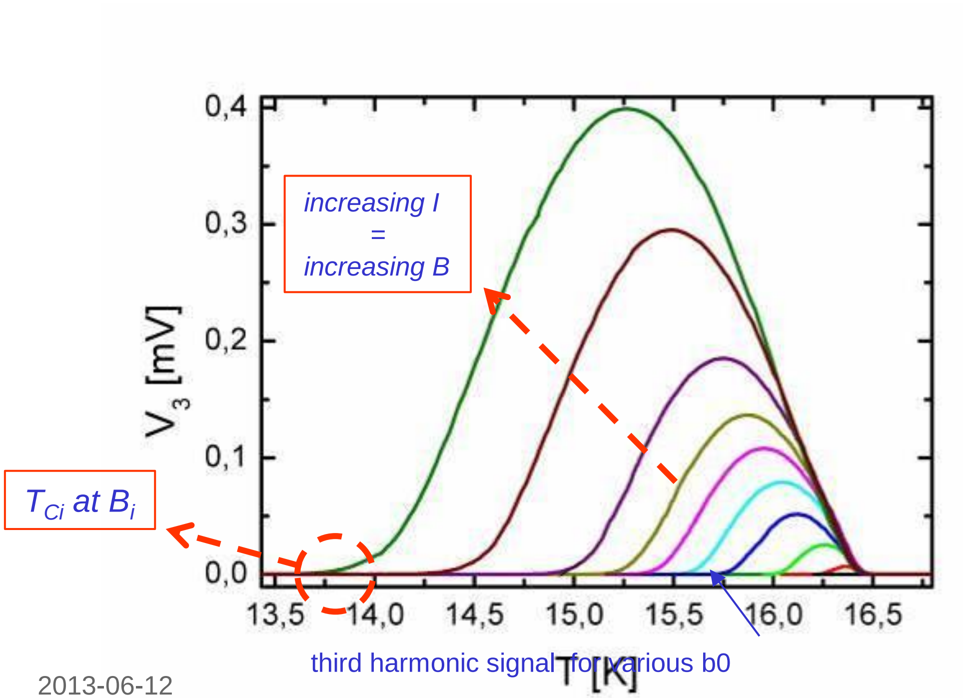
Back side of the sample

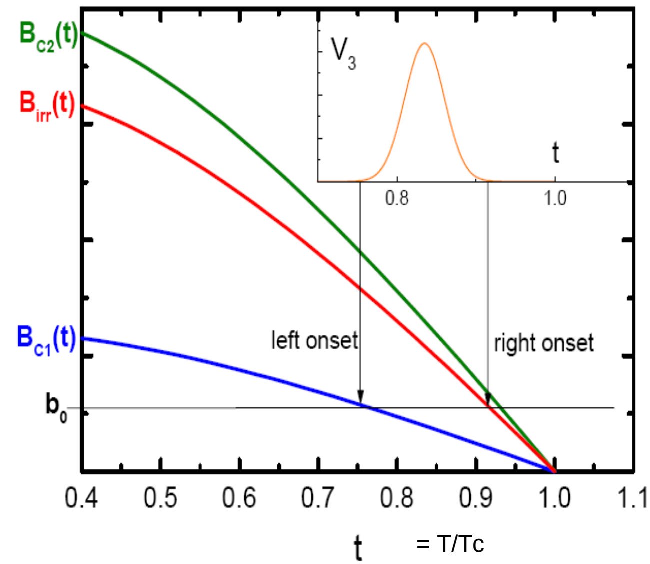


LOCAL MAGNETOMETRY @ SACLAY

- **E_{acc} in cavities is limited because of B^{RF}**
  - If $B_{RF} > B_{C1}$: vortex start to enter the SC material
  - Dissipation ↑↑
  - Measure of B_{C1} => limit in E_{acc} with good margin
    - $b_0\cos(\omega t)$ applied in the coil
    - below B_{C1} sample =perfect magnetic mirror
    - temperature ramp
    - third harmonic signal appears @ B_{C1}

