USPAS June 2015 Rutgers

SRF MATERIALS OTHER THAN BULK NIOBIUM

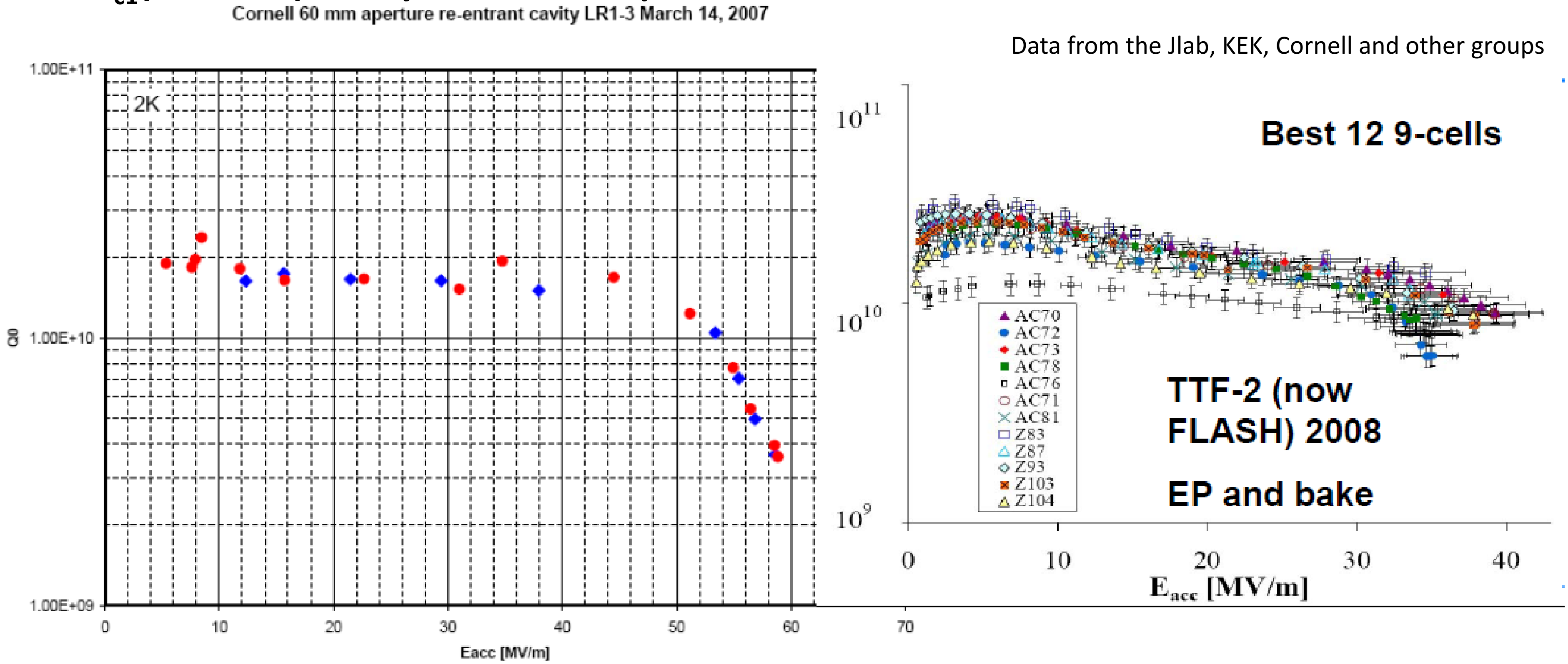
Anne-Marie Valente-Feliciano

Thomas Jefferson National Accelerator Facility

Jefferson Science Associates LLC

Why looking beyond bulk Nb?

Nb has the highest critical temperature T_c (=9.25k) and the highest lower critical magnetic field H_{c1}(≈180 mT) of any elemental superconductor



Breakdown fields close to the de-pairing limit of 50 MV/m for Nb have been achieved

Best Nb cavities approaching their intrinsic limit at $H_{max} = H_C$

For further improved cavity RF performance, innovation needed

Possibilities to use higher performance superconductors other than Nb?

Looking beyond Nb – Potential Benefits

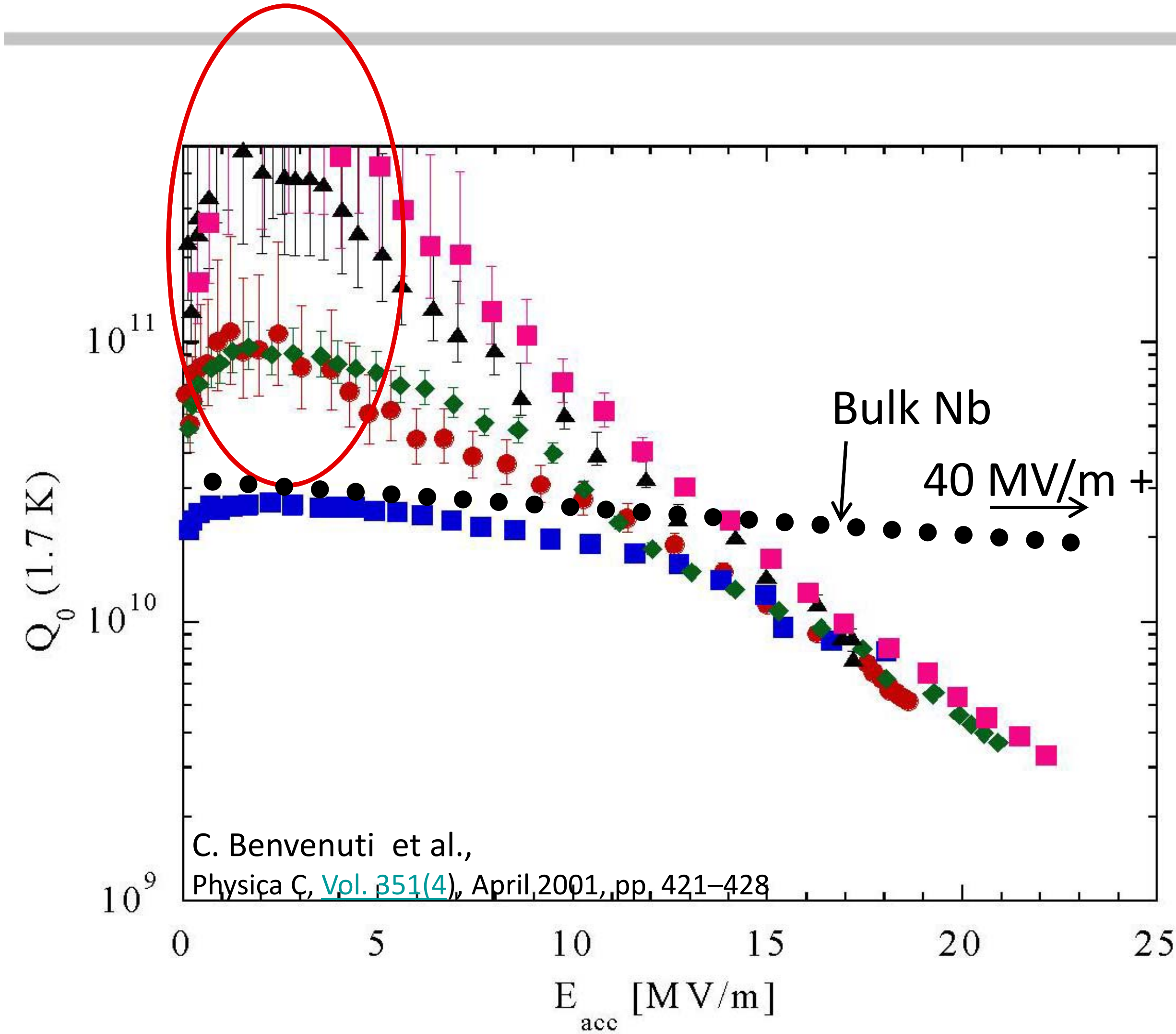
- Reduced material costs
  - Use of inexpensive, highly formable materials with higher thermal conductivity such as Cu or Al
- Simplified engineering, fabrication and assembly
  - Separation of cavity structure from superconducting surface
  - Maximum flexibility & largest variety of options in design of integrated cavity/cryostat structures
- Higher gradients

  Increasing gradients reduces capital expense of cryomodules – potentially several $100M savings & minimize conventional facilities
- Lower RF losses

  Low loss (high Q) cavities reduce He costs, >$10M potential capital savings, and several $M/year in operating costs
- Potentially higher operating temperatures (>4.2K)

Nb Thin films

Thin Films for SRF - State of the Art



1.5 GHz Nb/Cu cavities, sputtered w/ Kr @ 1.7 K (Q_0=295/R_s)

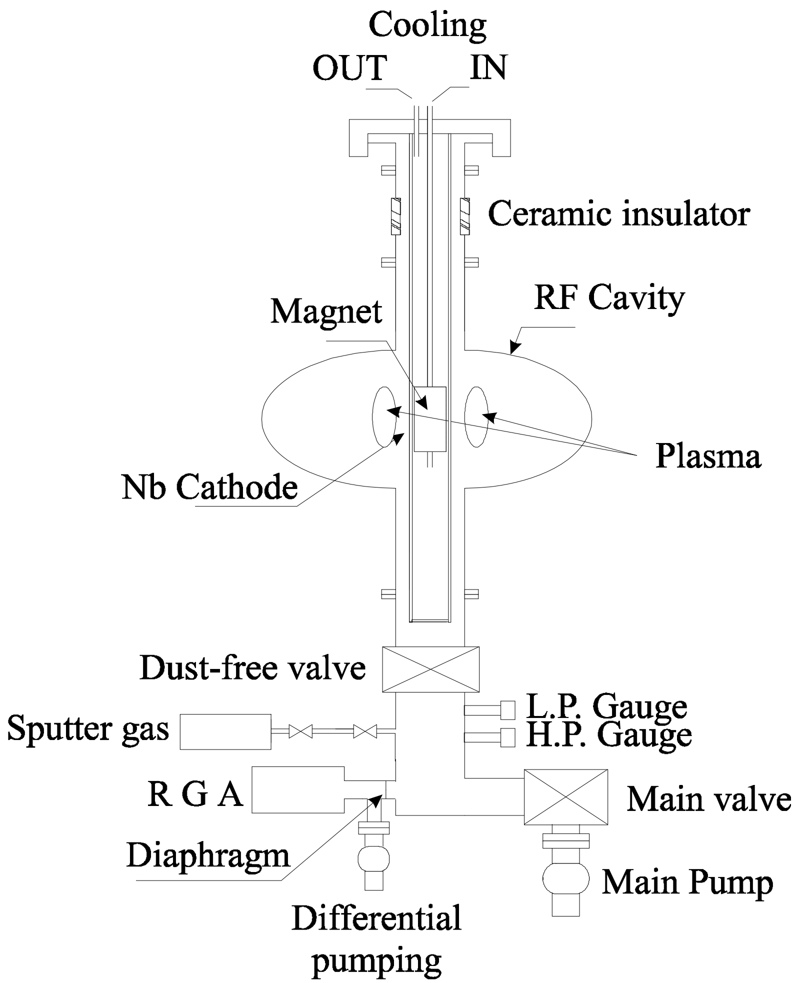
Thickness of interest for SRF applications = RF penetration depth, i.e. the very top 40 nm of the Nb surface.

High Q at low field
BUT strong Q-slope

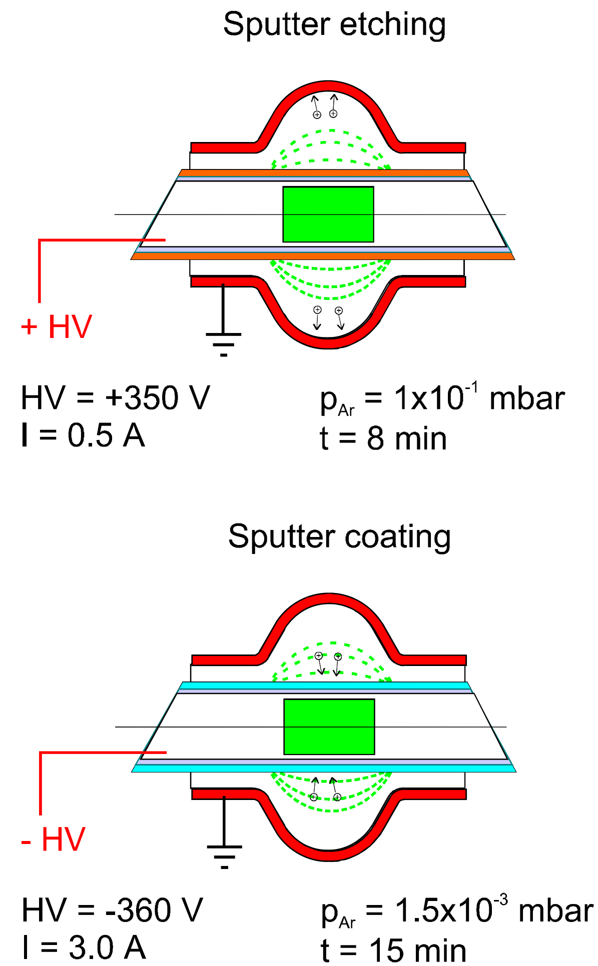
Nb/Cu Sputtered Films

Two Production Methods: standard and oxide-free coatings

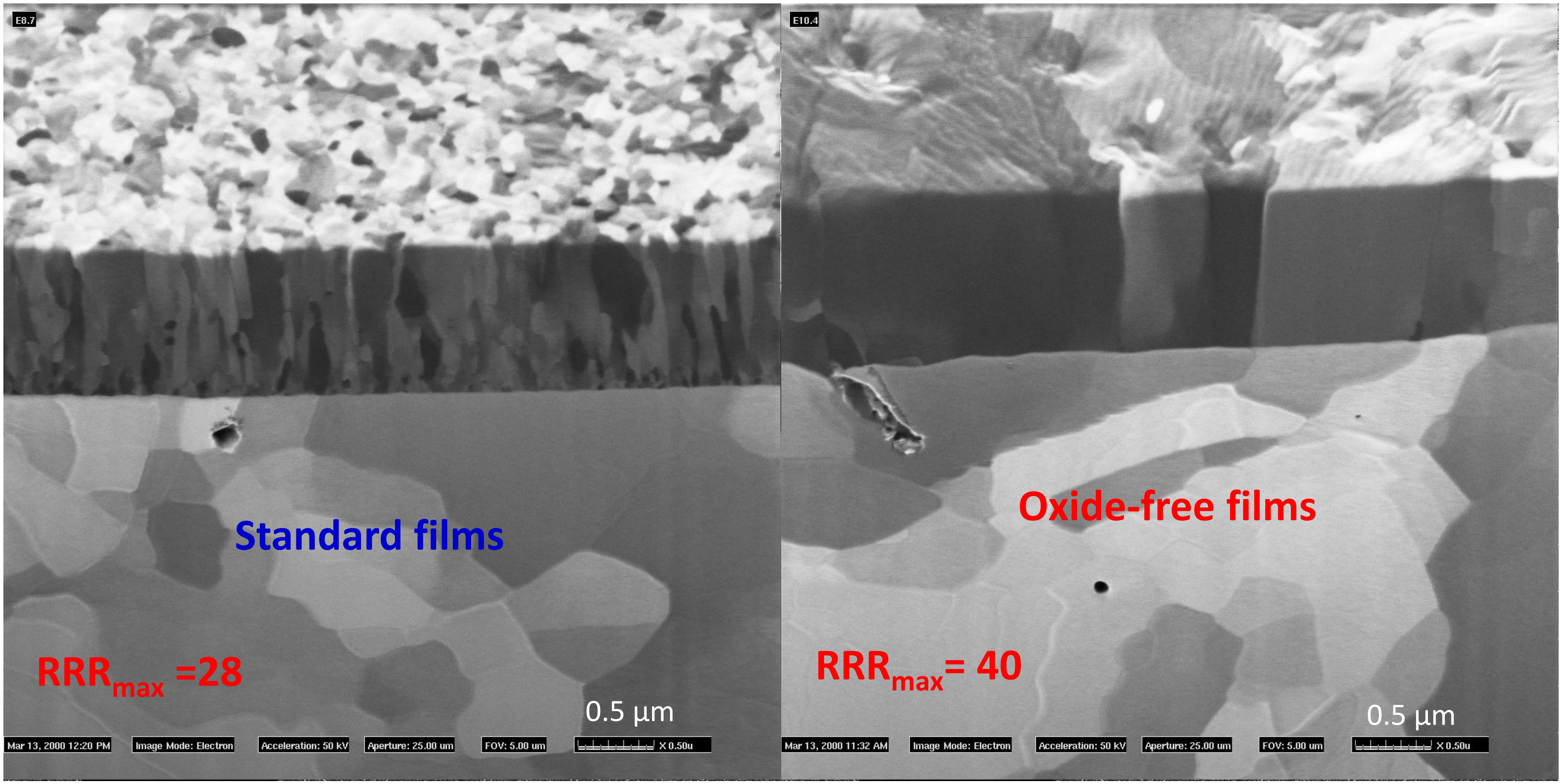
Single cathode system



Double cathode system



Nb/Cu Sputtered Films:
Film structure – FIB cross sections



Courtesy: P. Jacob - EMPA

Columnar grains, size ~ 100 nm
In plan diffraction pattern: powder diagram
(110) fiber texture ⊥ substrate plane

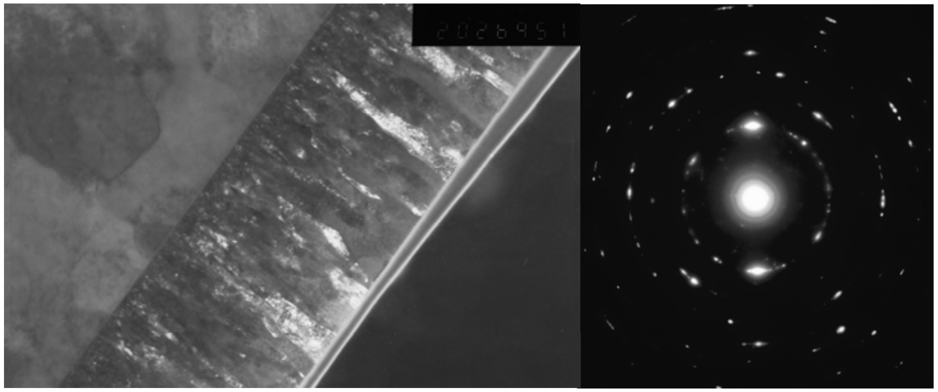
Equi-axed grains, size ~ 1-5µm
In plan diffraction pattern: zone axis [110]
Heteroepitaxy
Nb (110) //Cu(010) , Nb (110) //Cu(111),Nb (100) //Cu(110)

Nb/Cu Sputtered Films:
TEM cross-section & in-plane

cross-section

Nb/Cu Oxide

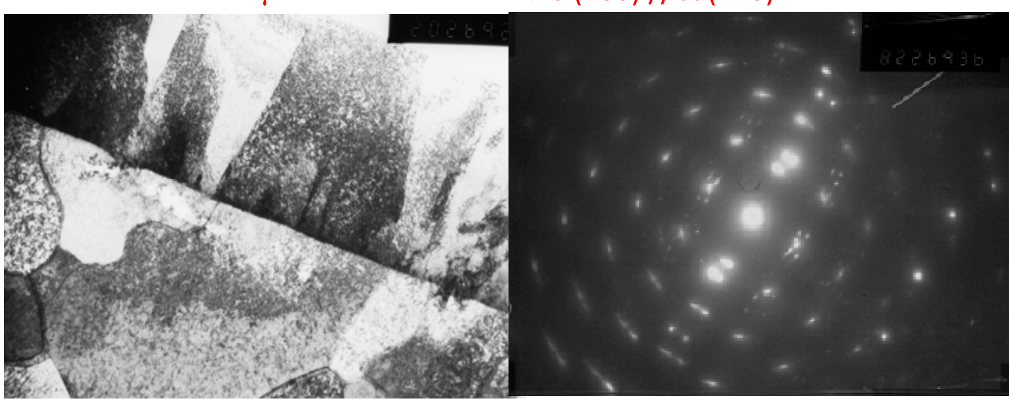
Grain size ~ 0.1 μm



Hetero-epitaxy relationships
Nb (110) //Cu(010)
Nb (110) //Cu(111)
Nb (100) //Cu(110)

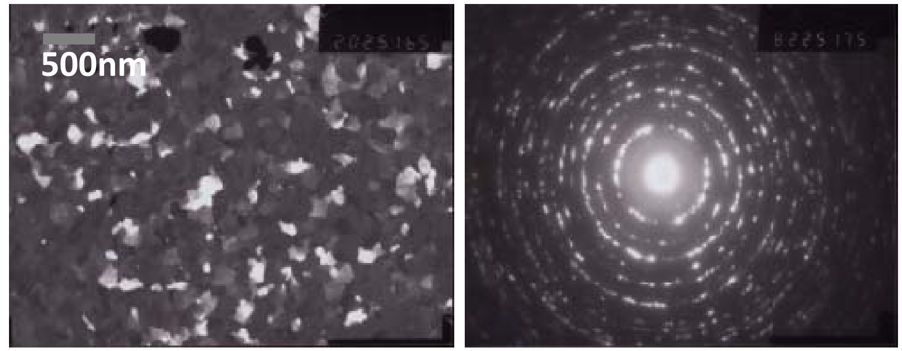
Nb/Cu

Grain size ~ 1-5μm



In-plane

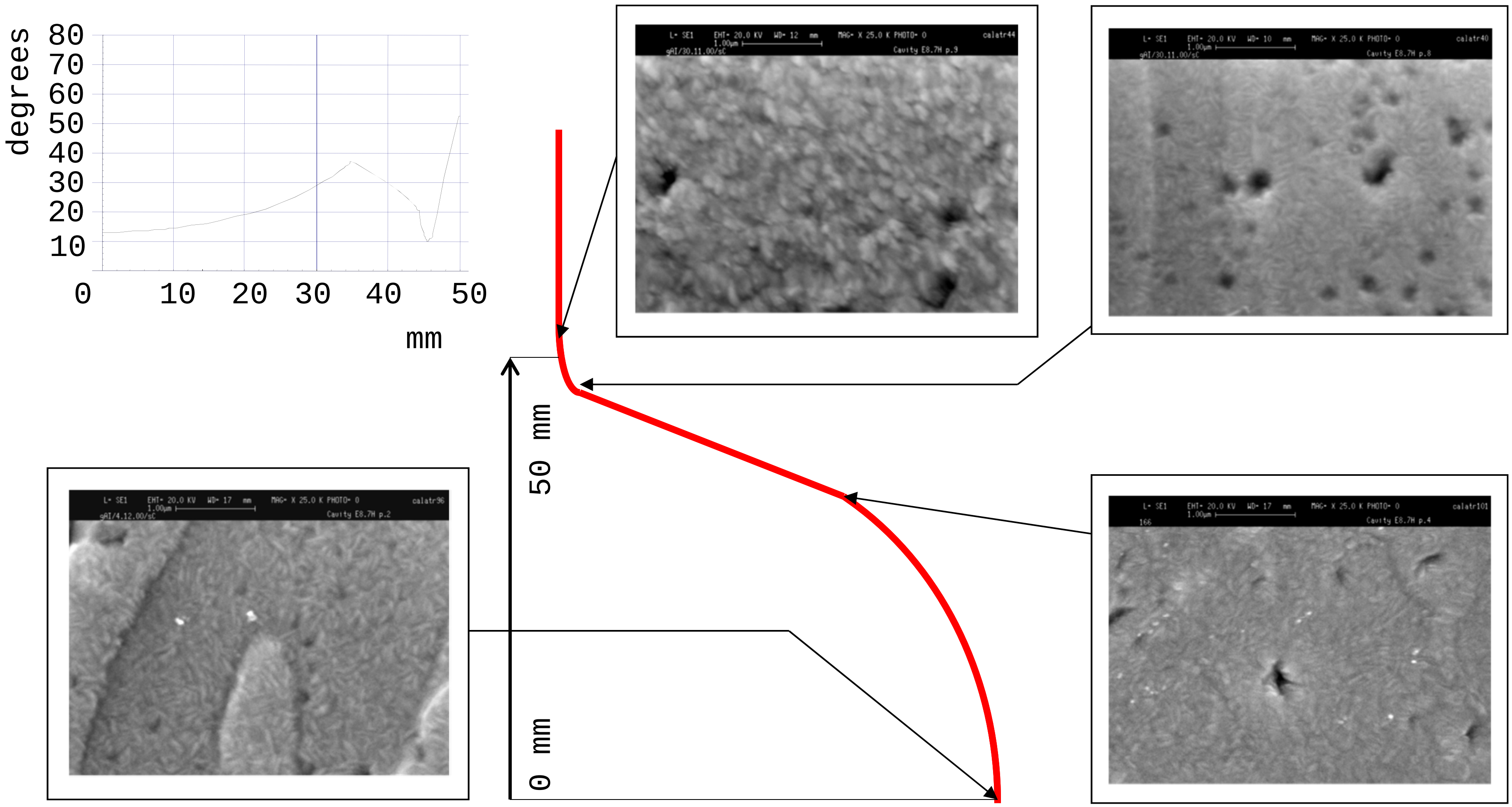
Grain size ~ 100 nm
Fiber texture
Diffraction pattern: powder diagram



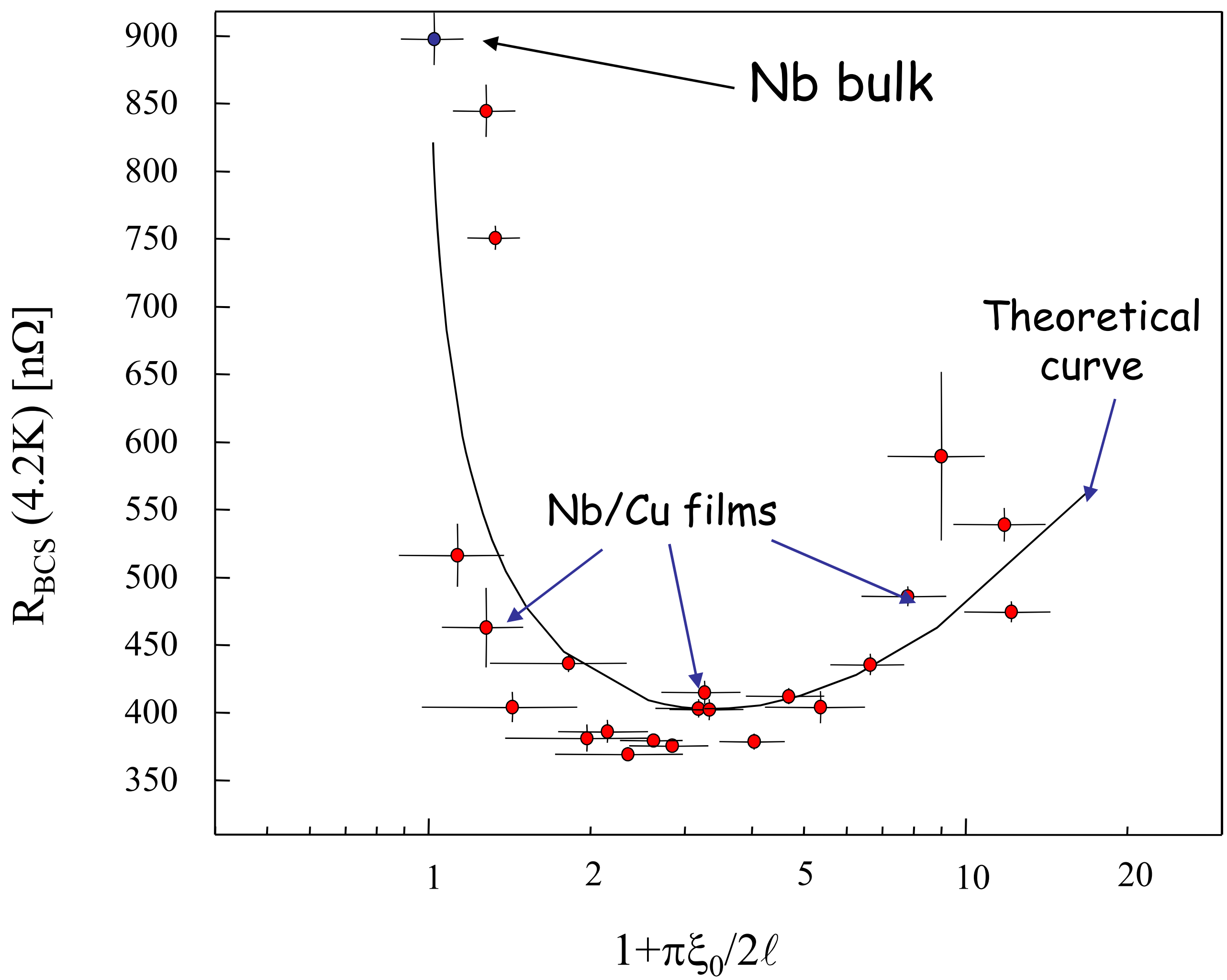
Grain size ~ 1-5μm
Heteroepitaxy
Diffraction pattern: zone axis [110]

Nb/Cu Sputtered Films:

Intrinsic film roughness & incidence angle of the niobium atoms



Theoretical and experimental BCS resistance at zero RF field

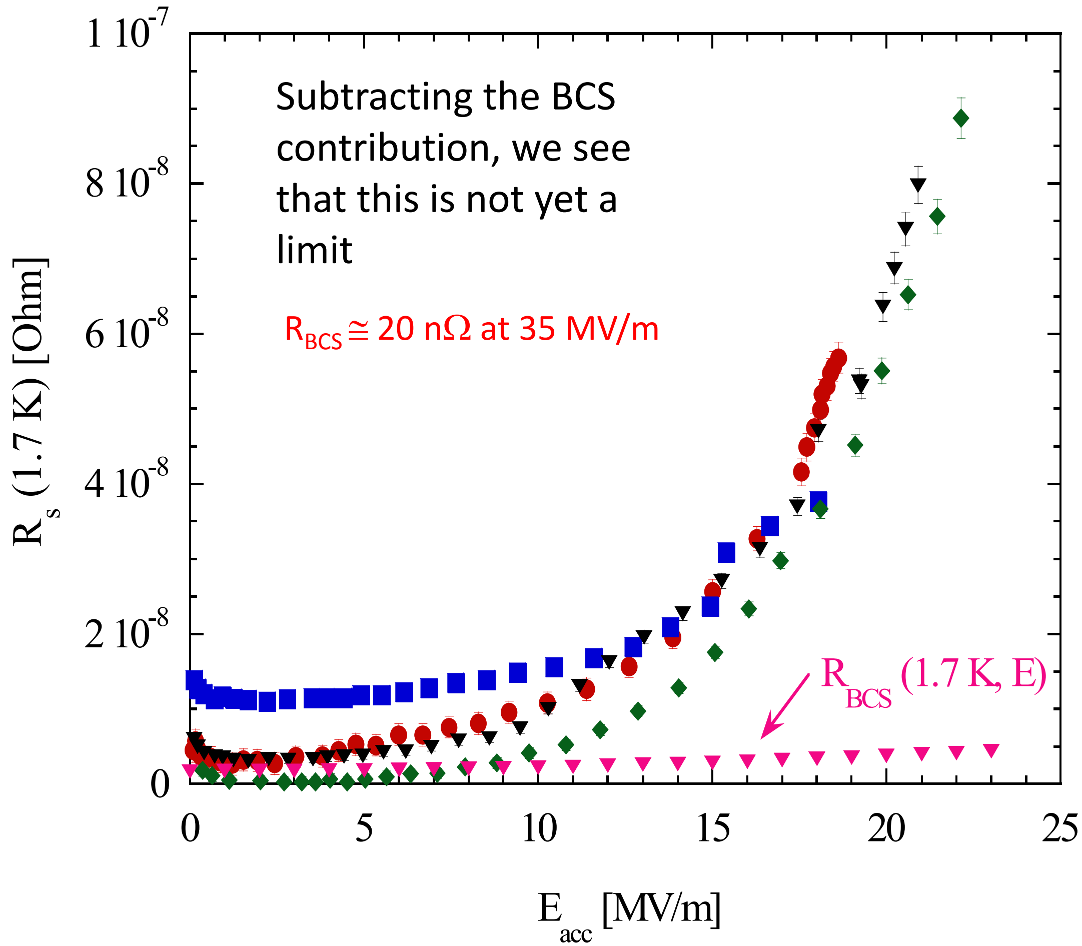


R_{BCS} at 4.2 K
Nb bulk: ~900 nΩ
Nb films: ~400 nΩ

R_{BCS} at 1.7 K
Nb bulk: ~2.5 nΩ
Nb films: ~1.5 nΩ

Compilation of results from several Nb/Cu and Nb bulk 1.5 GHz RF cavities

Best RF performance measured on 1.5GHz Nb/Cu sputtered cavities



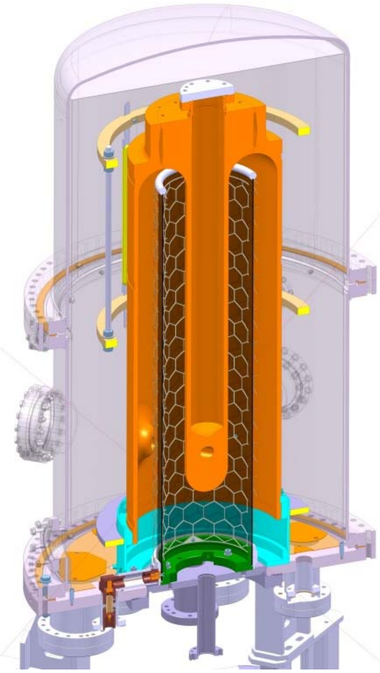
Coatings performed using krypton on electropolished spun copper cavities(Santa Fe 1999)

	Standard	Oxide-free
RRR	11.5 ± 0.1	28.9 ± 0.9
T_c	9.51 ± 0.01 K	9.36 ± 0.04 K
Ar cont.	435 ± 70 ppm	286 ± 43 ppm
Texture	(110)	(110), (211), (200)
Hc_1	85 ± 3 mT	31 ± 5 mT
Hc_2	1.150 ± 0.1 T	0.73 ± 0.05 T
a_0	3.3240(10)Å	3.3184(6) Å
$\Delta a_\perp / a_\perp$	0.636 ± 0.096 %	0.466 ± 0.093 %
Stress	-706 ± 56 MPa	-565 ± 78 MPa
Grain size	110 ± 20 nm	> 1 µm

Attaining even bulk-like performance with Nb film would enable major system simplifications.

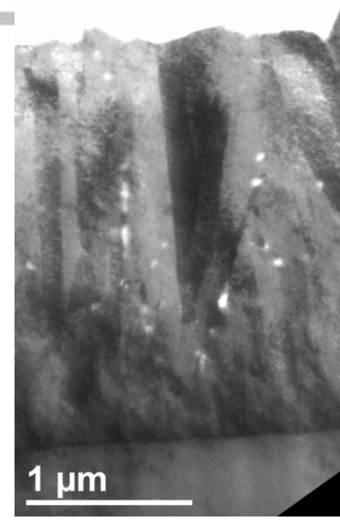
Deposited films, once a production process is developed, may offer the highest level of quality assurance and thus reliable performance.

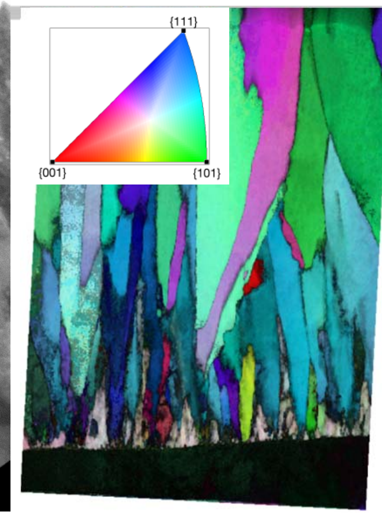
QWR Resonators for HIE-Isolde Upgrade



Nb thin film sputtered on 3D forged OFE Cu substrate
By **dc-bias diode sputtering**

→ ***average RRR = 35***





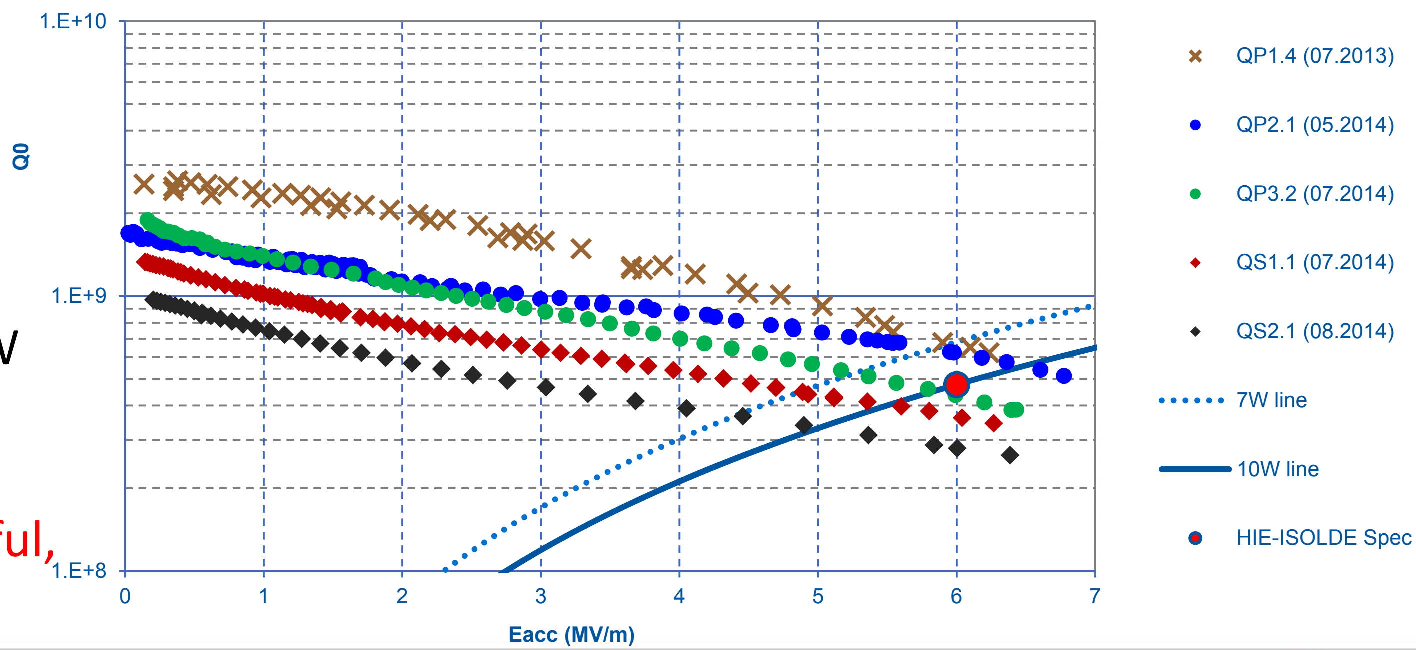
Specifications:

E_{acc} = 6MV/m

P_{cav} @6MV/m = 10W

Average P_{cav}~ 12W

Prototyping successful,
Production started



High-energy deposition techniques

- Crystalline defects, grains connectivity and grain size may be improved with an higher substrate temperature which provides higher surface mobility (important parameter is $T_{substrate}/T_{melting\_of\_film}$)
- However the Cu substrate does not allow heating

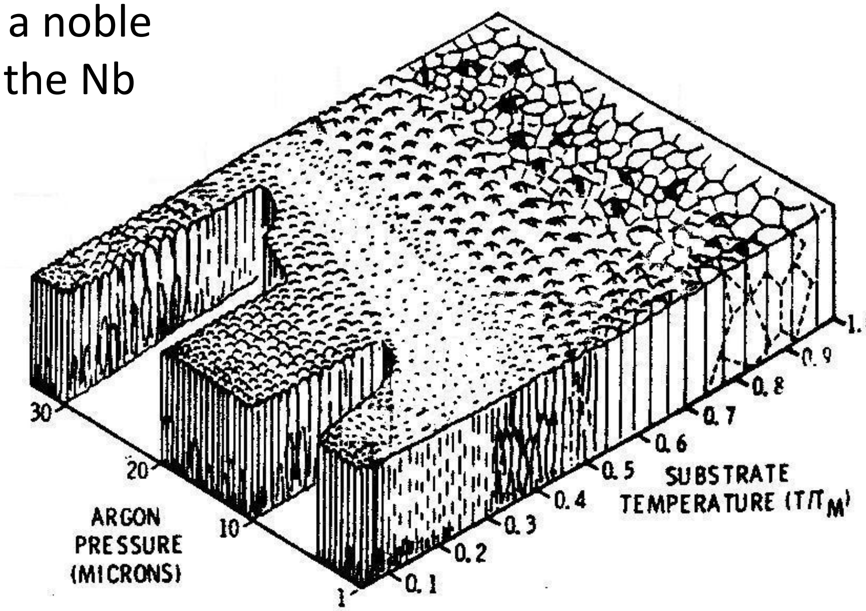
➢ **The missing energy may be supplied by ion bombardment**

  – In bias sputter deposition a third electron accelerates the noble gas ions, removing the most loosely bound atoms from the coating, while providing additional energy for higher surface mobility

  – Other techniques allow working without a noble gas, by ionising and accelerating directly the Nb that is going to make up the coating

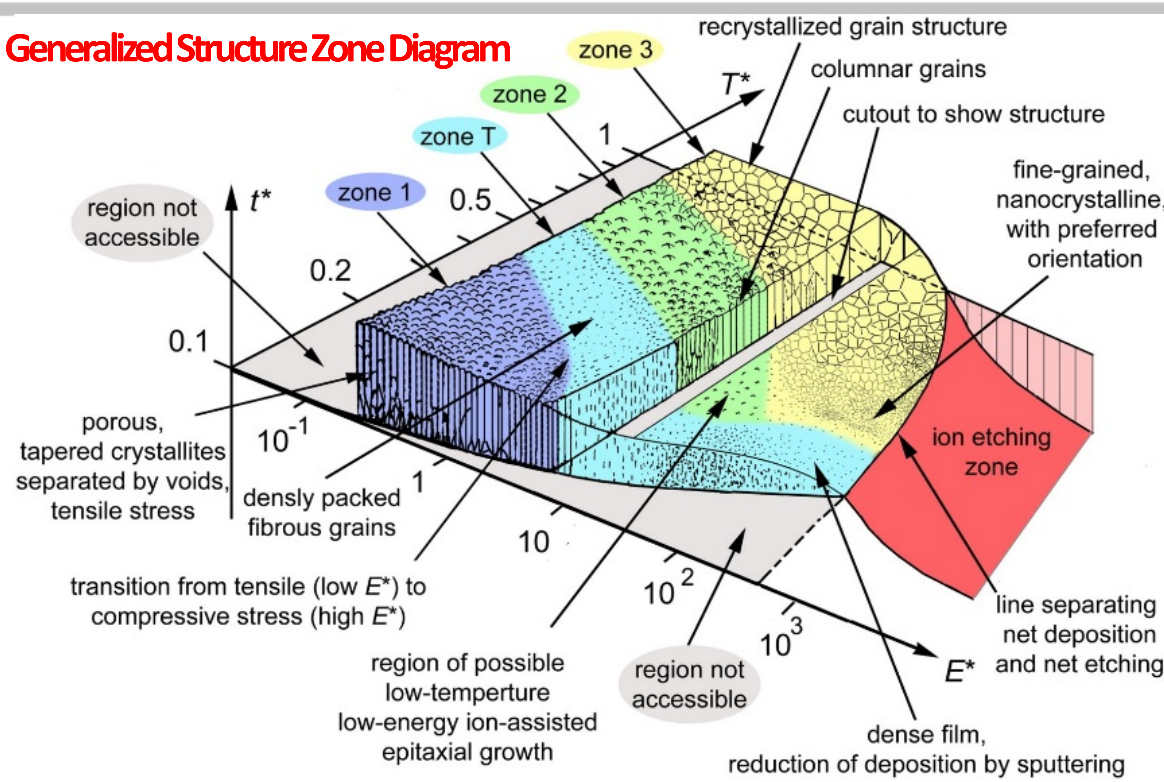
  – These techniques allow also to obtain "conformal" coatings that follow the surface profile better filling voids.

Thornton's "Structure Zone Model"



Energetic Condensation

Condensing (film-forming) species : hyper-thermal & low energies (>10 eV).



derived from Thornton's diagram for sputtering (1974)

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

Additional energy provided by fast particles arriving at a surface ⇒number of surface & sub-surface processes ⇒changes in the film growth process:

- residual gases desorbed from the substrate surface
- chemical bonds may be broken and defects created thus affecting nucleation processes & film adhesion
- enhanced mobility of surface atoms
- stopping of arriving ions under the surface

⇒ Changes in
- morphology
- microstructure
- stress

As a result of these fundamental changes, energetic condensation allows the possibility of controlling the following film properties:

- Density of the film
- Film composition
- Crystal orientation may be controlled to give the possibility of low-temperature epitaxy

Next generation Nb films

ALL film properties are a direct consequence of the film structure, defect/impurity content… thus the technique, environment, substrate are key factors

Full control of the deposition process
&
tailored
SRF performance

UNDERSTANDING OF

- The **chemistry** of the involved species
  - **Reactivity**
  - **Stoichiometric sensitivity**
  - Reaction process **temperatures**
- l structure **dependence on substrate structure**
- **In nce of deposition energy** on resulting structure
- **S ivity to** the presence of **contaminating species, defects**
- **ation** of desired film against subsequent **degradation**

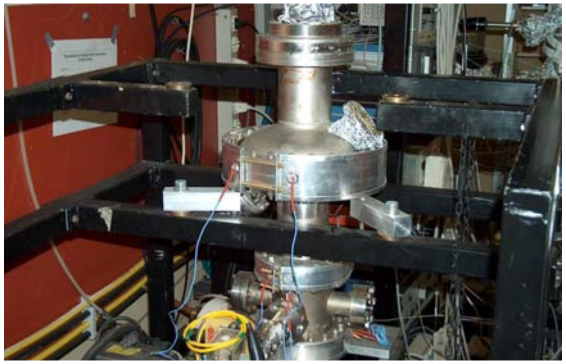
Careful **characterization of the attained composition and microstructure** (RHEED, STM, XRD, EBSD, AFM, optical profilometry, XPS, SIMS,TEM, FIB).