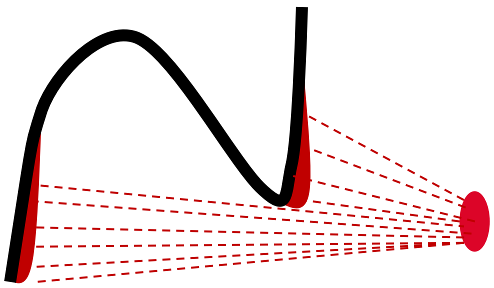


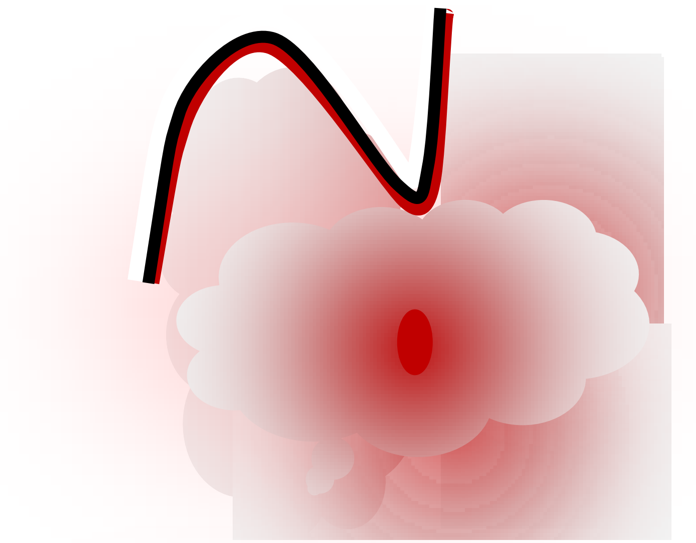




3 MAJORS DEPOSITION TECHNIQUES

- **High-energy deposition techniques**
  - line of sight techniques
  - issues: getting uniform thickness/structure
  - limited in complex geometry
- **Thermal diffusion films**
  - limited compositions available
  - non uniform composition
- **Chemical techniques CVD, ALD**
  - conformational even in complex shape
  - very quick for large surfaces
  - issues: get the right crystal structure

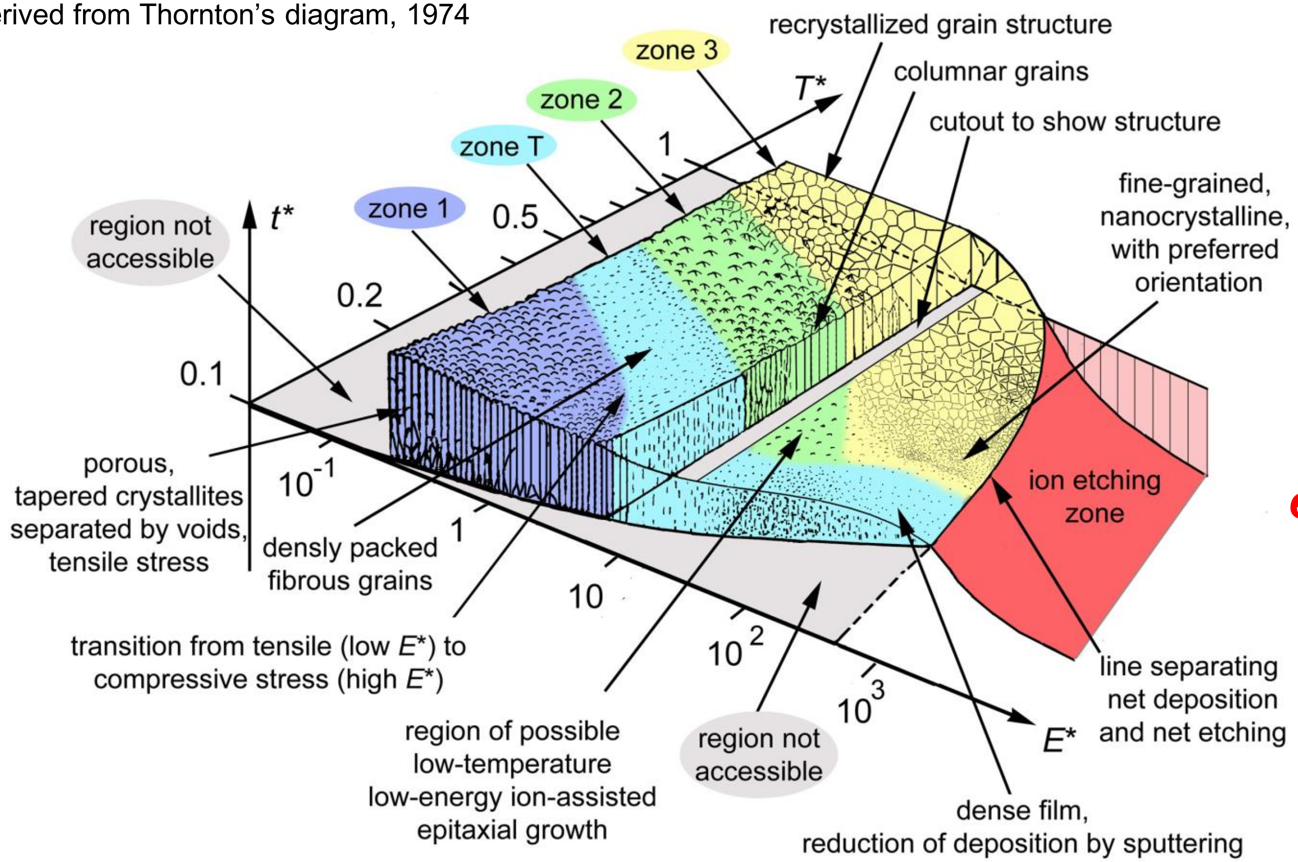




(from A. Anders)