+

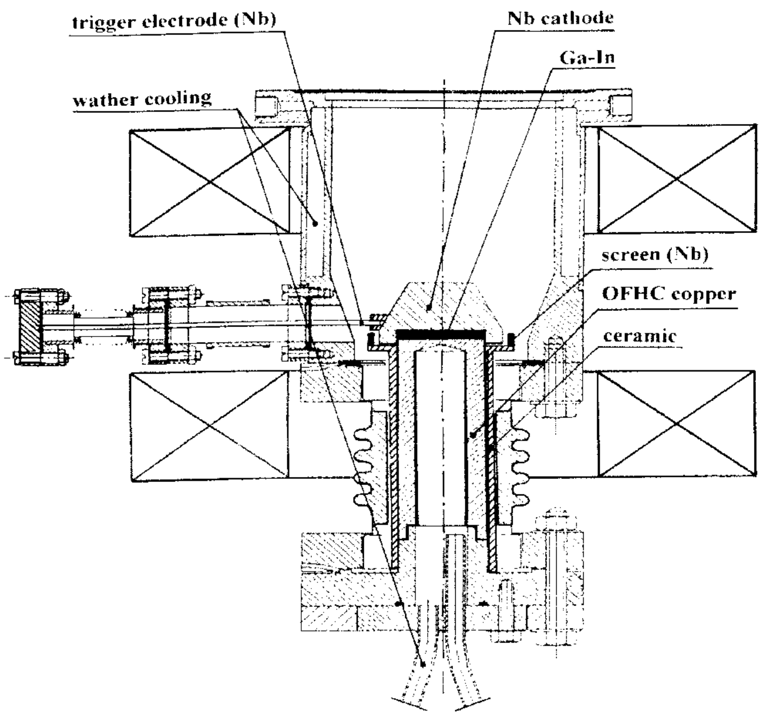
Close association with **resulting RF surface impedance & superconducting** properties (λ, Δ, T_c, H_c, RRR)

Plasma Arc (ARCO-INFN/Soltan Institute)

- **In the plasma arc an electric discharge is established directly onto the Nb target, producing a plasma plume from which ions are extracted and guided onto the substrate by a bias and/or magnetic guidance**
- **Magnetic filtering (and/or arc pulsing) is also necessary to remove droplets**

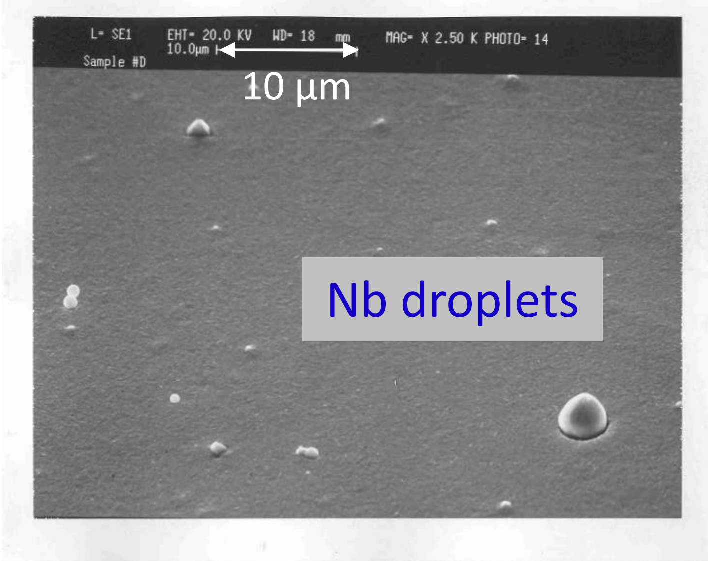


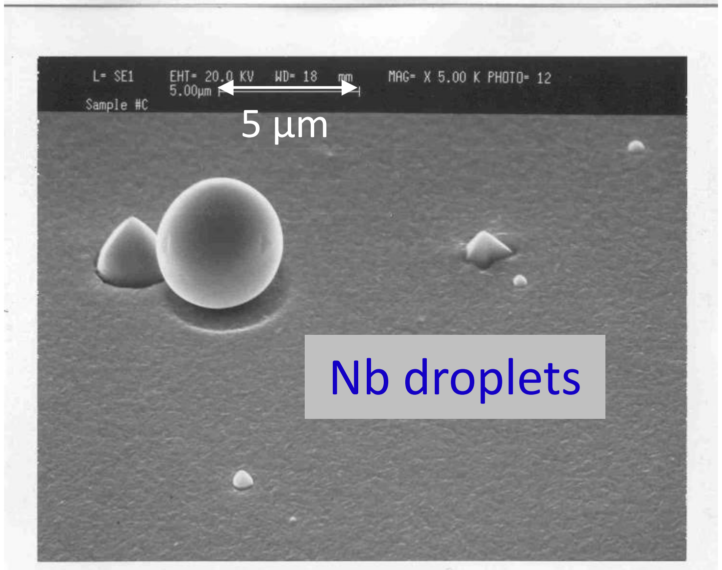
- A trigger for the arc is necessary: either a third electrode, or a laser
- Arc spot moves on the Nb cathode at about 10 m/s
- Arc current is 100-200 A
- Cathode voltage is ~ 35 V
- Ion current is 100-500 mA on the sample holder (2-10 mA/cm^2)
- Base vacuum ~ 10^{-10} mbar
- Main gas during discharge is Hydrogen (~ 10^{-7} mbar)
- Voltage bias on samples 20-100 V

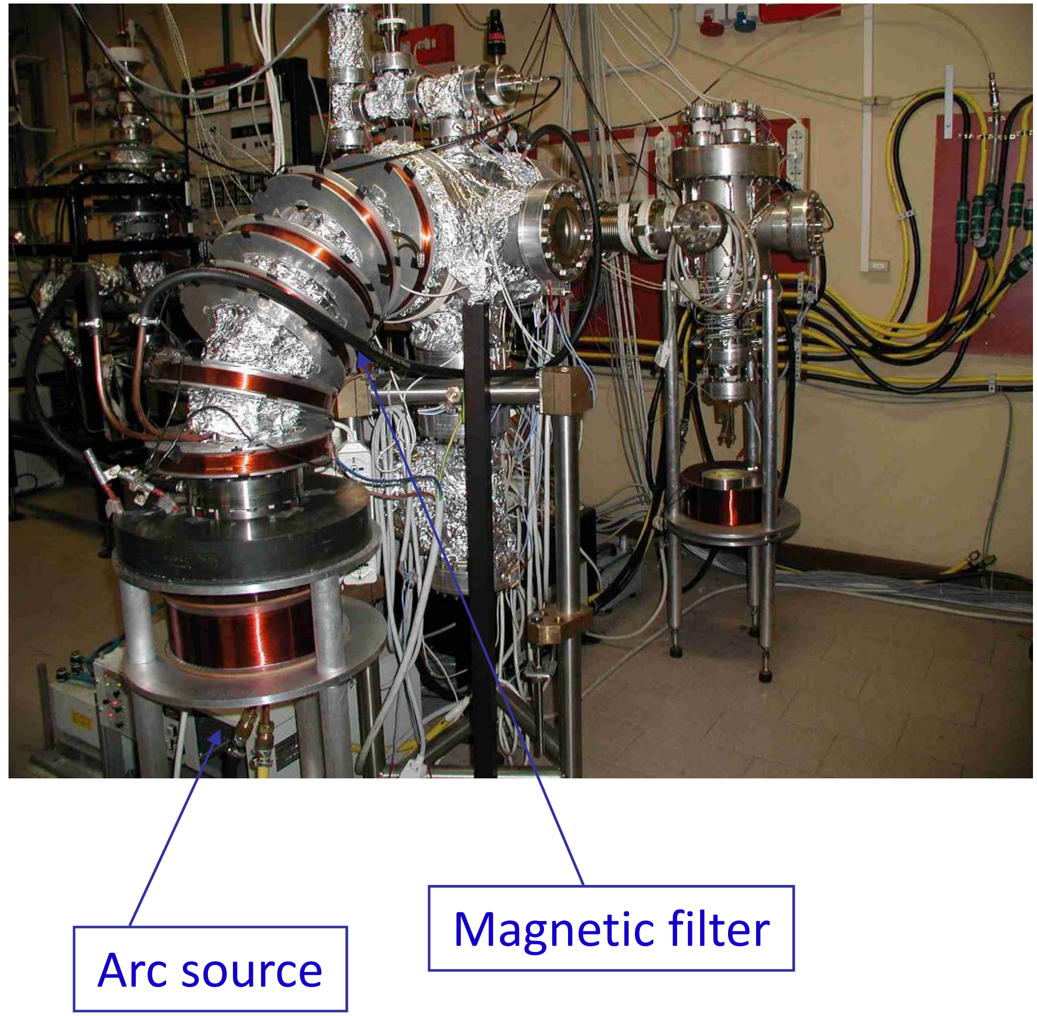


From: R. Russo, A. Cianchi, S. Tazzari

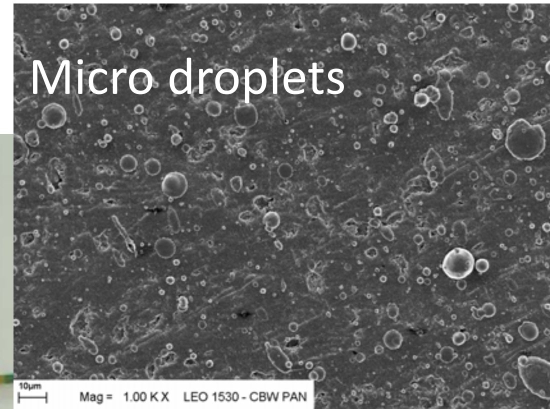
Plasma Arc – Presence of macro-particles

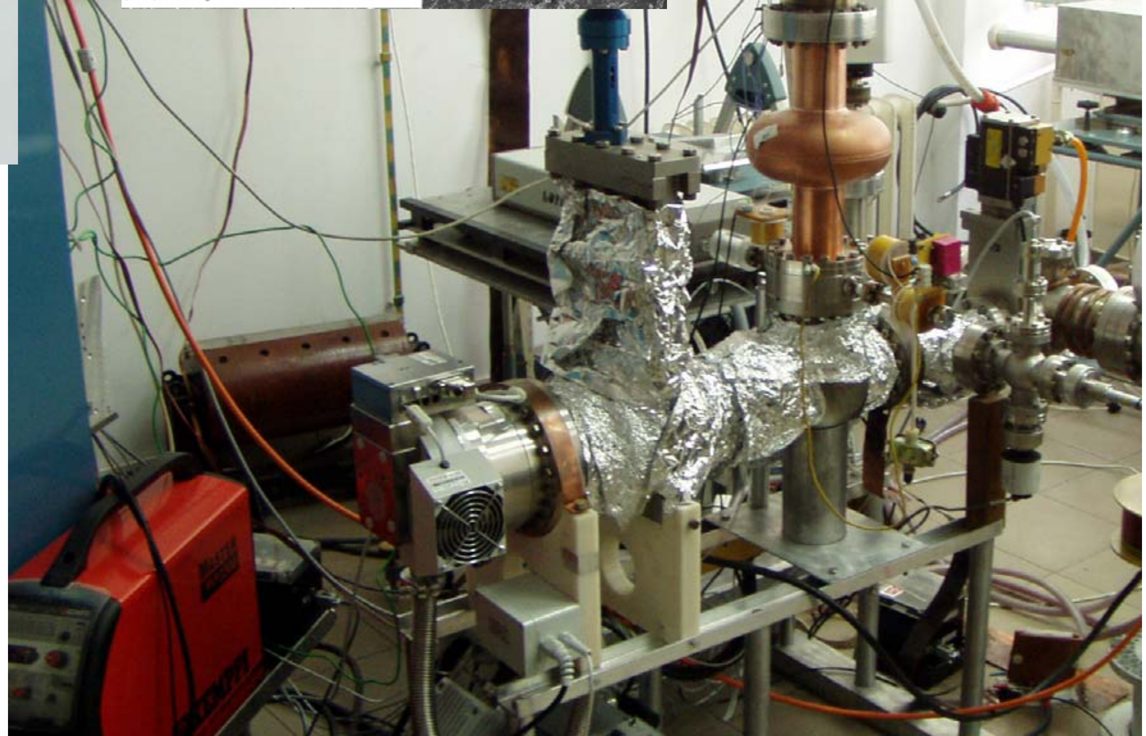






Thin Film Cavity Production





Linear arc coating at
IPJ Swierk

Planar arc – RF measurements on samples

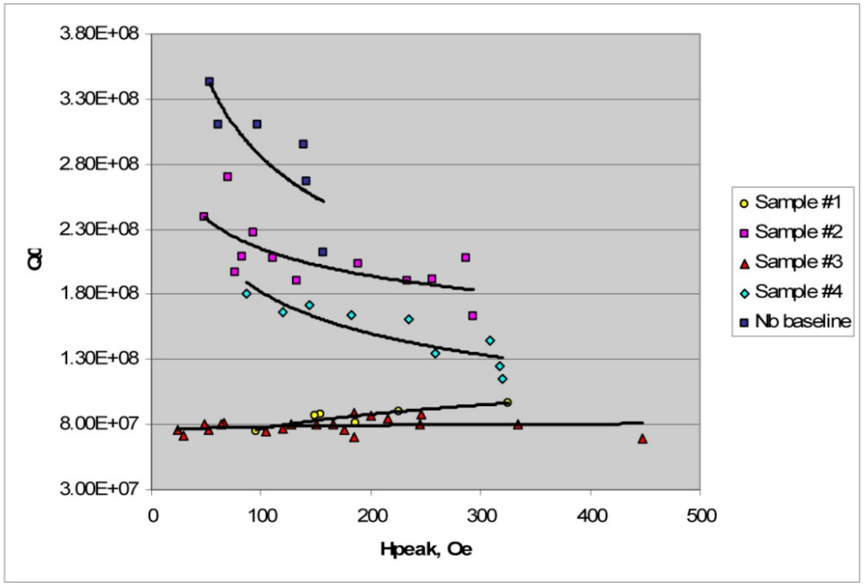


Figure 5: Q_0 versus peak magnetic field for different Nb/Cu end plates and a bulk Nb end plate.

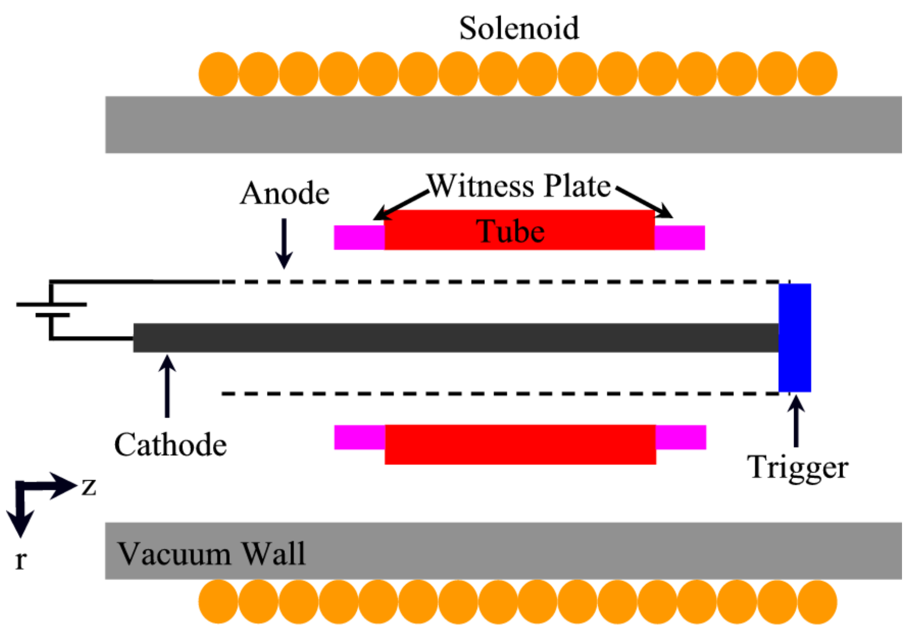
Cu samples with Nb ARC-coating. Used as a base plate of 6 GHz cavity operating in the TE011 mode. At low field, the surface resistance is in the range 3-6 $\mu\Omega$ as compared to the BCS Rs of 0.22 $\mu\Omega$ at 2.2 K and small mean free path. The Q remained constant up to a field of 300 Oe.

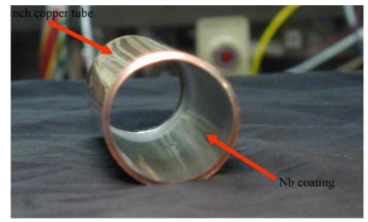
A baseline of 2.2 $\mu\Omega$ is measured with this cavity with a solid Nb plate

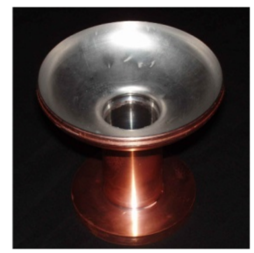
A. Romanenko and H. Padamsee, Proc. SRF2005, Cornell, USA, 2005

Coaxial Energetic Deposition™ (CED)

Alameda Applied Science Corporation

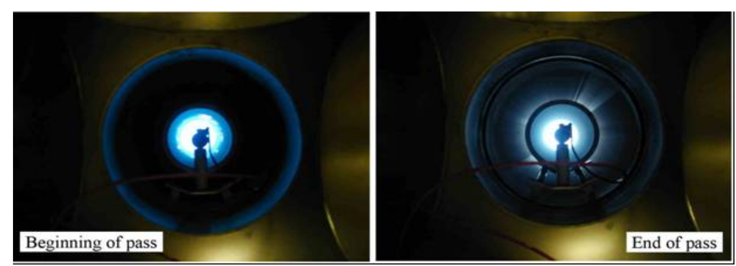






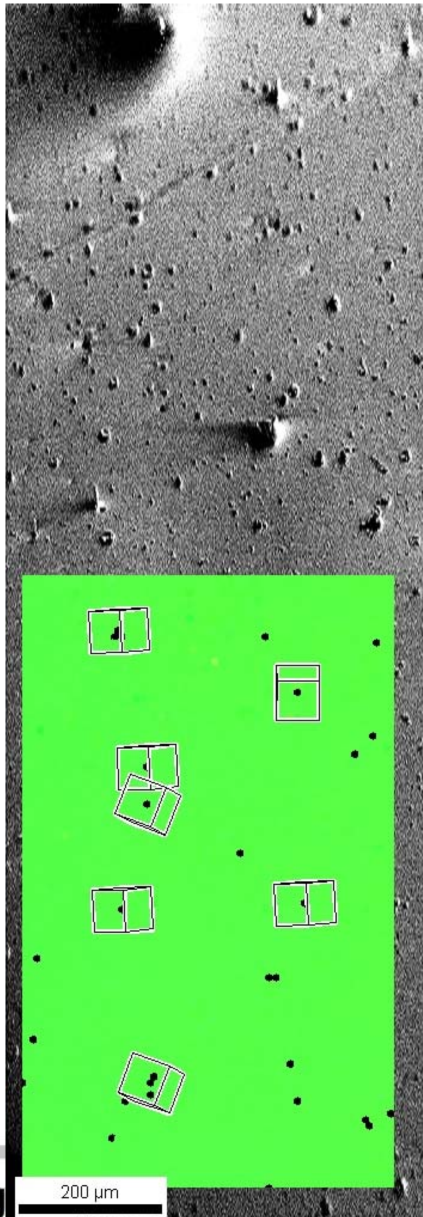
- Cathode: 60 cm conducting rod (1 cm dia).
- Anode: 45 cm Mo mesh tube (4.5 cm ID)
- Substrate: 5 cm ID minimum for this configuration
- Solenoid: **B** ranges from 0-10 mT in z^+ or z^- direction.

Note: Anode does not collect all the arc current. Mesh spacing is much larger than Debye length. Current is measured between the power supply and cathode through known resistor.



Rotating arc moves down the axis of a 4”ϕ tube

CED Films structure



Substrate Al_2O_3 (11-20)
T = **300^0**

Tc = 9.25K
RRR=131

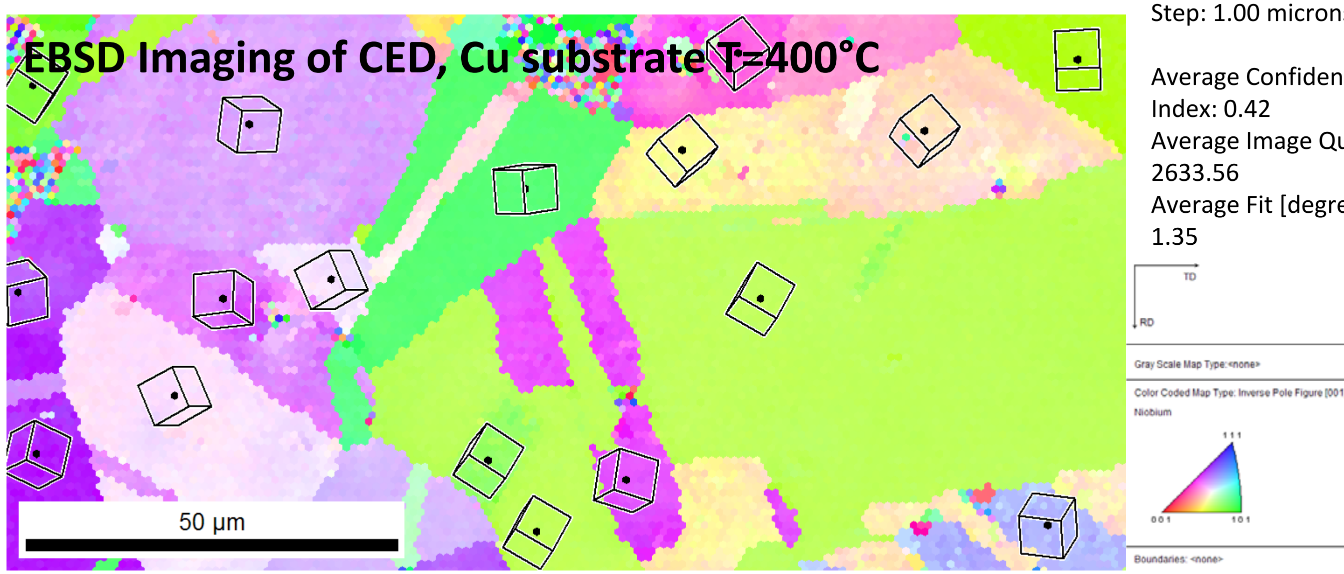
CED Nb Thin Film on a Polycrystalline Cu substrate
Demonstrated Feature of Heteroepitaxy

Working Distance: 15.000000

Number of points: 13094
Number of good points: 13093

150.00 microns x 74.48 microns
Step: 1.00 microns

Average Confidence Index: 0.42
Average Image Quality: 2633.56
Average Fit [degrees]: 1.35