Generalized Structure Zone Diagram

derived from Thornton's diagram, 1974



Bulk like ? => Go to energetic deposition ! HPIMS, ECR, CED…

A. Anders, Thin Solid Films **518**, 4087 (2010).

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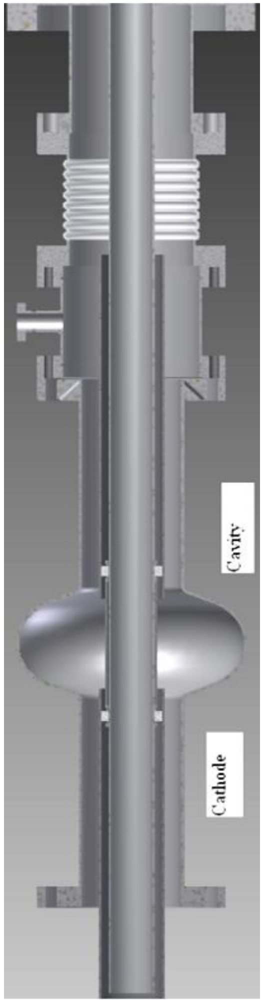
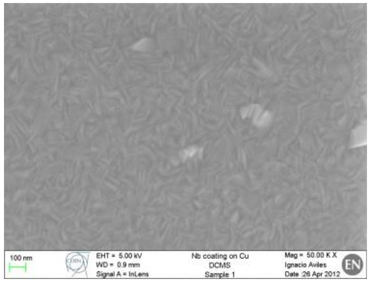
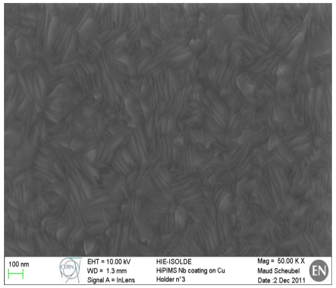
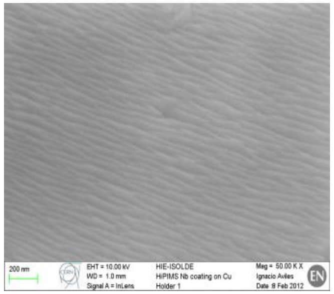
HPIMS @ CERN: bulk-like thin films

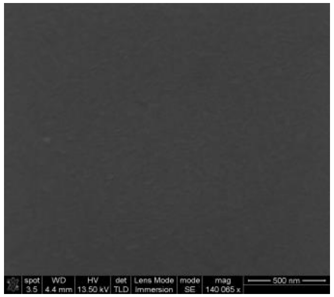


- **High energy compared to sputtering**
  - Self sputtering of the target => less Ar+/Kr+ in the layer
  - Ions reach the layer @ higher energy => less crystalline defects
  -









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Discharge Current

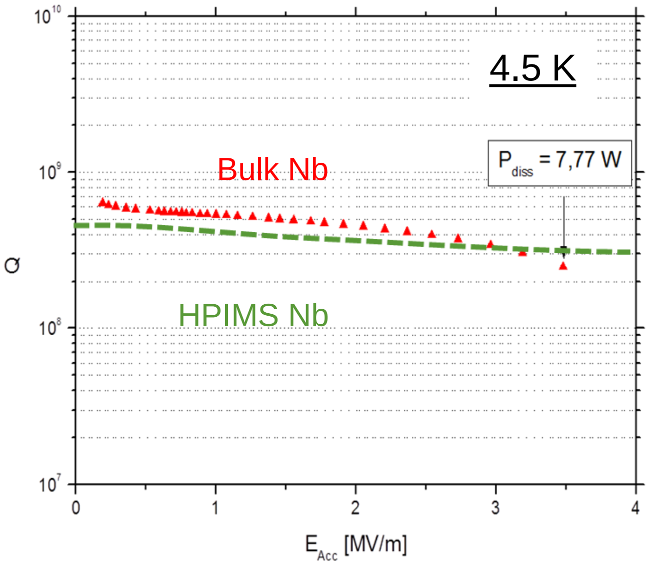
Material density

Crystalline quality

2013: activity started, collaboration with Sheffield University

1.3 GHZ DEPOSITED BY HPIMS @ CERN

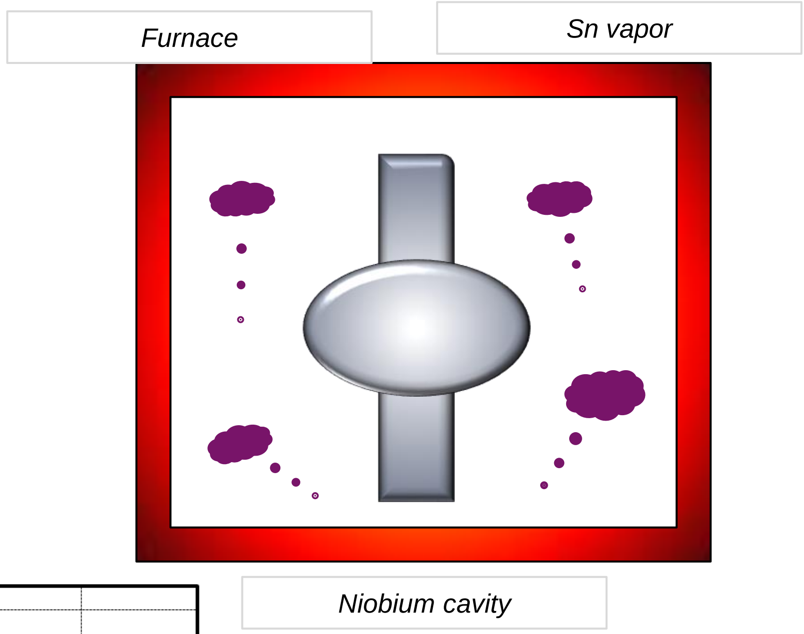
- **Similar as bulk Nb @ 4.5K, much less good @ 1.8K**
- **Bulk-like, high RRR + copper substrate =>**
  - better thermal stability
  - lower cost