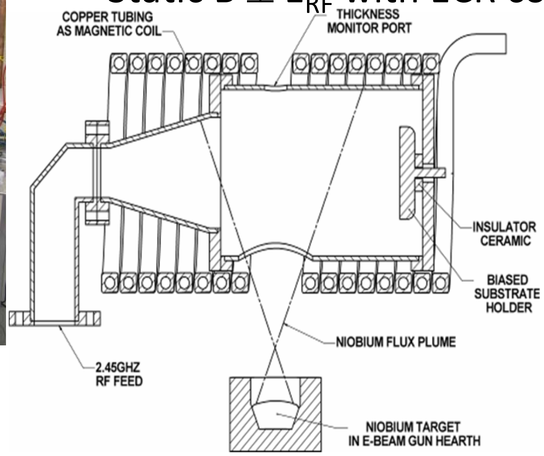


Jefferson Lab

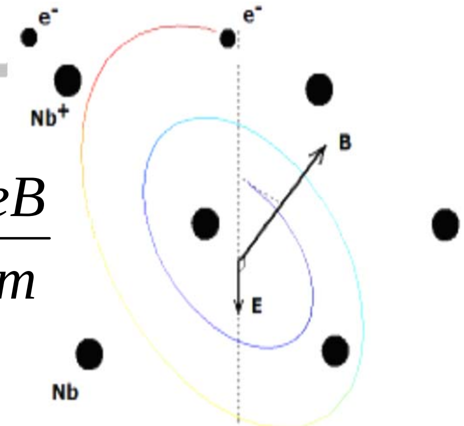
Energetic condensation with ECR

Generation of plasma - 3 essential components:

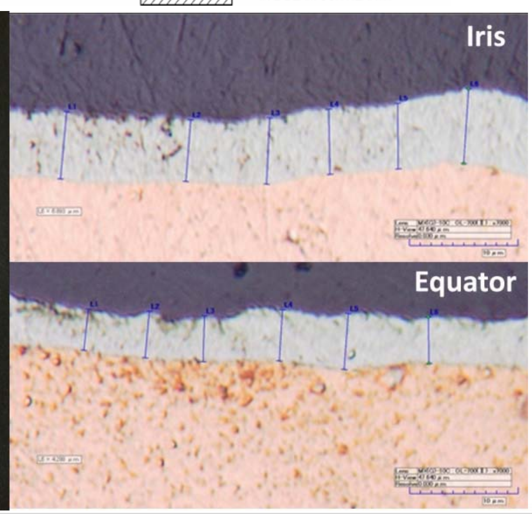
- Neutral Nb vapor
- RF power (@ 2.45GHz)
- Static B ⊥ E_{RF} with ECR condition



$$\omega = \frac{eB}{m}$$



- No working gas
- **Ions produced in vacuum**
- Singly charged ions **64eV**
- **Controllable deposition energy with Bias voltage**
- Excellent bonding
- No macro particles
- Good conformality

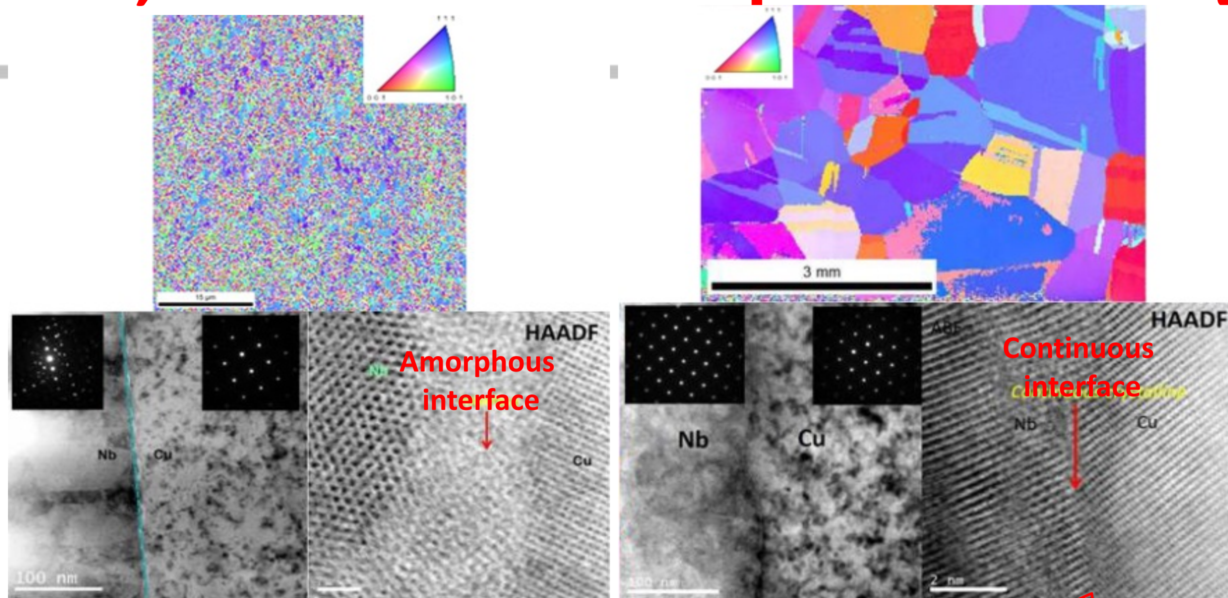


Conformality of the ECR process:

the film thickness along a 3GHz half-cell profile varies from 4mm (equator) to 6mm (iris)

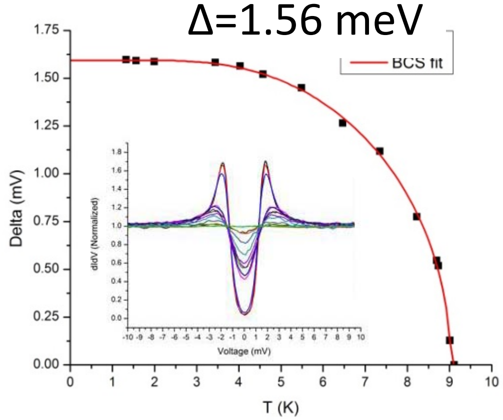
Note: the substrate is very rough, was only grossly mechanically polished

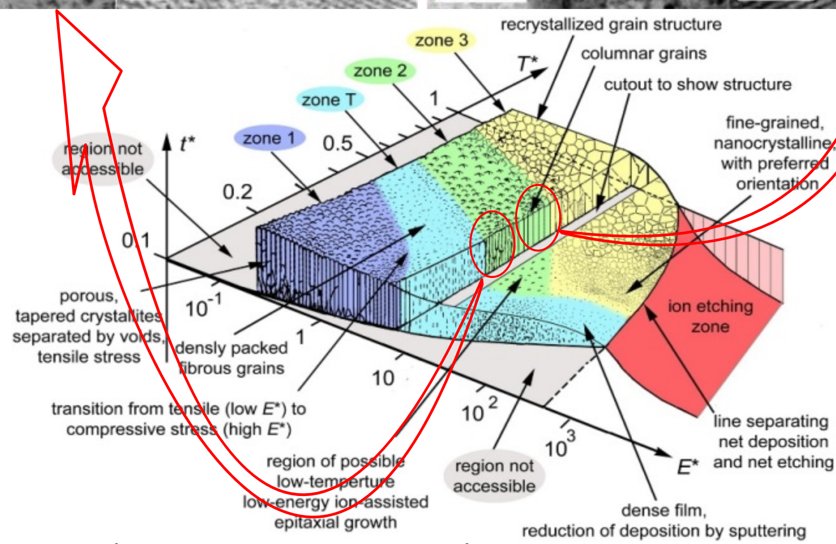
Structure, interface and superconducting gap



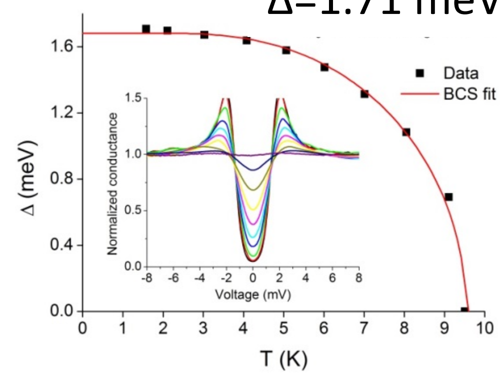
Gap measurements performed by PCT (point contact tunneling spectroscopy - T. Proslier)

Δ=1.56 meV





Δ=1.71 meV



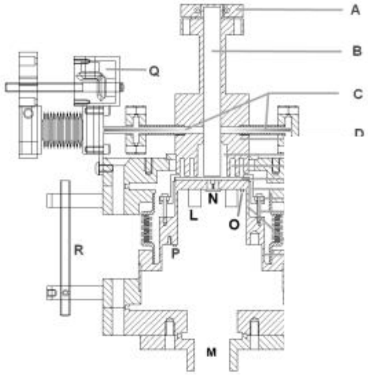
Superconducting gap (1.56-1.62meV) **similar to bulk Nb** ($\Delta_{Nb\ bulk}$ =1.55meV measured on the same setup) for hetero-epitaxial ECR Nb films on polycrystalline Cu.

Tailored Nb films via energetic condensation

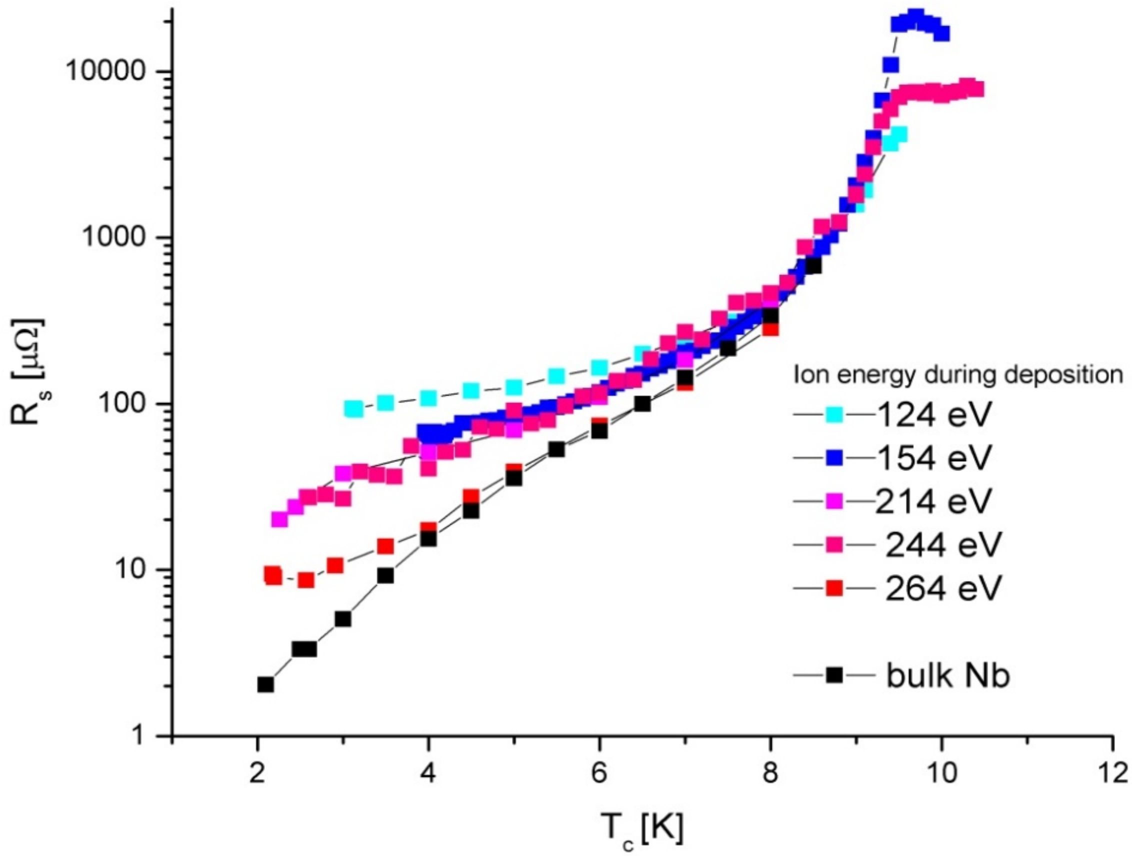
- Tune thin film structure and quality with ion energy and substrate temperature on a variety of substrates (amorphous, polycrystalline and single crystal)
- Achieve film structures and properties only achievable at higher temperature with classic coating methods
- Tune RRR values from single digits to bulk Nb values →No intrinsic limitations
- Lower impurity (H) content than bulk Nb
- Good adhesion to the substrate (delamination threshold determined as function of ion energy and temperature)
- Grain boundaries not necessarily detrimental (if dense) to R_s
- Tailoring interface with high energy and subsequent growth at energy minimizing defect creation can contribute to lower R_s

		Substrate	RRR_{max}
Insulating	Single crystal	a-Al_2O_3	488
		r-Al_2O_3	641
		c-Al_2O_3	247
		MgO (100)	188
		MgO (110)	424
		MgO (111)	270
	Polycrystalline amorphous	Al_2O_3 ceramic	135
		AlN ceramic	110
		Fused Silica	84
Metallic	Single crystal	Cu (100)	181
		Cu (110)	275
		Cu (111)	245
	Polycrystalline	Cu fine grains	193
		Cu large grains	305

Influence of ion energy on surface resistance



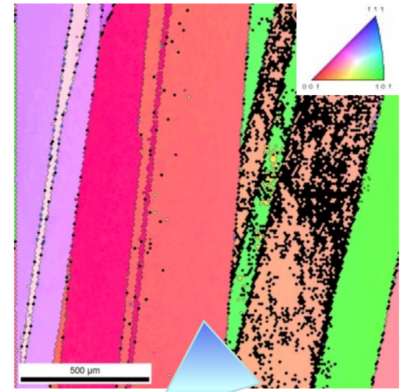
Growth at continuous energy (360 °C)

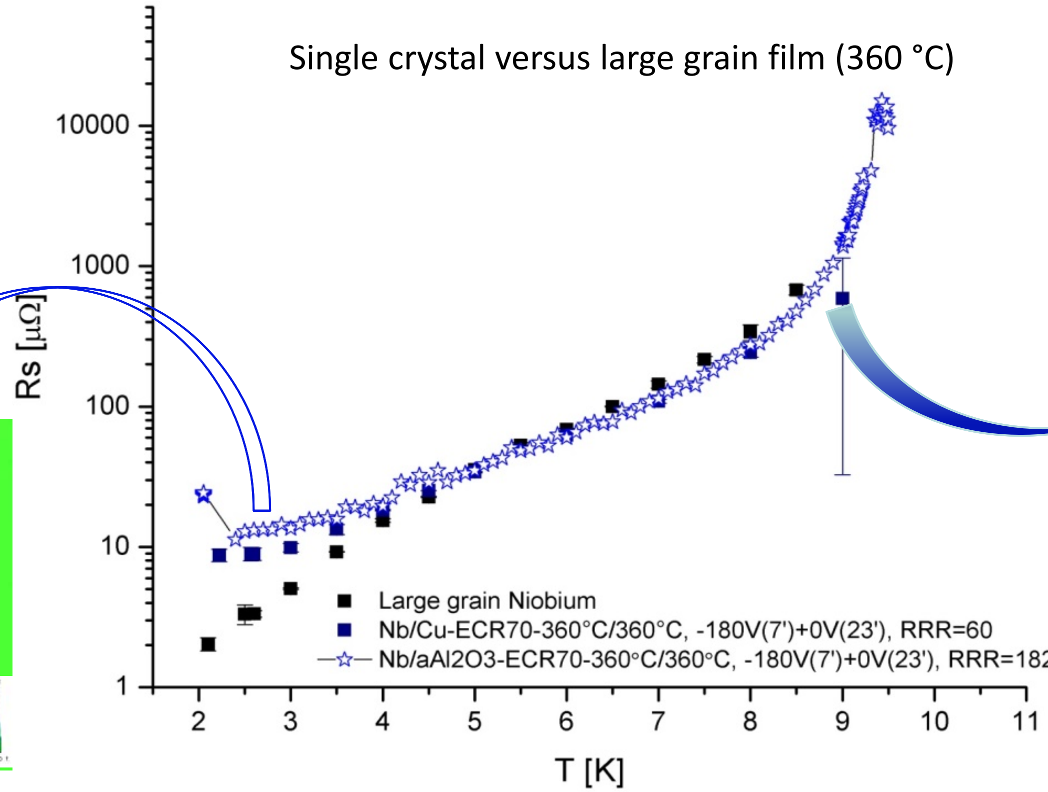


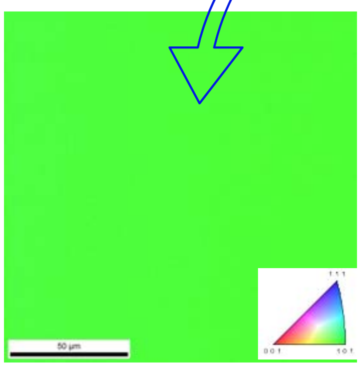
Decrease of R_s with increasing incident ion energy

ECR Nb/Cu – surface resistance

Polycrystalline Nb







Nb single crystal (110)

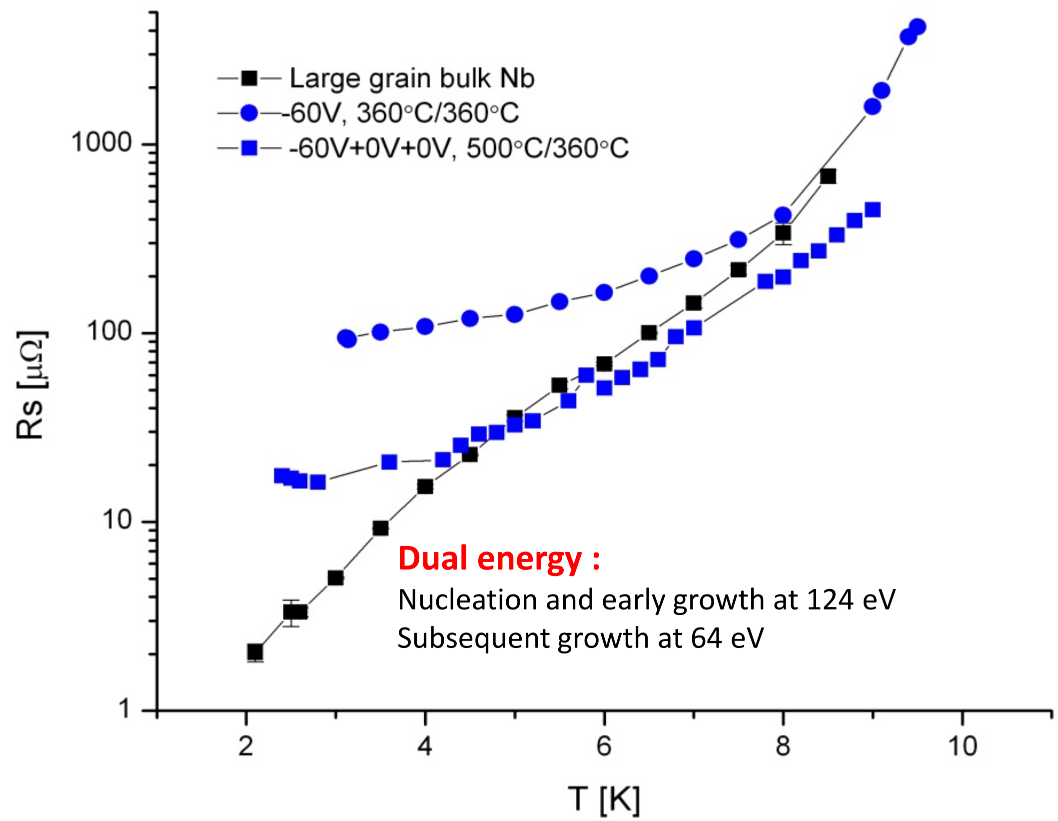
If dense, grain boundaries not necessarily detrimental to RF performance

ECR Nb/Cu – Surface resistance

Approach: 3 sequential phases for film growth

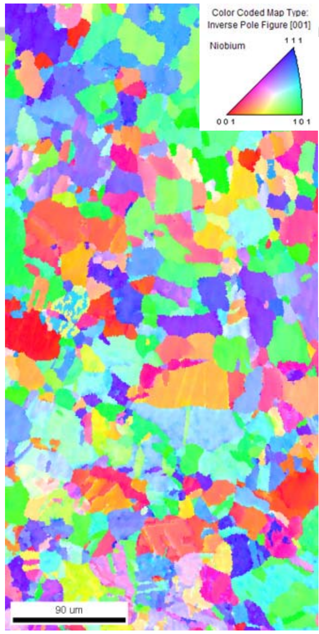
- Film nucleation on the substrate (Nb, Al_2O_3, Cu; single crystal, polycrystalline, amorphous)
- Growth of an appropriate template for subsequent deposition
- Depositi ne final surface optimize inimum defect density.