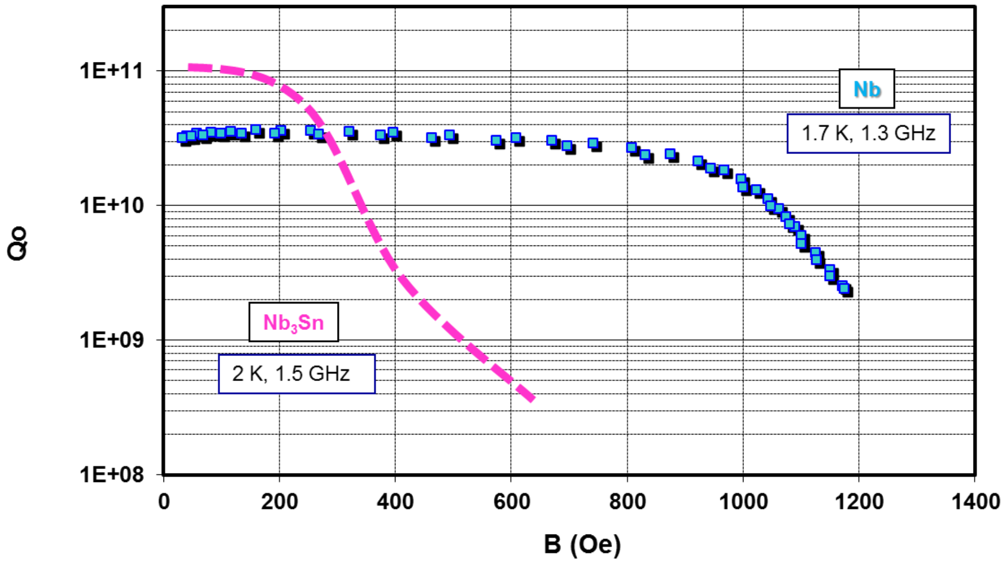


THERMAL DIFFUSION

Nb_3Sn developments @CERN

- Development of a thermal deposition set up.
- Comparison between :
  - thermal diffusion of tin into niobium
  - co-deposition by sputtering of Nb and Sn
    followed by a thermal reaction
- in 2013: design of furnace under study





CHEMICAL DEPOSITION TECHNIQUES: CVD, ALD

CVD : chemical vapor deposition *ALD atomic layer deposition*

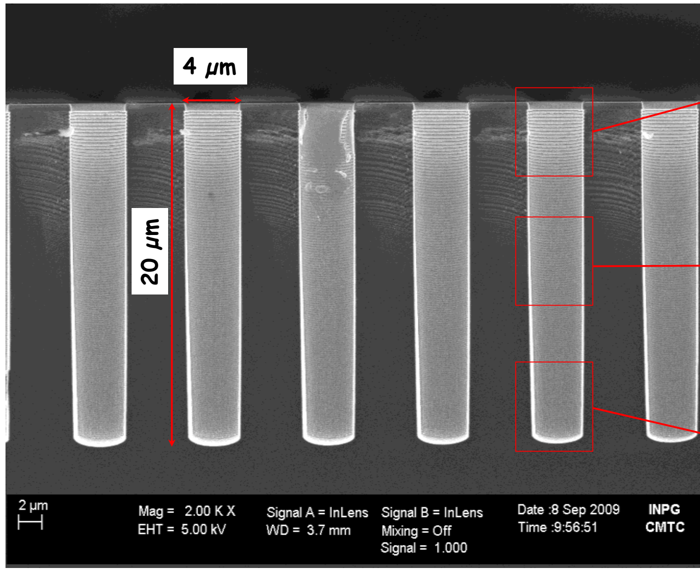
Advantage : conformal techniques,

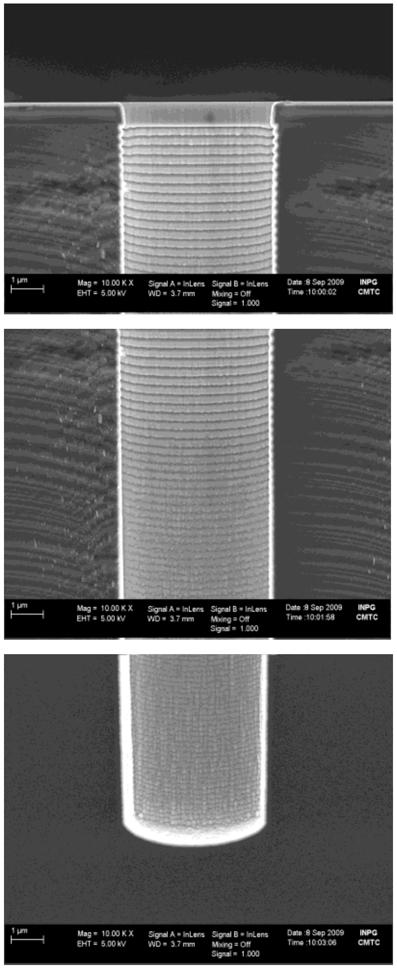
Can apply to large complex shapes

Bulk like ? => find the proper thermodynamic conditions

- **CVD : medium temperature pathway**
  - Precursors well known (mineral, e.g. $NbCl_3$…)
  - SC like NbN, NbTiN… have already done
  - Very sensitive to substrate surface state
  - Main difficulty: prepare multilayers structures
- **ALD : moderate temperature**
  - Better adapted to copper substrates
  - Organometallic precursors => high reactivity
  - Issue: get the right crystal structure
  - Fabrication of SC like NbN not well known, but close compounds like TaN, TiN… well known
- **∃ known (chemical) strategies for the choice of precursors**
- **∃ advanced (chemical) software that can model thermodynamic + hydrodynamic environment for reaction optimization**