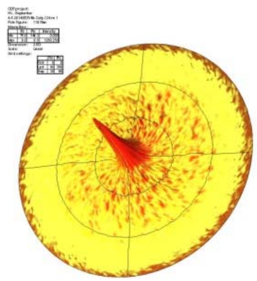
- **Film nucleation on the substrate**
- **Subsequent Growth**

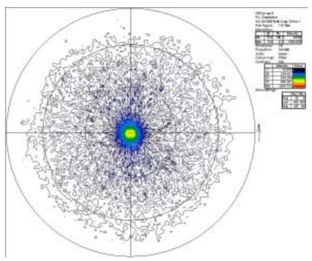


Addressing the film deposition in 2 phases (nucleation @ high energy, subsequent growth @ 64 eV) shows some improvement in R_s

ECR Nb/Cu– Surface resistance







Bake & coating temperature: 360 °C

Coating with dual ion energy: 184 eV for nucleation/early growth
64 eV for subsequent growth

Hetero-epitaxial film Nb on OFHC Cu

Tc= 9.36 ± 0.12 K

RRR = 99 (witness sample, 179 for Nb/a-Al_2O_3)

EBSD IPF map and XRD pole figure show very good crystallinity and grain sizes in the range of the typical Cu substrate

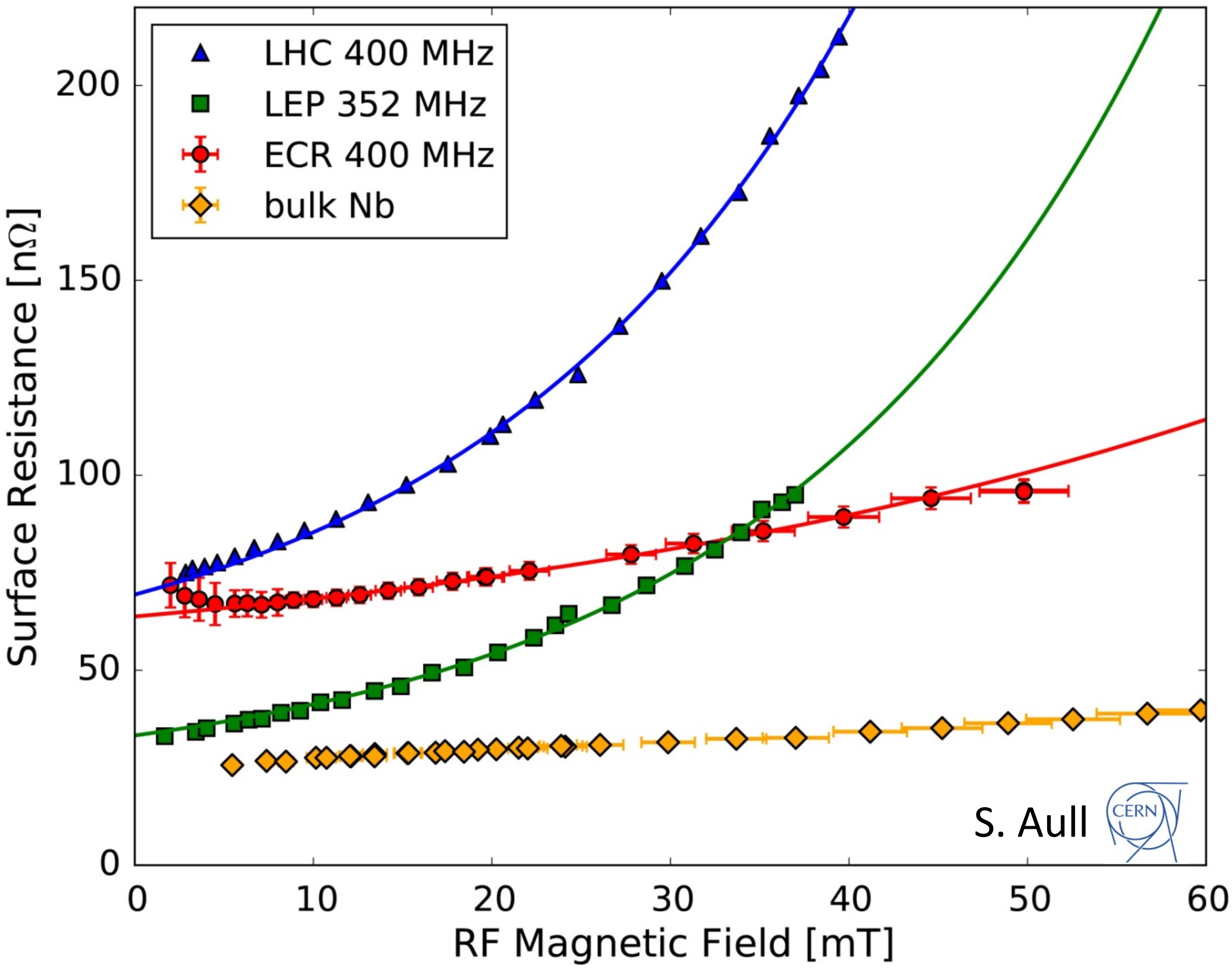
	R_{res} [nΩ]	λ(0K) [nm]
400 MHz	46.6 ± 0.8	40 ± 2
800 MHz	79 ± 2	38 ± 1
1200 MHz	156 ± 11	38 ± 1

ℓ^* [nm]	RRR
144 ± 20	53 ± 7

* with λ_L = 32 nm and ξ_0 = 39 nm

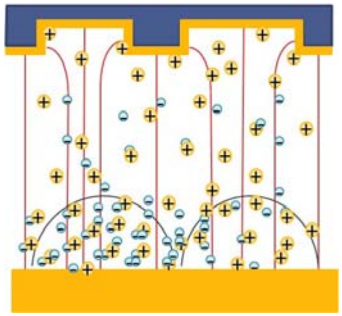
Nb film in the clean limit

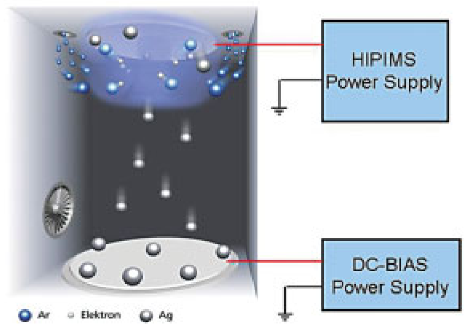
Comparison with Sputtered Nb/Cu and bulk Nb

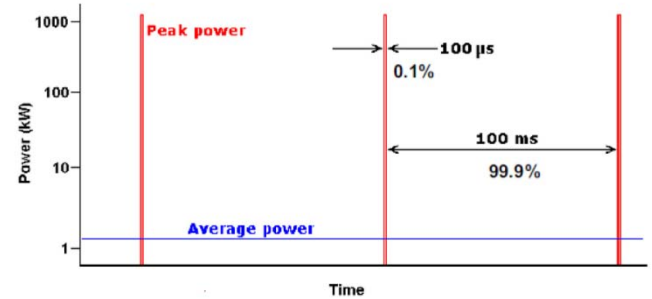


HiPIMS

High power impulse magnetron sputtering (HiPIMS) is an emerging technology





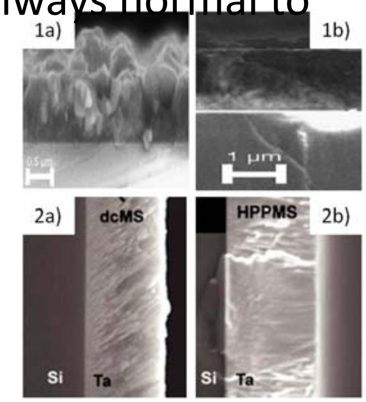


Use of High Power Impulse Magnetron Sputtering (HiPIMS) for Nb coating with enhanced properties

The target material is partly ionized such that the ions will reach the substrate with a higher energy and, in case of an applied bias voltage to the substrate, always normal to the surface.

- very high purity
- better adhesion
- better (normal) conductivity,
- Large crystal grains, low defect density
- dense & smooth films

Homogeneous coating even on non-flat surfaces

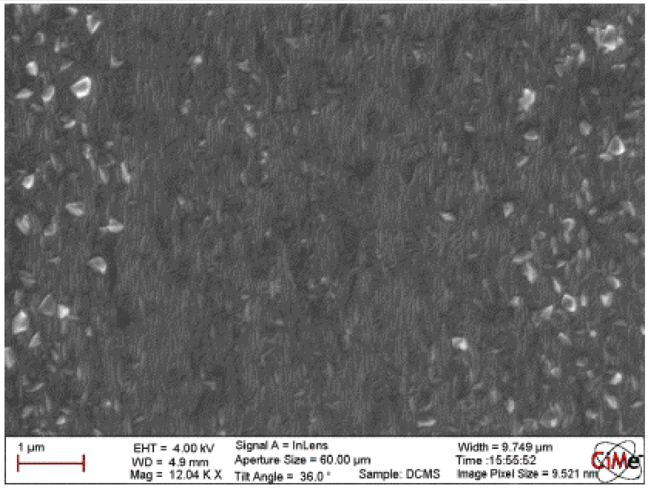


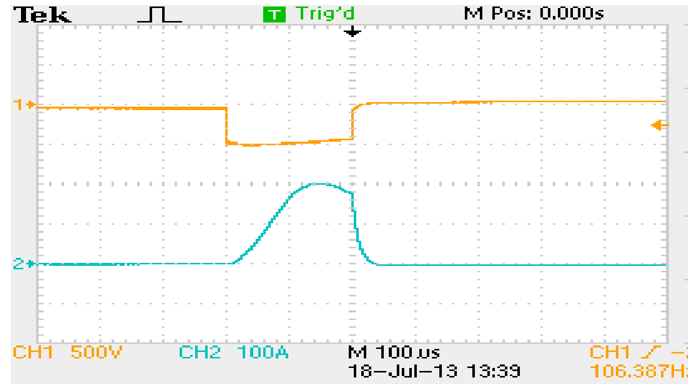
NEW METHODS FOR THIN FILM DEPOSITION AND FIRST INVESTIGATIONS OF THE USE OF HIGH TEMPERATURE SUPERCONDUCTORS FOR THIN FILM CAVITIES

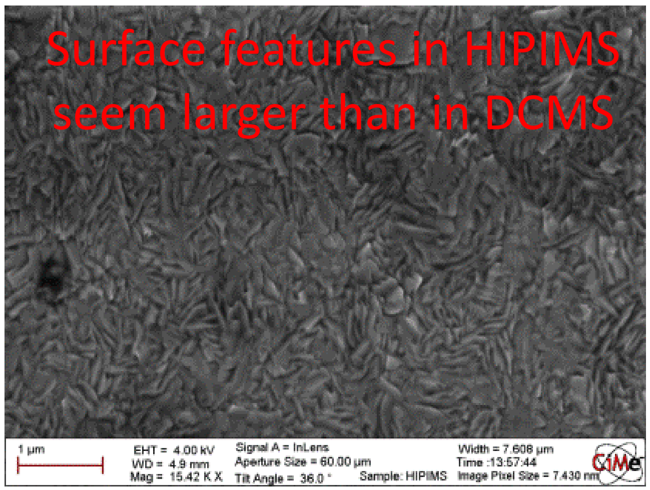
A. Gustafsson *et al., CERN (WEPEC047)*

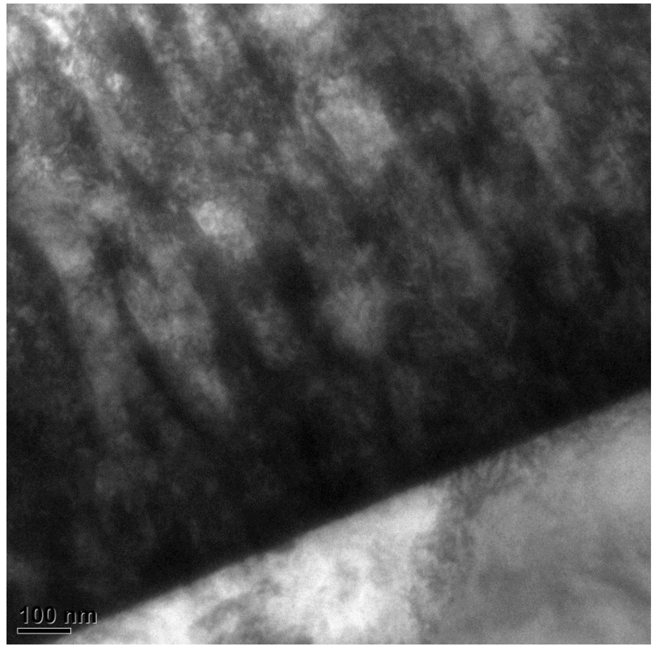
Nb films – Energetic condensation with HiPIMS

CERN (G. Terenziani, S. Calatroni, T. Junginger)
Sheffield-Hallam University (A.P. Ehisarian)

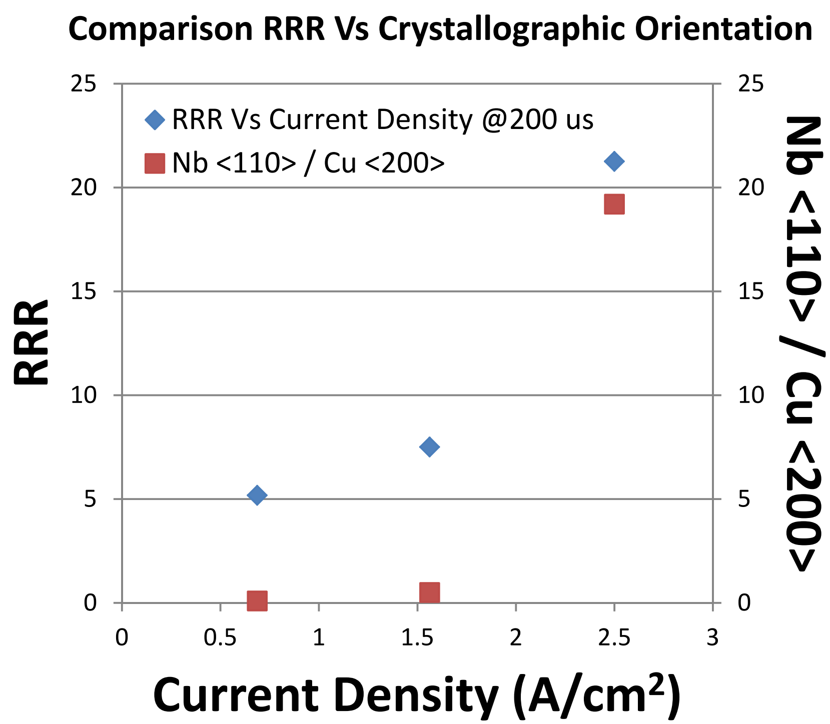


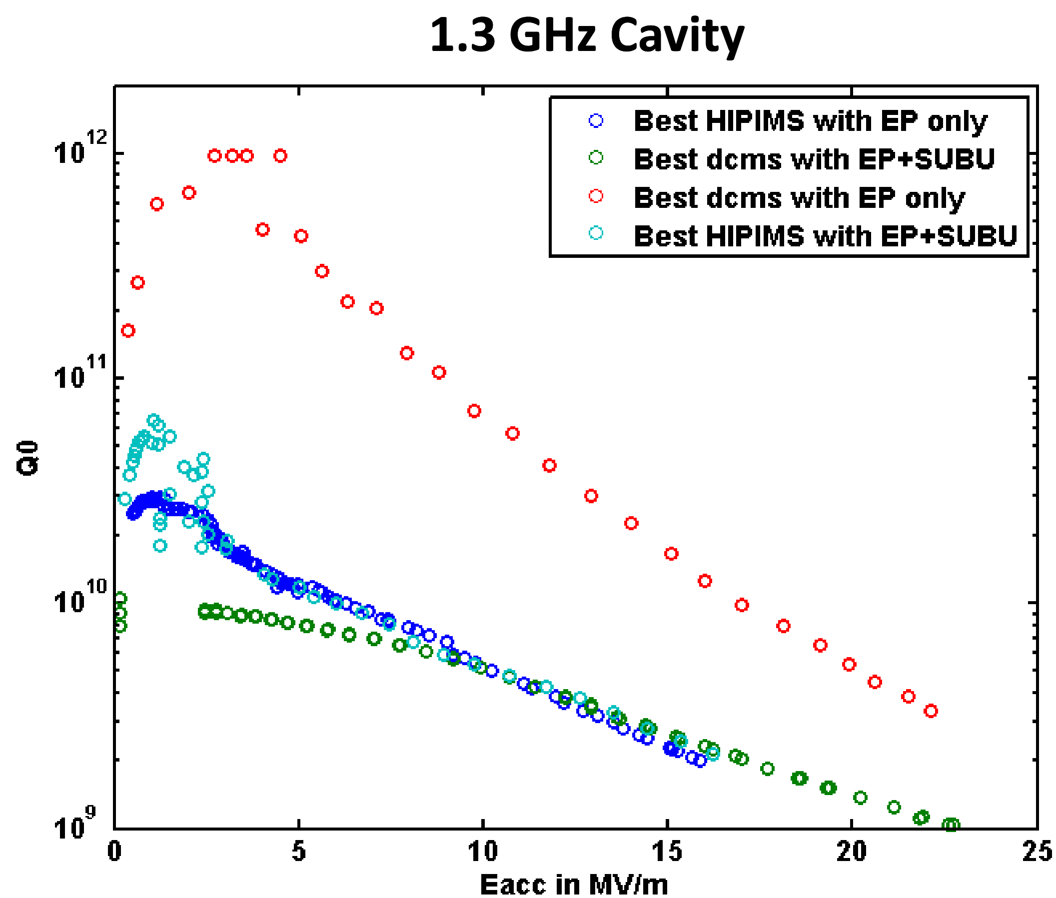






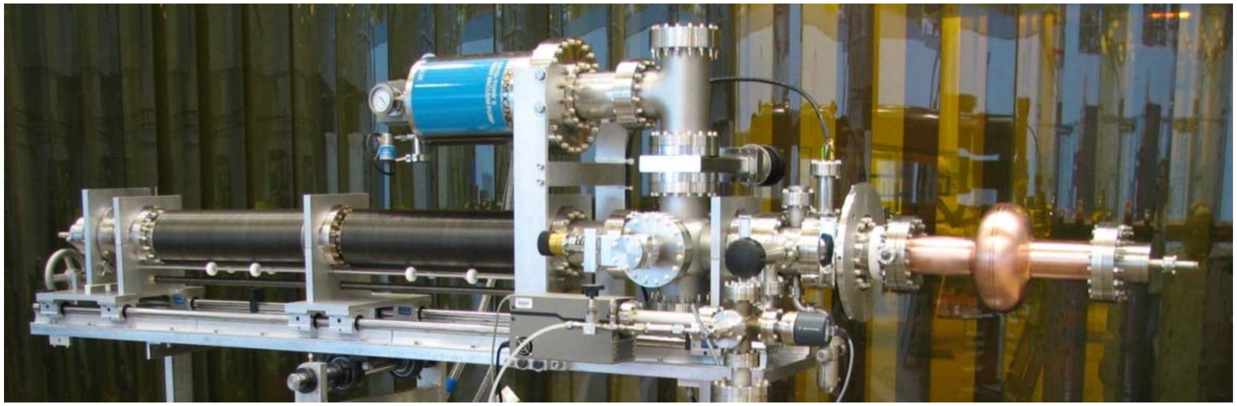
Nb films – Energetic condensation with HiPIMS



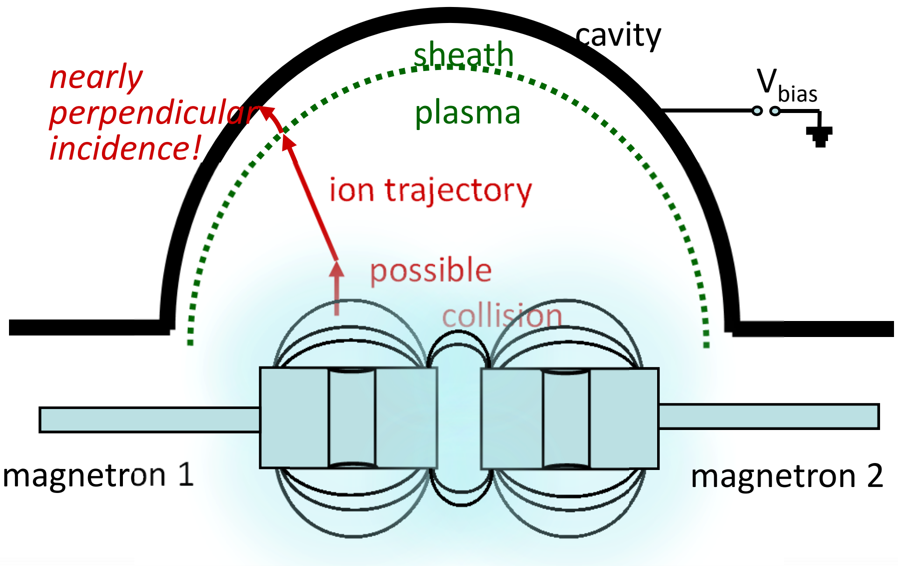


Nb films – Energetic condensation with HiPIMS

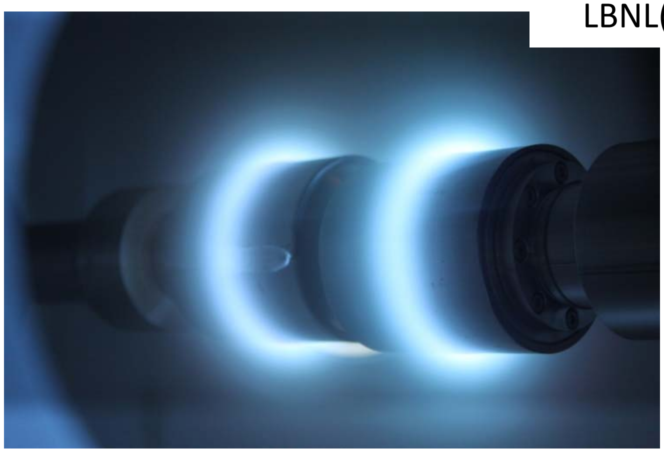
HiPIMS cylindrical coating system for single cell under commissioning



HiPIMS dual magnetron system Most effective for Biasing & influencing Ion Energies & Trajectories



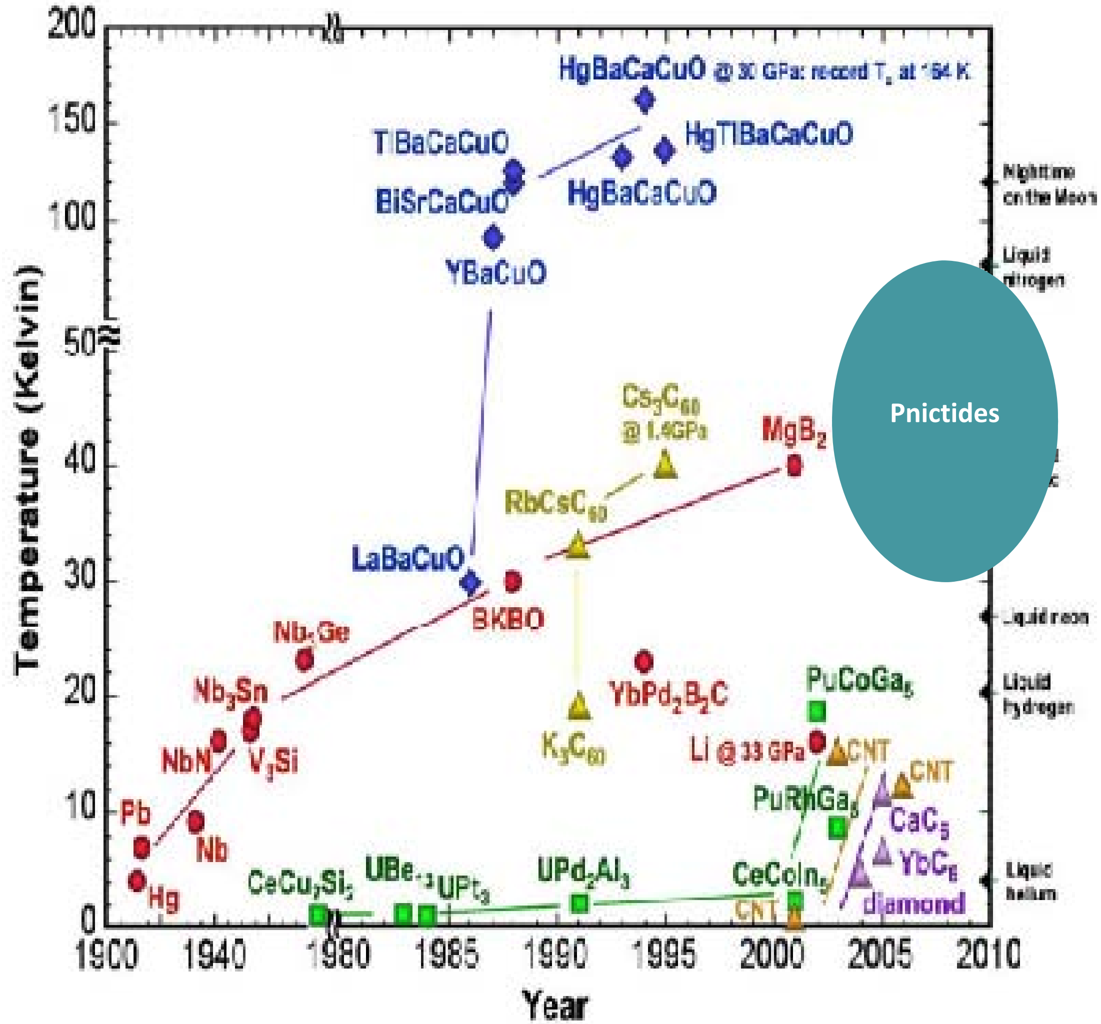
LBNL(A. Anders)



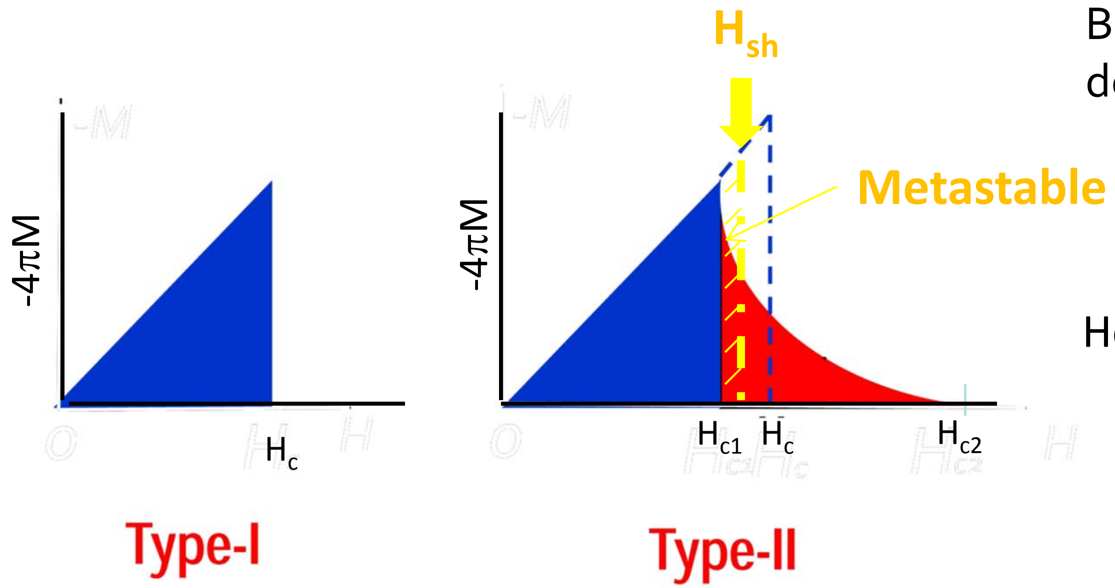
- high power mode (above runaway threshold)
- Dominated by niobium emission

Which materials are suitable for SRF cavities?