High conformability





Layer ~ 100nm

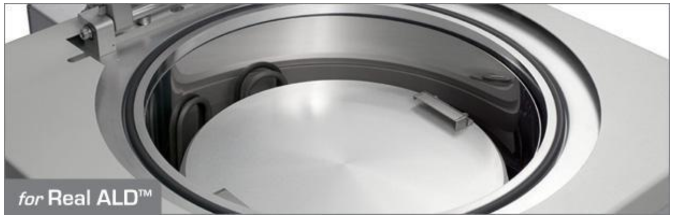
Example

- **Tantalum nitride (Ta_3N_5):**
  - PDMAT ($Ta(N(CH_3)_2)_5$) et NH_3
- **Tantalum oxide (Ta_2O_5) :**
  - TaEtO ($Ta(O(C_2H_5))_5$) et H_2O
- **Niobium nitride (NbN) :**
  - $NbCl_3$ et Zn ou Hydrazine (N_2H_4) , but high Tp°
  - Organometallic precursors under study

ALD MOVIE

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

CVD/ ALD @ GRENOBLE INP

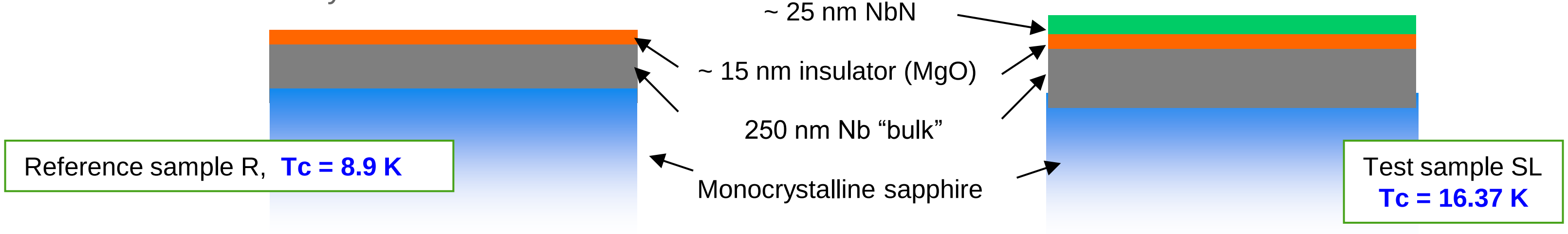


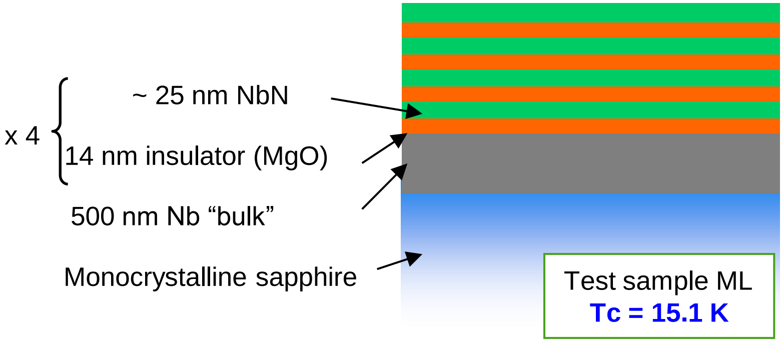
- **Long standing expertise of Grenoble INP on:**
  - superconducting heterostructures
  - CVD and ALD of oxides & nitrides (TiN, TaN, AlN, YBCO/PBCO,……)
- **Need to develop a specific ALD reactor for multilayer NbN/insulator/NbN coatings**
- **Need to develop a suitable coordination chemistry for the ALD precursors (+ plasma ALD to help)**
- **Extensive sample characterization**
- **Process scaling up to cavity deposition will be performed with specific simulation tools.**

FOCUS ON MULTILAYERS

FIRST EXP. RESULTS ON HIGH QUALITY MODEL SAMPLES

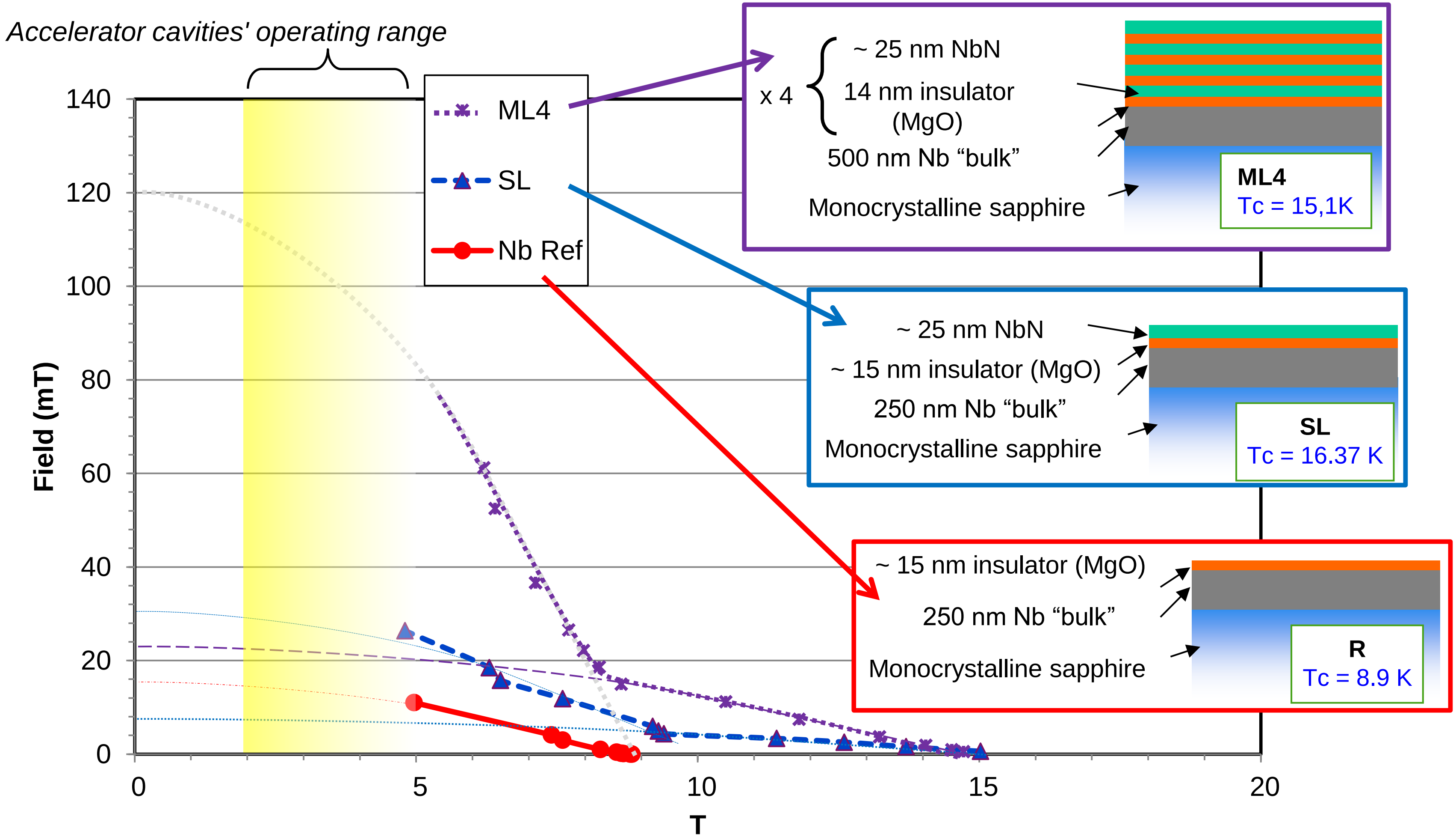
- Choice of NbN:
  - ML structure = close to Josephson junction preparation (SC/insulator compatibility)
  - Use of asserted techniques for superconducting electronics circuits preparation:
    - Magnetron sputtering
    - Flat monocrystalline substrates