Highest T_c=164 K (under GPa)



Critical Field



Boundary between Type I and Type II determined by the Ginzburg-Landau parameter

$$\kappa = \lambda/\xi$$

Hc is the thermodynamic critical field
&
$H_c = H_{c2}/\sqrt{2}\kappa$
(for type-II superconductors).

- Meissner state at $0 < H < H_{c1}$
- Mixed vortex state at $H_{c1} < H < H_{c2}$
- Exponentially small R_s at $H < H_{c1}$ ($Q = 10^{10}$-10^{11})
- Drastic Q drop due to vortex dissipation at $H > H_{c1}$

The superheating field H_{sh} is the field up to which the Meissner state metastably persists above H_{c1}
For type-II superconductors, at T = O in the clean limit with a Gindzburg-Landau parameter $\kappa=\lambda/\xi \gg 1$, H_{sh} has been calculated to be ~ $0.75H_c$.

$H_{RFcrit} \approx H_{sh}$

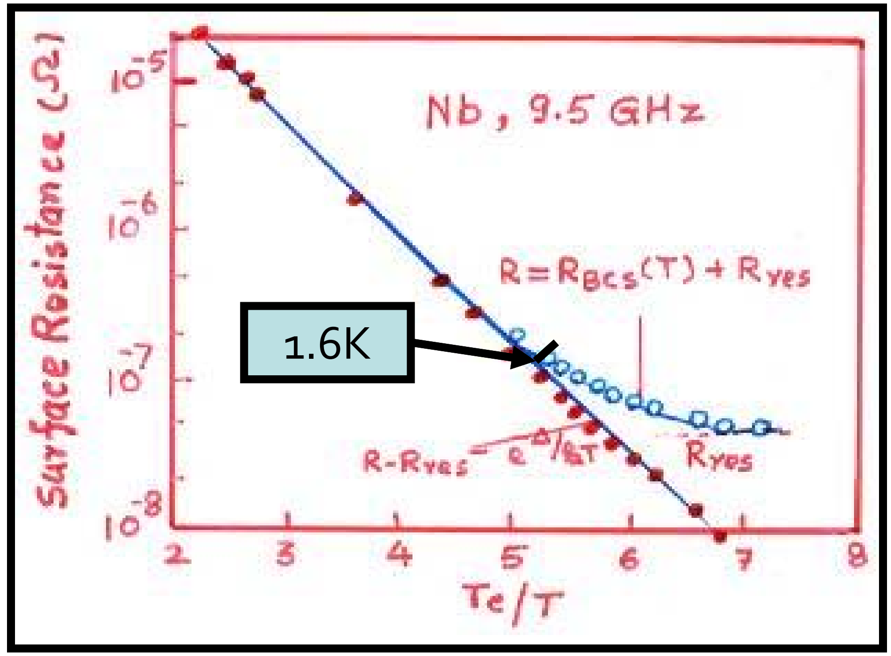
Surface Resistance

The power dissipated per unit area of SC in RF regime $P = R_S \cdot \frac{H^2}{2}$

and

Surface Resistance

$$R_S = R_{BCS}(T) + R_{res}$$



V. Palmieri, 10th Workshop on RF Superconductivity Proceedings, Tsukuba 2001 (Noguchi)
"New materials for superconducting radiofrequency cavities"

BCS Surface Resistance R_{BCS}

If **T < T_c / 2, for dirty limit superconductors**

$$R_{BCS} \cong \frac{R_n}{\sqrt{2}} \left(\frac{\eta \omega}{\pi \Delta} \right)^{\frac{3}{2}} \frac{\sigma_1}{\sigma_n} = A \sqrt{\rho_n} \; e^{-\frac{\Delta}{K_B T}} \left(1 + O(\Delta, \omega, T) \right)$$

A constant weakly dependent on material

ω = RF frequency

ρ_n = Normal State conductivity

Δ = Superconducting gap

T_c = Transition Temperature

dependence on ρ_n and T_c represents an immediate criterion for selecting the most favorable candidates for cavities

The higher Tc (= 0.57Δ), the smaller the BCS surface resistance

Material with high normal state conductivity and high Tc (high superconducting gap Δ)should be selected

Residual Resistance R_{res}

Temperature independent

Contributions to residual losses:

Intrinsic:

Inhomogeneties, Metallic Inclusions within l, Grain Boundaries, Oxides

Extrinsic:

Trapped Flux during cooling (can be avoided)

Variety of phenomena involved ➡ Not one formula predicting R_{res}

From literature

Empirically, R_{res} found proportional to at least $\sqrt{\rho_n}$

For two materials with the same R_{BCS} and different T_c and ρ_n,
the one with the smallest ρ_n should have the smallest R_{res}

Metallic behaviour is favored

Criteria of choice

THERE IS NO IDEAL SUPERCONDUCTOR FOR CAVITY

CHOICE IS BASED ON COMPROMISE

For low RF losses ⇒ **high T_C**

Metallic behavior in the normal state , small r_n

For high gradients ⇒ **High H_{sh}, H_c; small k**

Possible Choices among Superconducting Materials

Material	T_c [K]	ρ_n(μΩcm)	H_c(0) [T]	H_{c1}(0) [mT]	H_{c2}(0) [T]	λ(0) [nm]	Δ [meV]	Type
Nb	**9.22**	**2**	**0.2**	**180**	**0.28**	**40**	**1.55**	II
Pb	**7.2**		**0.08**	**N/A**	**N/A**	**48**		I
NbN	**16.2**	**70**	**0.23**	**20**	**15**	**200**	**2.6**	II, B1 comp.
NbTiN	**17.5**	**35**		**30**	**15**	**151**		II, B1 comp.
Nb_3Sn	**18**	**20**	**0.54**	**50**	**30**	**85**	**3.1**	II, A15
V_3Si	**17**				**24.5**	**179**		II, A15
Mo_3Re	**15**		**0.43**	**30**	**3.5**	**140**		II, A15
MgB_2	**40**	**0.1-10**	**0.43**	**30**	**3.5-60**	**140**	**2.3; 7.2**	II- 2 gaps
Pnictides	**30-55**		**0.5-0.9**	**30**	**>100**	**200**	**10-20**	
YBCO	**93**		**1.4**	**0.01**	**>100**	**150**	**20**	d-wave

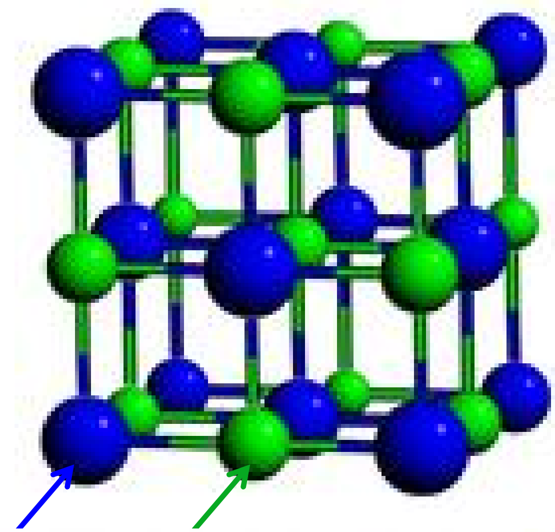
Large gap Δ (good for SRF) is usually accompanied by low H_{c1} (bad for SRF)

$$R_s = \mu_0^2 \sigma_n \lambda^3 \omega^2 \frac{\Delta}{kT} \ln\left(\frac{9kT}{4\hbar\omega}\right) e^{-\Delta/kT}$$

d-wave high-T_c cuprates with nodal gap and $R_s \propto T^s, \quad s \simeq 2-3$ are not useful for SRF

B1 compounds – NaCl structure

Metallic atoms A form an fcc lattice
Non-metallic atoms B occupy all the octahedral interstices.

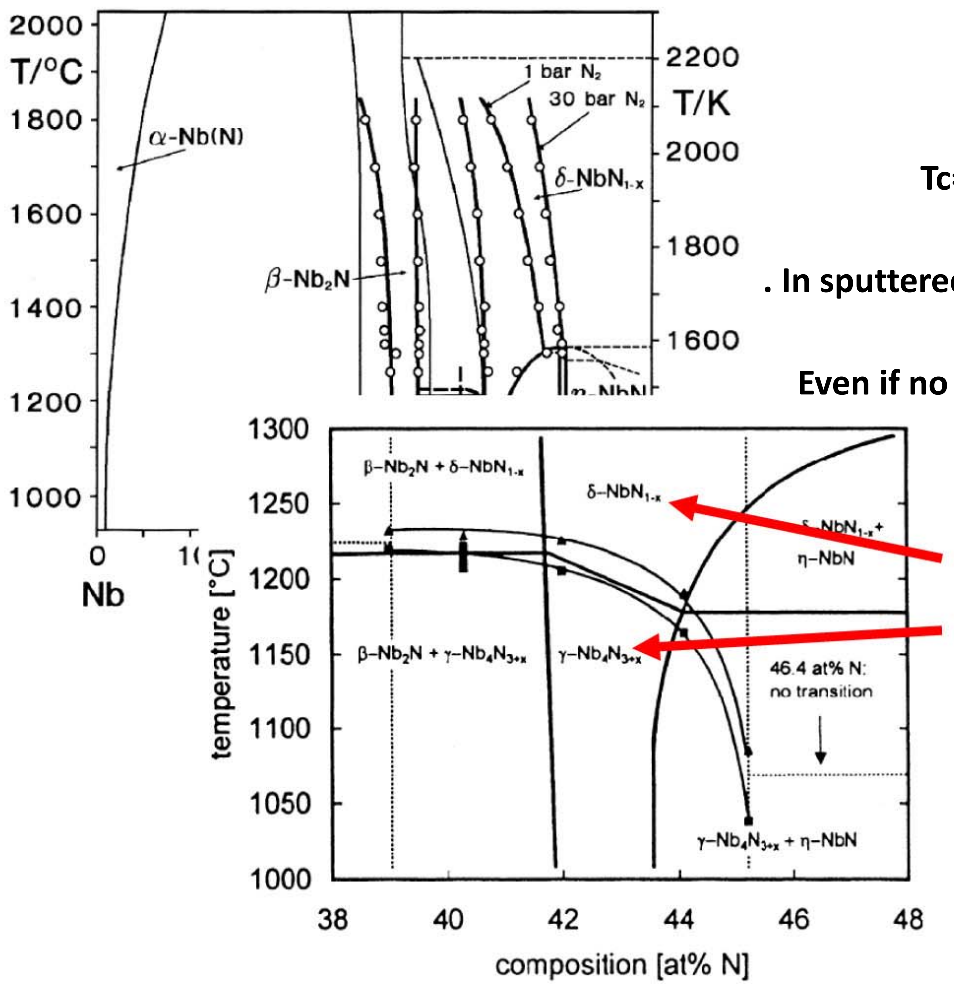


NB COMPOUNDS

B \ A	Sc	Y	La	Ti	Zr	Hf	V	Nb	Ta	Cr	Mo	W	Re
B					3.4	3.1							
C	<1.38	<1.38		3.42	<0.3	<1.20	0.03 3.2*	12	10.35		14.3	10.0	3.4
N	<1.38	<1.4	1.35	5.49	10.7	8.83	8.5	17.3	6.5	<1.28	5.0	<1.38	
P			<1.68										
Sb		<1.02	<1.02										
O				2.0			<0.3	1.39					
S	<0.33	1.9	0.87		3.3								
Se	<0.33	2.5	1.02										
Te		2.05	1.48										

* T_c = 3.2 K was registered in vanadium carbide after implantation of C^+ ions

NbN phase diagram



Good SC properties, even if deposited at low temperature
Low secondary emission coefficient
Very stable surface properties

The right B1-NbN superconducting phase is the so-called δ-phase

Tc= 17.2 K for δ-phase (lattice parameter = 4.388 Å)
***T_C* very sensitive to Nitrogen stoichiometry**

. In sputtered films, the δ -phase can be found mixed to some other low *T_C* phases

Even if no grain boundaries are present and δ-phase single crystal is considered the single grain resistivity is not so low.

$$\delta - \mathrm{NbN} \rightarrow T_c \sim 15 - 17.3\ \mathrm{K}$$
$$\gamma - \mathrm{NbN} \rightarrow T_c \sim 12 - 15\ \mathrm{K}$$

Anomalously high resistivity of NbN in the normal state, often higher than 100 μΩcm due to both metallic and gaseous vacancies randomly distributed in both sublattices

Equiatomic composition is $Nb_{0.987}N_{0.987}$ not $Nb_{1.0}N_{1.0}$
Common problem for B1 compounds

Nb Compounds - NbN

The only B1 simple compound that has widely tested for accelerating cavities

Mainly two different techniques have been investigated for this application:

- **Thermal diffusion of N into Nb followed by rapid quench cooling**
- **Reactive Sputtering on metallic or ceramic substrates to Nb cavities**

Thermal Diffusion:

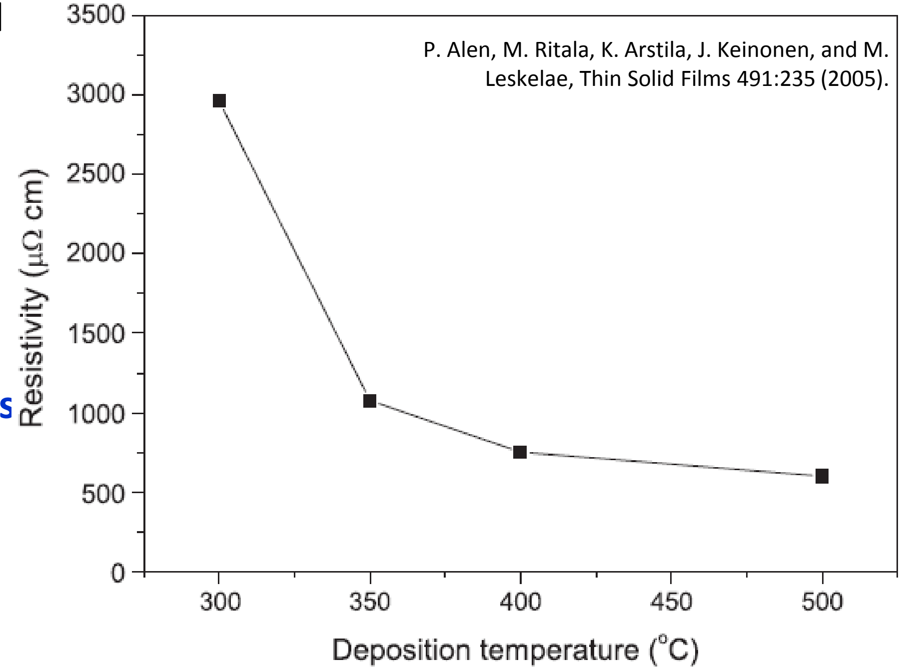
Bulk Nb (RRR 300) annealed @ 1550˚C for 2h

+

reacted in N_2 vapor(150mbar) @ 1400˚C for 4h

Rs=1.3 10^{-6} @ 4.2K and 4 10^{-9} @1.8K @7.9GHz

G.Gemme et al., J.Appl.Phys. 77**(1)**, Jan. 1995



Reactive Sputtering:

Sputtering from high purity Nb target in Ar+ N_2 in DC triode magnetron sputtering system
Highest Tc for substrate temp. > 500˚C, P_{Ar}=8.10^{-3}mbar, P_{N2}=1.10^{-3}mbar

A. Nigro et al., Physica Scripta Vol. 38, 483-485, 1988

Nb Compounds - NbTiN

Ternary Nitride $Nb_{1-x}Ti_xN$

Presence of Ti found to reduce significantly the resistivity
And facilitate formation of a pure cubic structure.
The δ-phase remains thermodynamically stable even at RT.
T_c as high as for good quality NbN, for Nb fraction (1-x)>0.5

extreme hardness, excellent adherence on various substrates, very good corrosion and erosion resistance, high-sublimation temperature, and relative inertness

More metallic nature and better surface properties than NbN should result in better RF performance

Nb Compounds - NbTiN

INFN : reactive sputtering with Ar/N_2 in DC Triode Magnetron Sputtering @ 600˚C and 200˚C

($Nb_{1-x}Ti_x$)N films with 1-x<0.5 present a lower calculated surface impedance, lower critical fields and better surface properties than NbN, especially when deposited at low temperatures.

R. Di Leo et al. J. of Low Temp. Phys, vol 78, n1/2, pp41-50, 1990

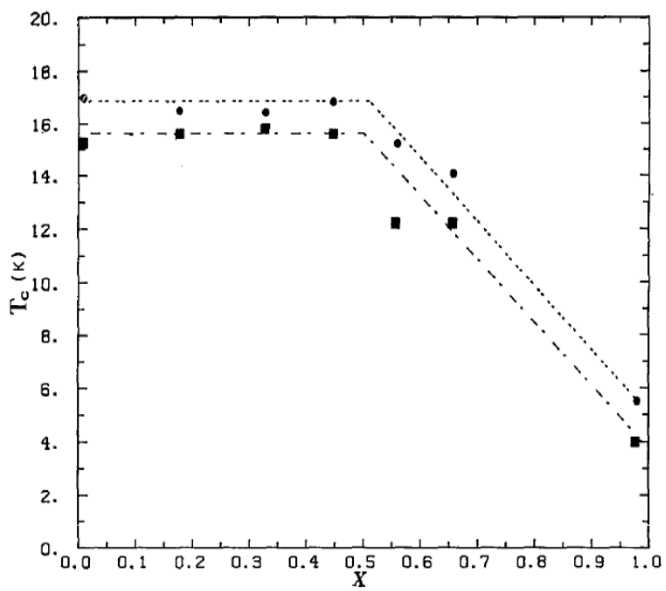


Fig. 1. Superconducting critical temperature T_c as a function of the titanium composition (x) for the ($Nb_{1-x}Ti_x$)N films deposited at T_s = 600°C (circles) and at T_s = 200°C (squares).

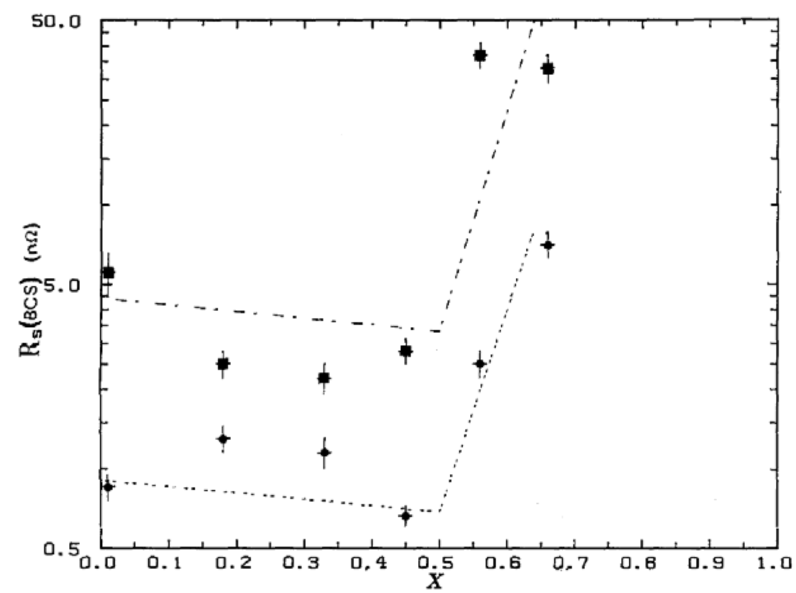


Fig. 3. Calculated BCS surface impedance R_s(BCS) as a function of the titanium composition (x) for the ($Nb_{1-x}Ti_x$)N films deposited at T_s = 600°C (circles) and at T_s = 200°C (squares). The continuous lines correspond to the values of the lines through the data in Figs. 1 and 2.

Nb Compounds - NbTiN

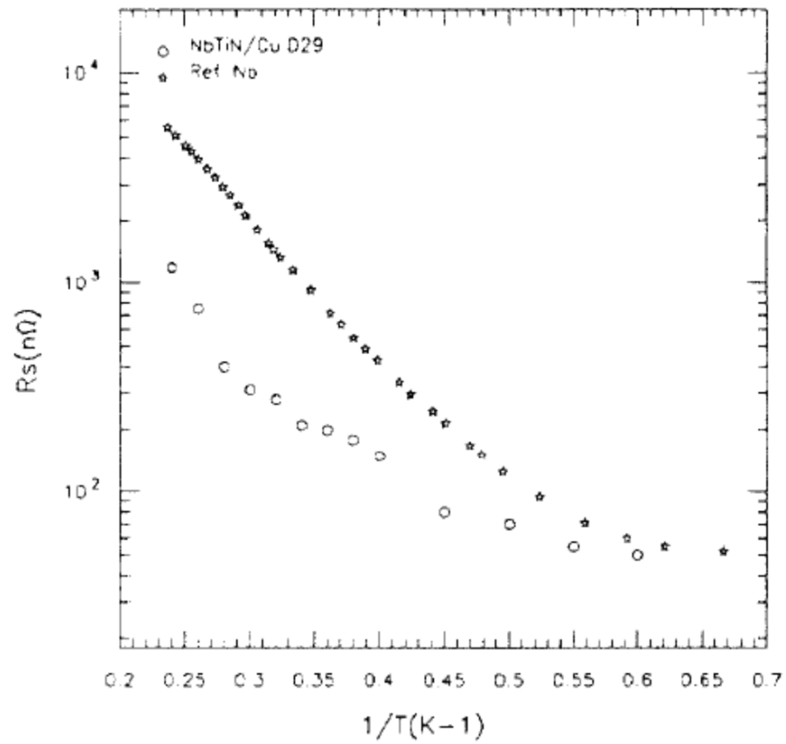


Figure 3 Surface resistance vs temperature for a NbTiN sample, at 4 GHz.