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

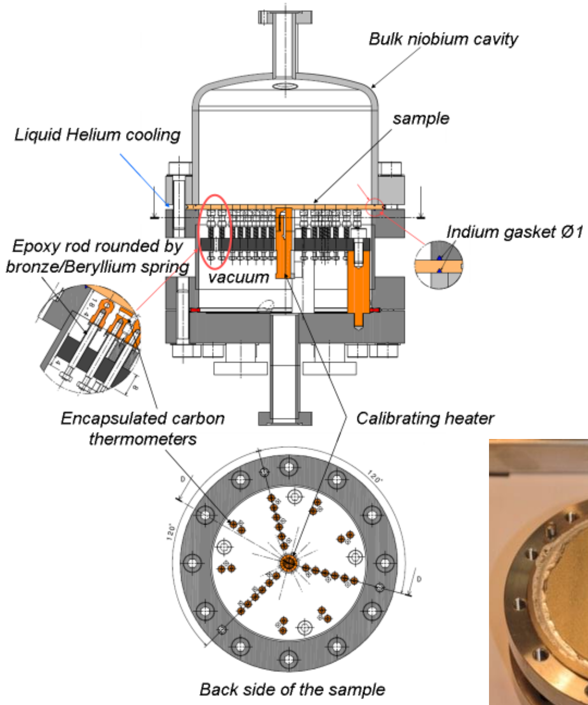
MULTILAYERS' H_{C1}

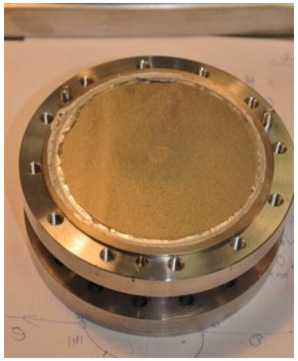


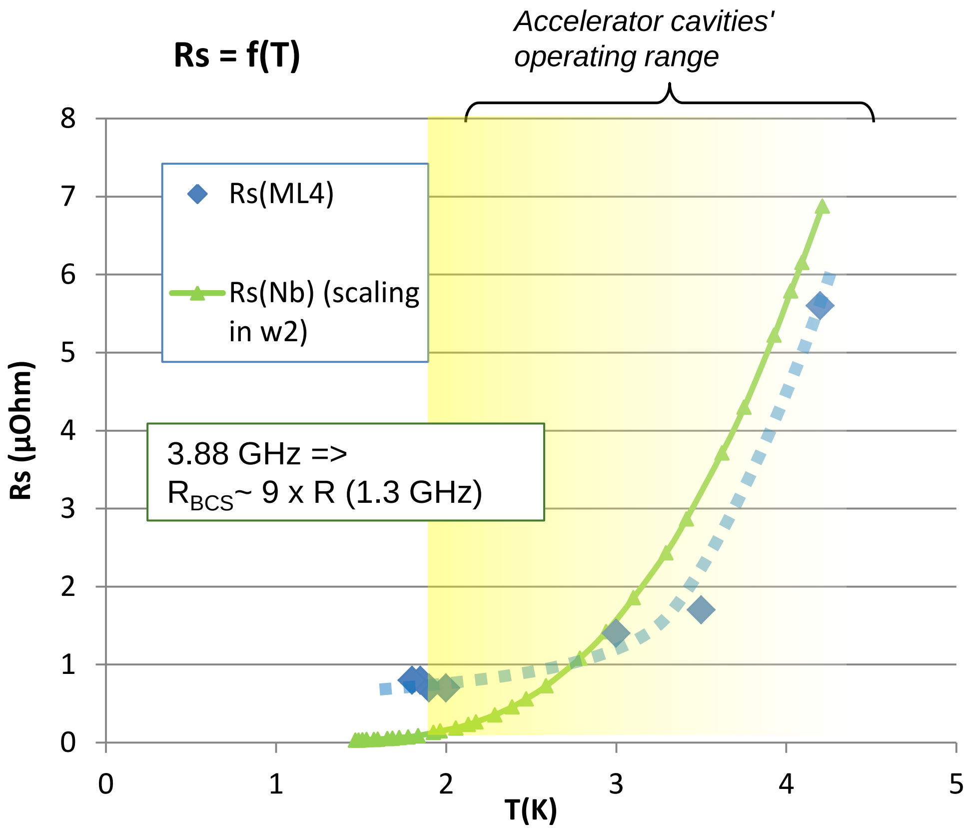
ML sample : 250 nm Nb + (14 nm MgO + 25 nm NbN) x **4**

Multilayer tested for the first time B_{C1} > 55 mT @ 8K !

1st 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.

CONCLUSION AND PERSPECTIVES

CONCLUSIONS AND PERSPECTIVES

- Superconducting cavities are dominated by their surface quality (Niobium AND other SC !)
- Niobium is close to its ultimate limits
- 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 beyond Nb for accelerator cavities
- 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 !

STRUCTURE OF THE TASK 12.2 (EUCARD2)

- **Niobium on copper (µm)**
  - After ~ 20 years stagnation : new revolutionary deposition techniques
  - Great expectations in cost reduction
  - No improved performances/ bulk Nb
- **Higher Tc material (µm)**
  - Based on superheating model.
  - Higher field and lower Q_0 expected
- **Higher Tc material (nm), multilayer**
  - Based on trapped vortices model (Gurevich)
  - Higher field and lower Q0 expected
  - Recent experimental evidences
- **Specific characterization tools needed**
- **Better understanding of SRF physics needed**

Subtask 1

Subtask 2

Subtask 3


SRF2013
PARIS
16th International conference on RF Superconductivity
September 23-27, 2013
Cité Universitaire Internationale, PARIS
Tutorials : September 19-21, 2013
GANIL, CAEN (France)
http://www.srf2013.fr
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THANK YOU FOR YOUR ATTENTION

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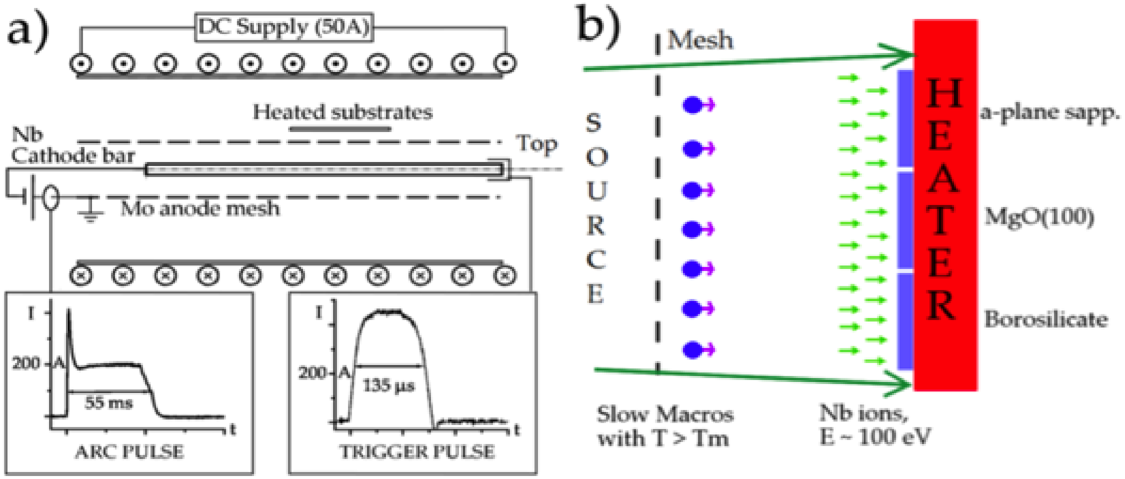
DSM
Irfu
SACM
LIDC2

SPARES

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.

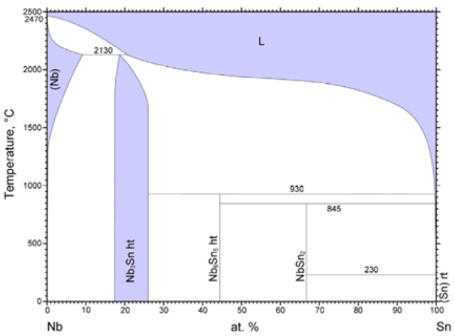
- Ions Energy 60-120 eV
- Arc source is scalable for large scale cavity coatings
- UHV and clean walls important

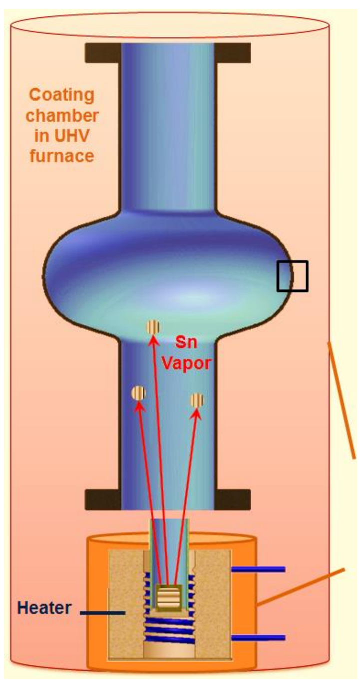
Coaxial Energetic Deposition (CED™)

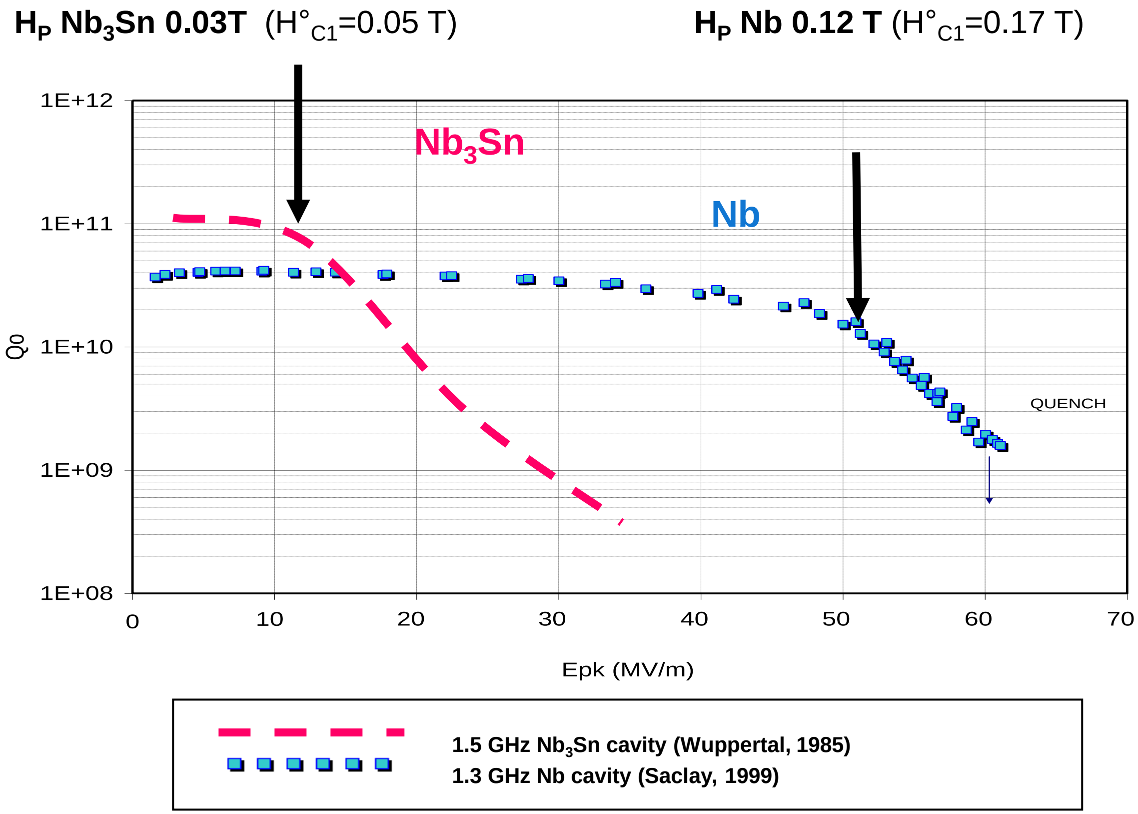
Ch. Reece; JLab

Nb films grown by Jlab and AASC Almeda Applied Science Corporation. Balk like RRR values

Nb_3Sn FAILURE : DUE TO VORTICES ?







- Nb : the best because of its high H_{C1} ?
- Nevertheless it is interesting to master Nb_3Sn for SRF applications => on going activities @ Cornell, (re-) starting @ CERN