Reactive Magnetron Sputtering:

CEA Saclay :

NbTiN films deposited on 12 cm copper disks by magnetron sputtering and tested in a cylindrical TE_{011} cavity reached RF field levels of 35 mT

low residual surface resistance (< 100 nΩ at 4 GHz) with a very small BCS resistance

4 cavities deposited but no RF measurement due to film blistering on large area of the cavity.

Rs slope significantly decreased when coating with bias ranging from -50V to -100V

P. Bosland et al.

S. Cantacuzène et al.

CERN:

Samples and six 1.5 GHz Cu cavities coated by reactive cylindrical magnetron sputtering

Best cavity result for thicker film (4.3µm) and lower deposition temperature (265˚C)

Rs = 330nΩ @ 4.2K

Q_0 at zero field is higher than the Q-value of Niobium cavities but Eacc limited under 10 MV/m

As for NbN, N stoichiometry critical to obtain the right SC phase

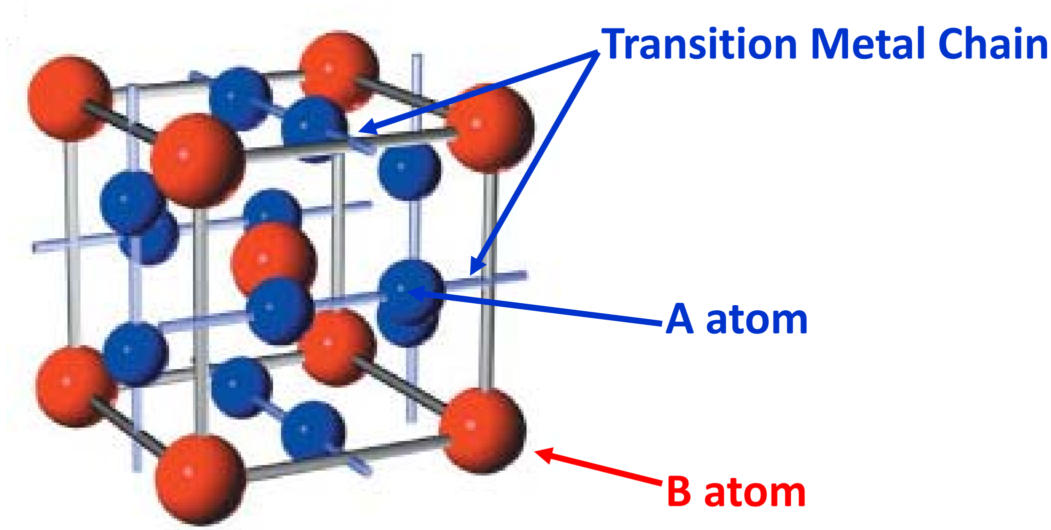
M. Marino, Proceedings of the 8th Workshop on RF Superconductivity, October 1997, Abano Terme (Padua), (Rep) 133/98, vol.IV, p.1076

A15 COMPOUNDS

A15 Compounds - Structure

A atoms = Transition elements of group IV, V or VI
B atoms = Non transition or transition elements

A_3B



B atoms occupy corners and centre of BCC structure
A atoms form orthogonal chains bisecting the faces of the BCC unit cell.
Linear Chain Integrity is crucial for Tc (long-range order required)

A15 Compounds – Potential candidates for RF Cavities

Nb_3Sn, Nb_3Al, Nb_3Ge, Nb_3Ga, V_3Si, Mo_3Re

- ❑ **Among the Nb and V based high Tc (15 – 20 K)**
- ❑ **Nb_3Ga and Nb_3Ge do not exist as stable bulk materials at 3:1 stoichiometry**
- ❑ **Nb_3Al exists only at high temperature causing excessive atomic disorder**
- ❑ **Production of above materials need non equilibrium processes**
- ❑ **V_3Ga, V_3Si & Nb_3Sn are stable bulk material and have high T_c**
- ❑ **Another A-15 compound holding promise is Mo_3Re (Tc=15K)**

Sharma, International Workshop on Thin Films and New Ideas for Pushing The Limits Of RF Superconductivity, LNL-INFN , Oct.2006

Extreme brittleness so A-15 bulk structure cannot be formed
The A-15 should be produced as thin layer on the interior of the already formed structure
Such a layer need to be only 1 or 2 microns thick
λ_L (Nb3Sn) = 65 nm

Thin film route ideal

A15 Compounds – Preparation Methods III

Chemical Vapor Deposition (CVD)

- MOCVD (*Metal Organic Chemical Vapour Deposition)* is a particular case of CVD in which the precursor is a metallorganic compound
- Process in which one or more precursors, present in vapor phase, chemically react on an appropriate warm substrate, giving rise to a solid film
- Deposition rate and structure of the film depend upon temperature and reagent concentration
  - ⇒ Uniformity of temperature and flow of gaseous over entire cavity surface may be difficult with complex geometry

Diffusion Reaction

- Technique proved successful for magnet conductor application
- Simple equipment compared to sputtering and CVD

Co-Sputtering

- Considerable success achieved in synthesizing difficult materials like Nb_3Ge with highest Tc(~23k) or V_3Si
- Typically two constituents are sputtered simultaneously onto a temperature controlled substrate
- Stoichiometry dependent on relative positions of target and substrate (can be manipulated to get perfect stoichiometry)
- Stoichiometry control difficult over large areas like accelerating system and if stoichiometry range for A-15 phase is narrow.

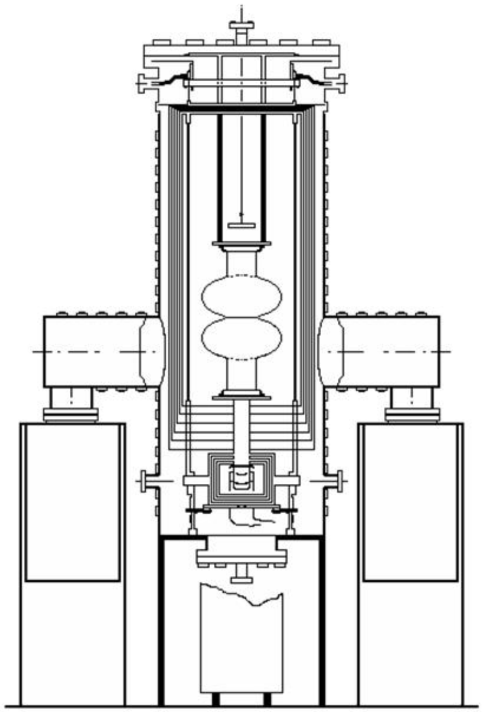
Sputtering

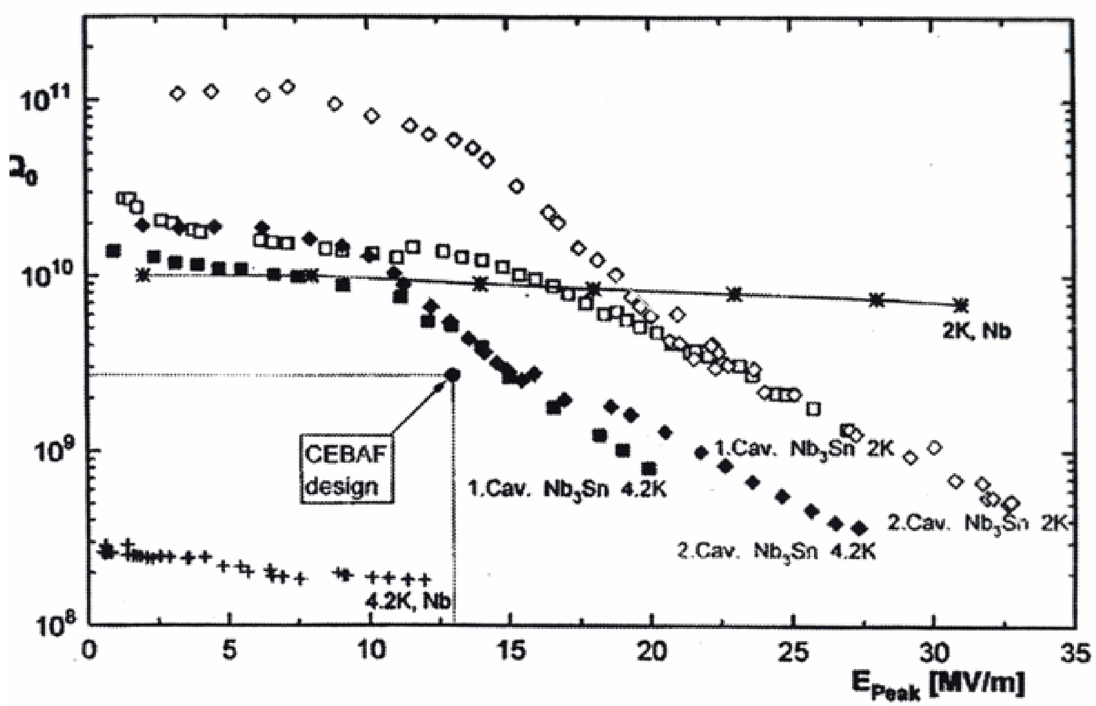
- To sputter from a single target of correct stoichiometry (prepared by powder sintering)
- Stoichiometry, Substrate Temperature, Deposition Rate, Deposition Thickness Can be varied independently

Nb_3Sn SRF History

Wuppertal, end ’80s :

Nb3Sn cavity (1.5 GHz) obtained trough Sn vapour phase diffusion @ 1200˚C





Q vs. E_{peak} of the 1st two Nb_3Sn-coated 1.5GHZ single cell cavities in comparison to pure Nb at 4.2K and 2K from CEBAF

5-cell 1.5GHz cavity also coated: Q_o~10^9, E_{acc}=7MV/m with Q=8.10^8

G. Müller et al.,
M. Peiniger & H. Piel , IEEETrans. On Nucl. Sc. Vol NS-32, nº5, Oct. 1985

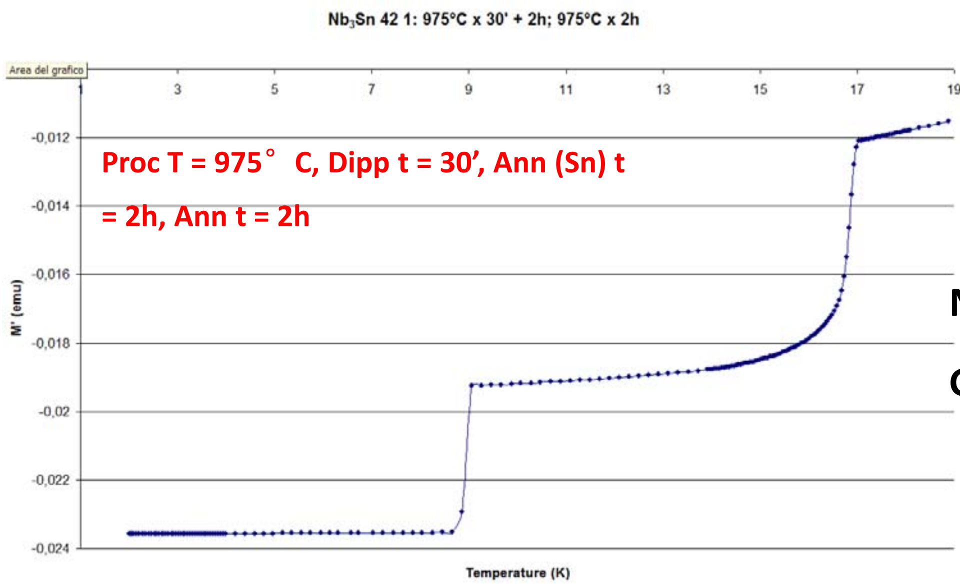
A15 Compounds – Nb_3Sn through liquid diffusion

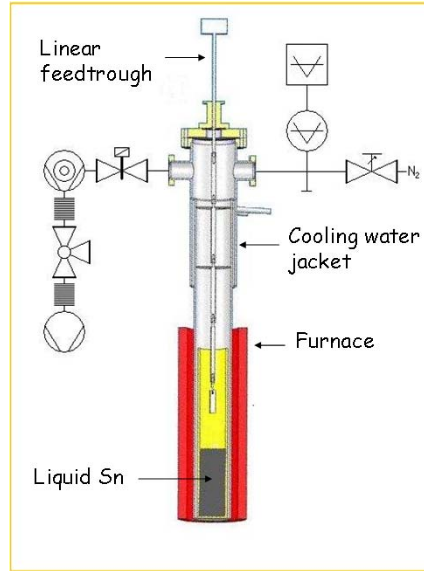
S. Deambrosis, Sharma, International Workshop on Thin Films and New Ideas for Pushing The Limits Of RF Superconductivity, LNL-INFN , Oct.2006
S. Deambrosis et al., Physica C 441 (2006) 108-113

Nb_3Sn coatings on Nb by liquid diffusion method at INFN Legnaro

"Hybrid" Process"

- Substrate thermalization (30 min - 1 h)
- Dipping (few min - 2 h)
- Sample annealing with Sn vapor for a few hours
- Sample annealing without Sn vapor for a few hours





No Residual Sn traces on the sample surface

Good Nb_3Sn film superconductive properties

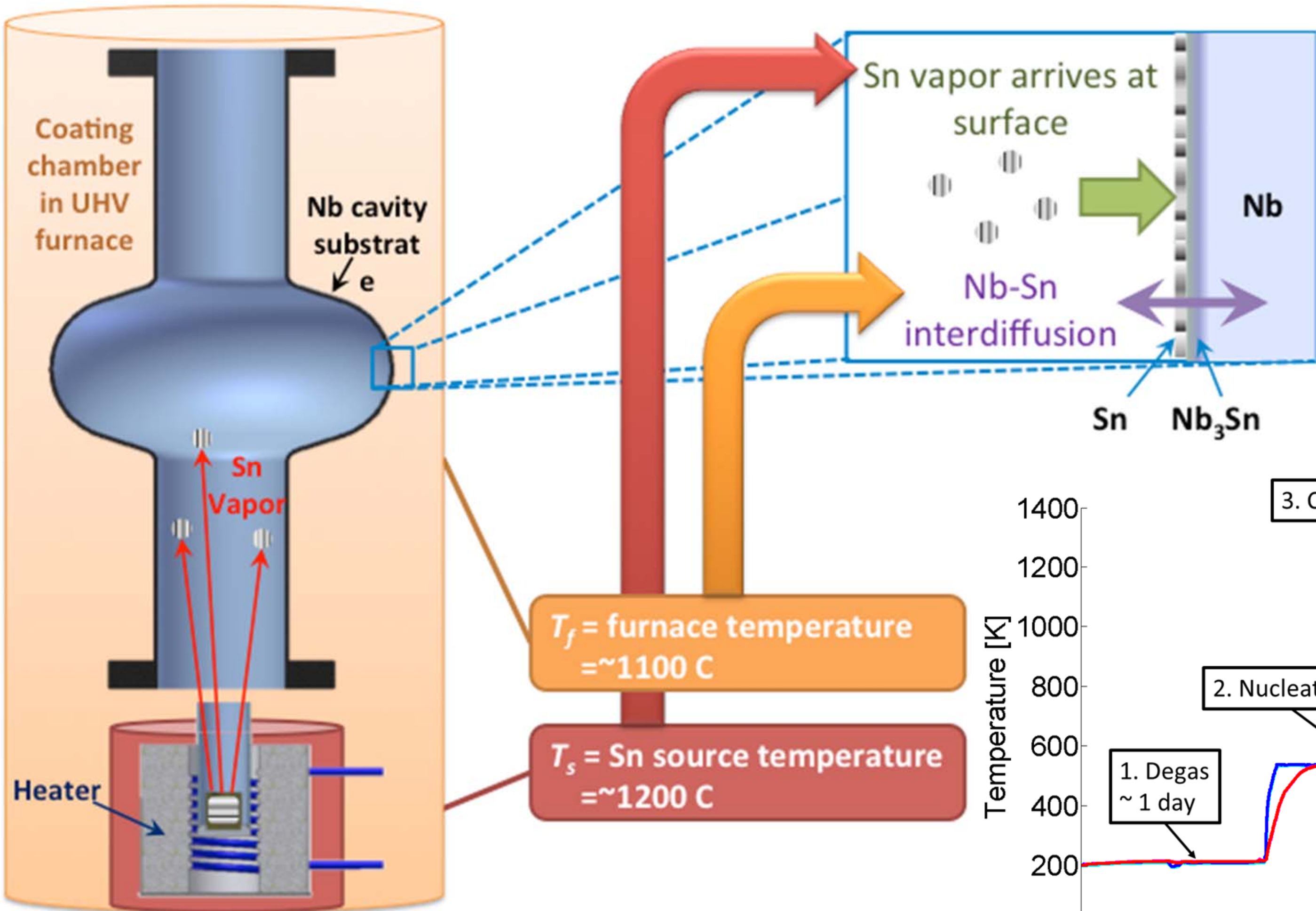
T_c = 16.8 K, DT_c = 0.16 K

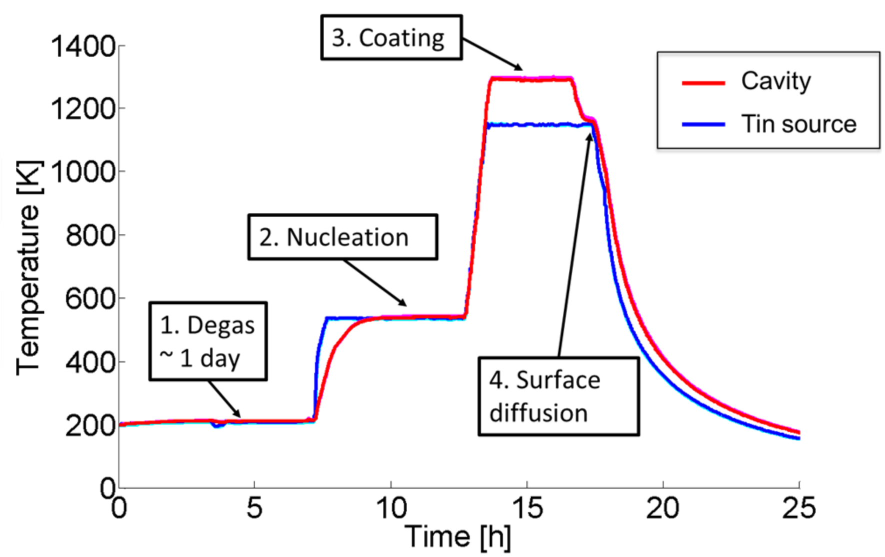
No Sn rich Phases

Diffusion temperature to be kept above 930˚C to avoid formation of low Tc phases like Nb_6Sn_5 (2.6 K) and NbSn2 (2.1 K)
Diffusion time optimize to obtain desired Nb3Sn thickness
Post diffusion heat reaction important to get rid of the outer Sn layer
Post diffusion annealing to have enlarged grains and perfect ordering

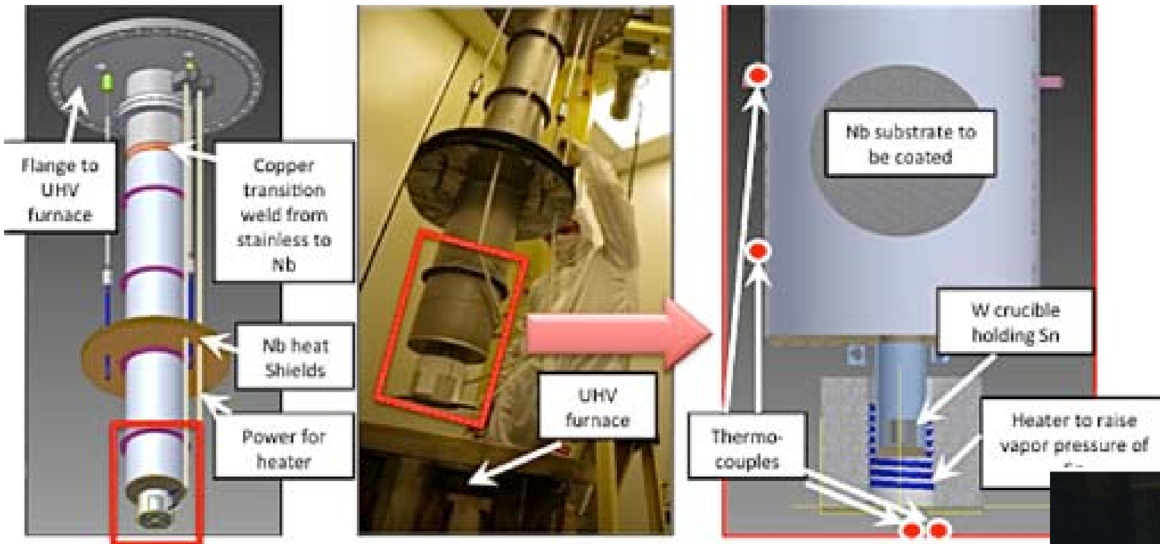
Nb_3Sn Coating via Vapor Diffusion

M. Lieppe, Cornell



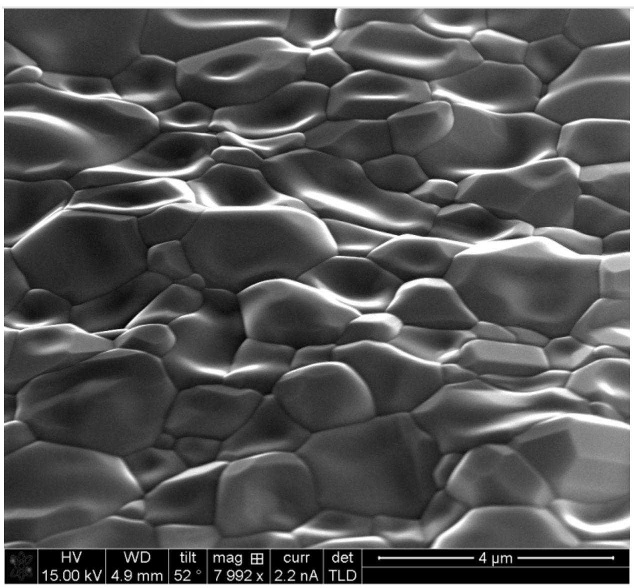


Nb_3Sn



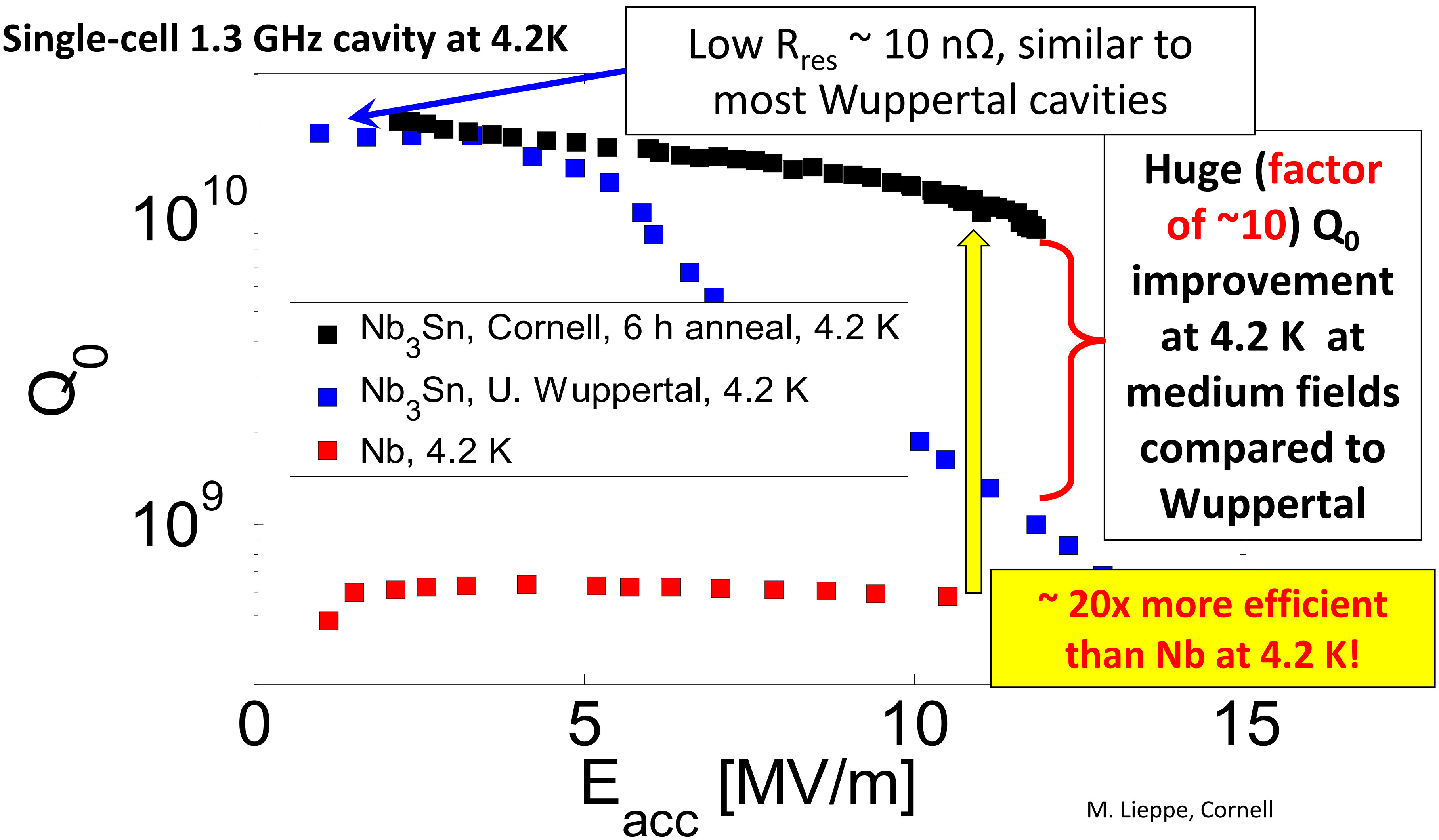
S. Posen, M. Lieppe, Cornell
G. Eremeev, JLab

Dedicated furnace systems at Cornell University and Jlab for Nb_3Sn synthetization via Sn diffusion



Nb_3Sn Cavity Result

Single-cell 1.3 GHz cavity at 4.2K

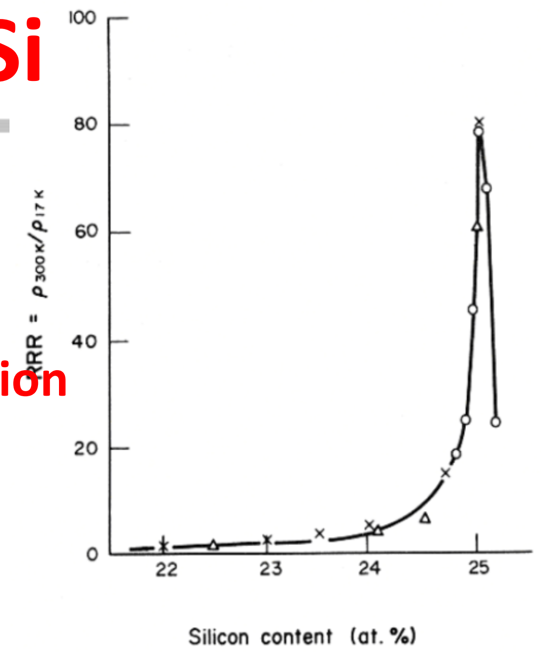


M. Lieppe, Cornell

A15 Compounds – V_3Si

S. Deambrosis et al., Physica C 441 (2006) 108-113

Highly ordered compound, RRR~80 achievable, max Tc (17.1K) when stoichiometric composition (25at.% Si)



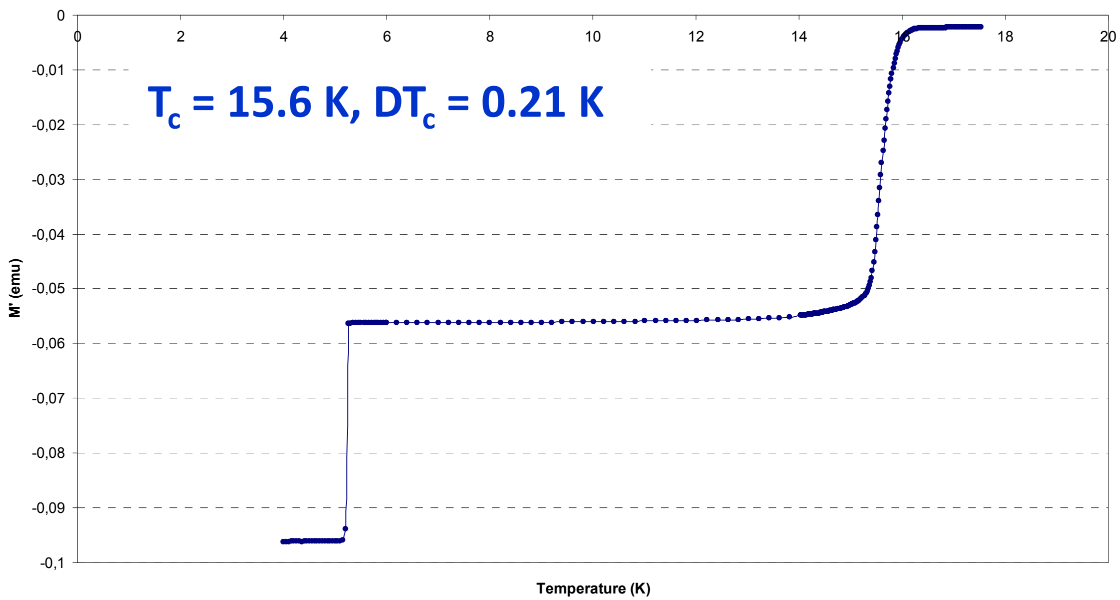
V_3Si layers by silanization of V substrate and Thermal Diffusion

V substrate heated to get SiH_4 decomposition and Silicon diffusion

Film grown by silanization with p (SiH_4) ~ 10^{-3}-10^{-4} mbar

Annealing in vacuum to get rid of hydrogen

825˚C, 4h+8h



* Diffusion parameters and silane flow rate have been optimized

* Tc ~ 16 K is routinely obtained

A15 Compounds – Mo_3Re

Mo_3Re thin films by DC magnetron deposition: $Mo_{75}Re_{25}$, $Mo_{60}Re_{40}$

Solid solution , free of bulk and surface inhomogeneities, low intersticials solubility compared to Nb, low κ, high H_{c1} (500G)

Bulk in σ phase, tetragonal low T_c (6K)

but T_c up to 18K reported in literature with bcc structure

S.M. Deambrosis et al., Physica C 441(2006) 108-113

* Deposition on Sapphire, Cu and Nb substrates
* Substrate temperature up to 950⁰ C
* Post-annealing to increase crystallinity and transition sharpness
* Tc = 12K obtained for composition $Mo_{60}Re_{40}$

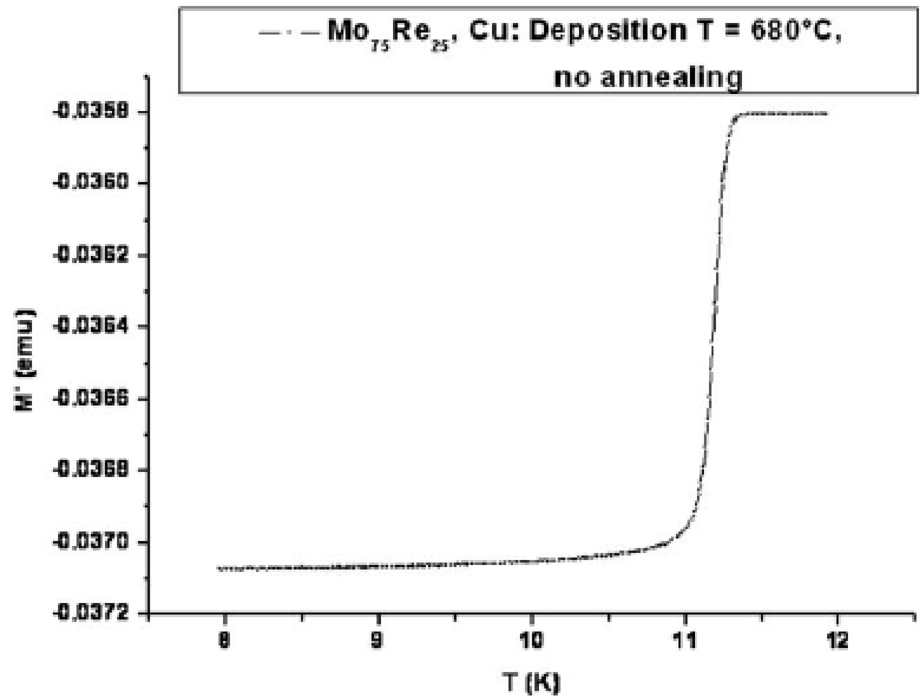


Fig. 4. A $Mo_{75}Re_{25}$ film deposited on Cu transition curve: deposition $T = 680\,°C$, $T_c = 11.18$, $\Delta T_c = 0.08$ K.

Higher deposition temperature, longer annealing time

→ Higher Tc

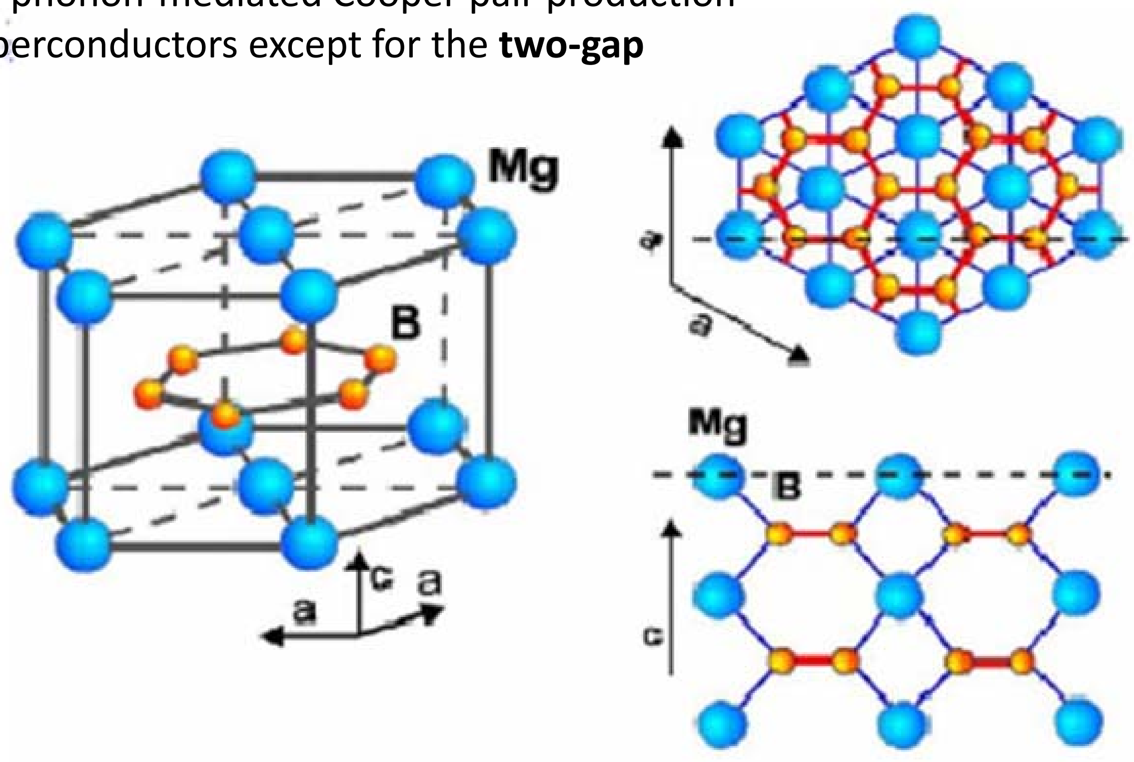
MgB_2

Magnesium Diboride (MgB_2)

Graphite-type boron layers separated by hexagonal close-packed layers of magnesium

Superconductivity comes from the phonon-mediated Cooper pair production similar to the low-temperature superconductors except for the **two-gap nature**.

T_c ~ 40 K



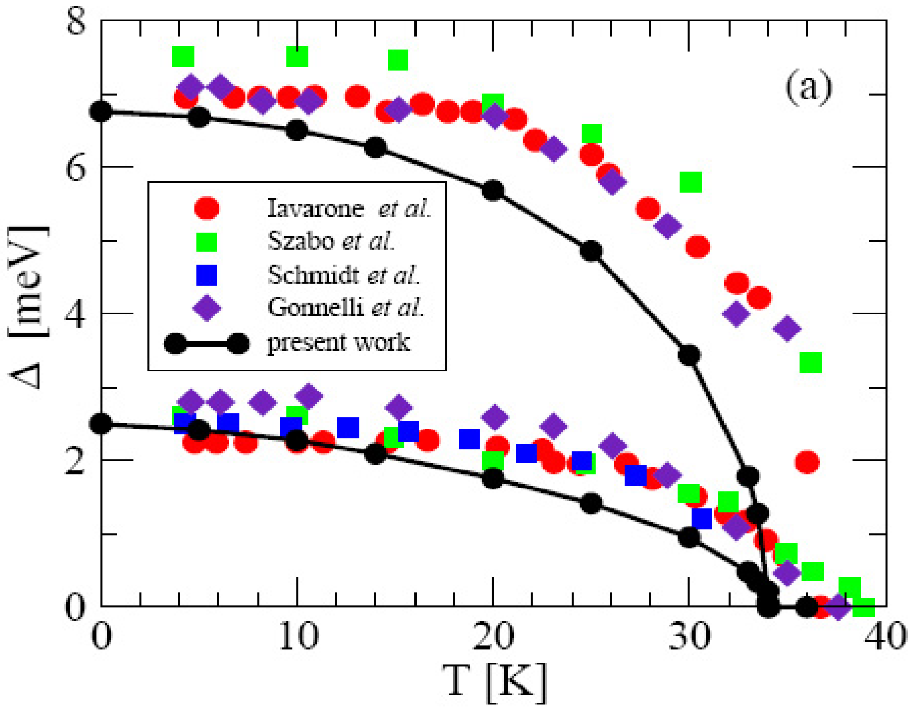
Compared to cuprates:

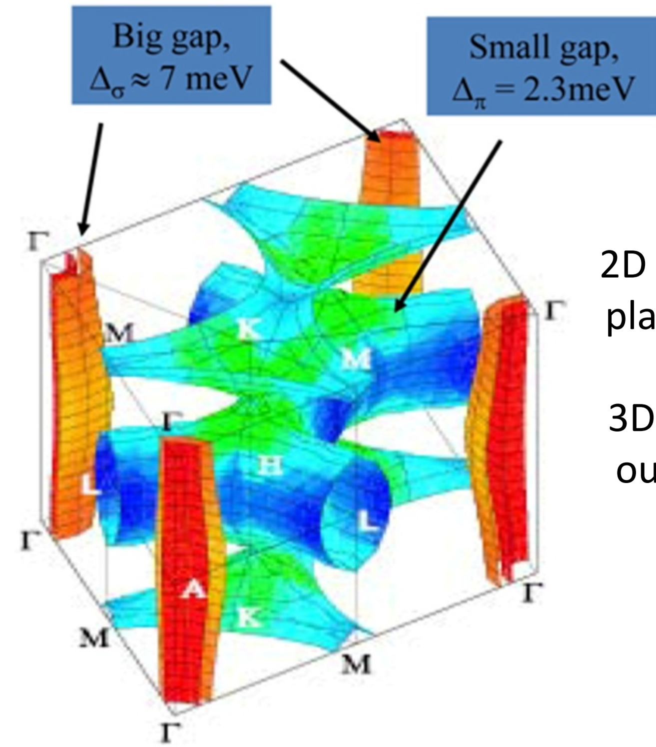
- **Cheaper**
- **Lower anisotropy**
- **Larger coherence length**
- **Transparency of grain boundaries to current flows**

C. Buzea and T. Yamashita, Superconductor Sci. Technol. 14 (2001) R115.

MgB_2: Two Energy Gaps

A. Floris et al., cond-mat/0408688v1 31 Aug 2004





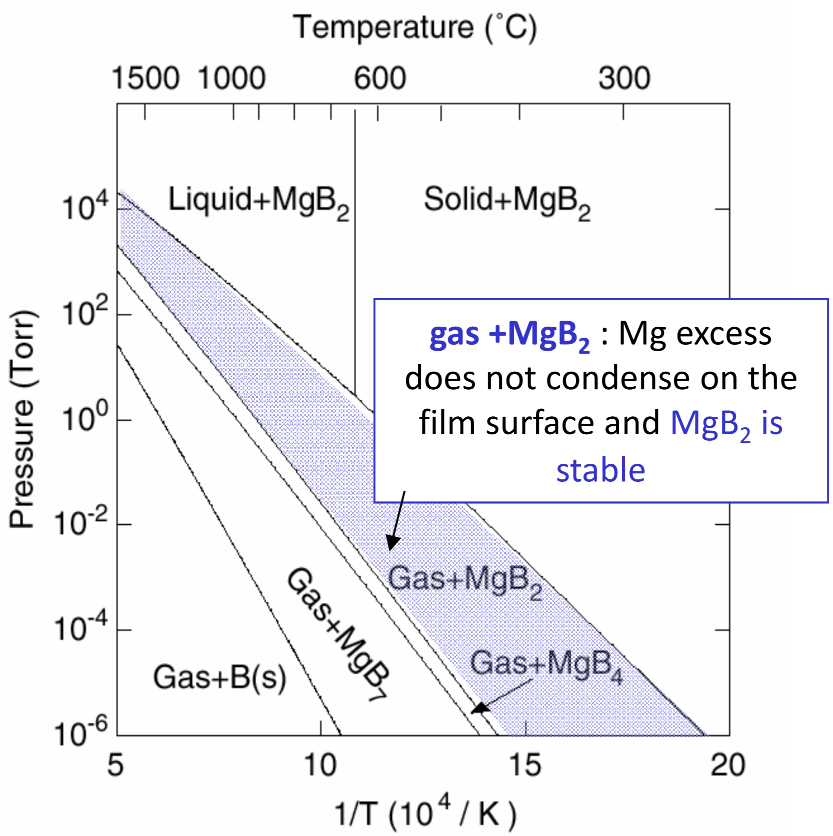
Liu, Mazin and Kortus (2002); Choi et al, (2002)

2D big gap for in-plane σ-orbital s & 3D small gap for out-of-plane π-orbitals

R_s is dominated by the smaller gap, so MgB_2 may not be better than Nb_3Sn because Δ_π^{MgB2}= 2.3 meV < Δ^{Nb_3Sn}= 3.1 meV, but better than Nb (Δ^{Nb}= 1.5 meV)

RF response has shown lower energy gap behavior. This must be compared to $\Delta \approx 1.5$ meV for Nb. There is room for better performance than Nb, since the resistivity can also be made quite low (best values are ≤1 μΩcm).

MgB_2-Thin films growth



Z.-K. Liu et al., APL 78(2001) 3678.

evaporation Mg pressure from MgB_2 < decomposition curve of MgB_2 < Mg vapor pressure

optimal T for epitaxial growth ~ $T_{melt}/2$

For MgB_2 , 540° C → it requires P_{Mg} ~11 Torr

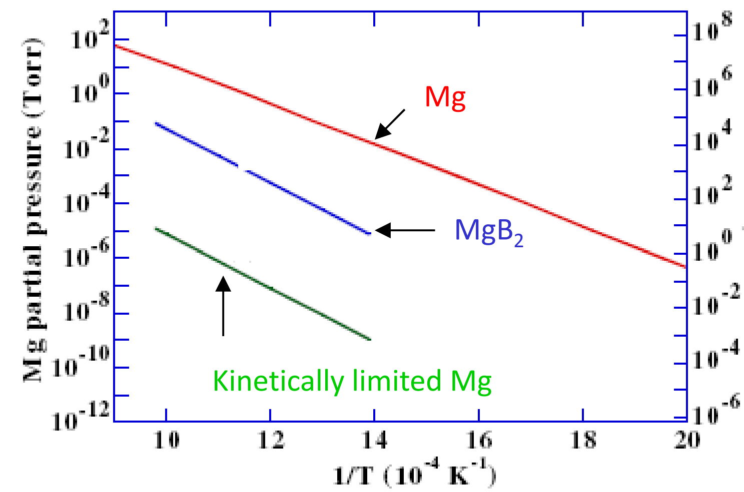
Too high for UHV deposition techniques (PLD, MBE...)

At P_{Mg} = 10^{-4}-10^{-6} Torr, compatible with MBE, Tsub ~ 400° C

MgB_2 is stable, but no MgB_2 formation:

Mg atoms re-evaporate before reacting with B

Kinetic of Mg is also important

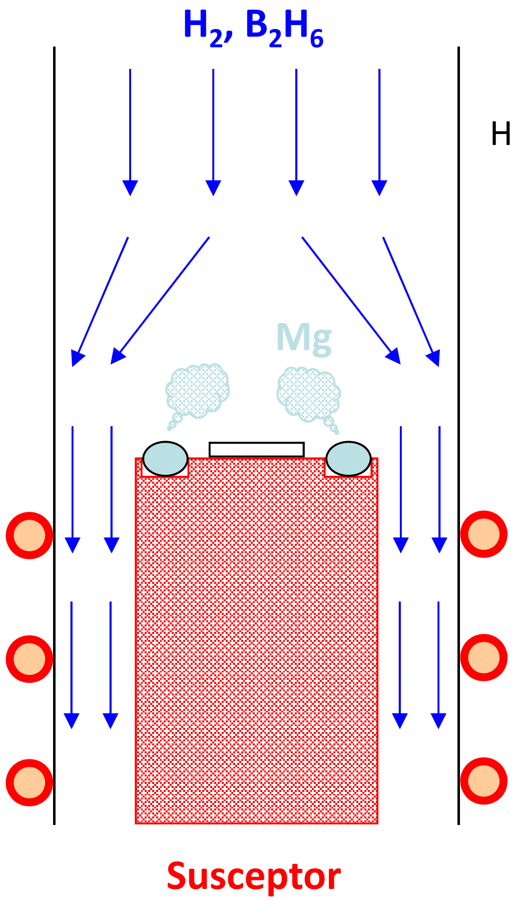


M. Naito and K. Ueda, SUST 17 (2004) R1

At P=10^{-6} Torr and T> 250°C no accumulation of Mg will take place on the substrate and the growth of the superconducting phase is very slow due to a large kinetic energy barrier.

At low Mg pressure only extremely low deposition temperatures can be used

MgB_2 – HPCVD on metal substrates



Hybrid Physical Chemical Vapor Deposition

High T_c has been obtained in polycrystalline MgB_2 films on stainless steel, Nb, TiN, and other substrates.

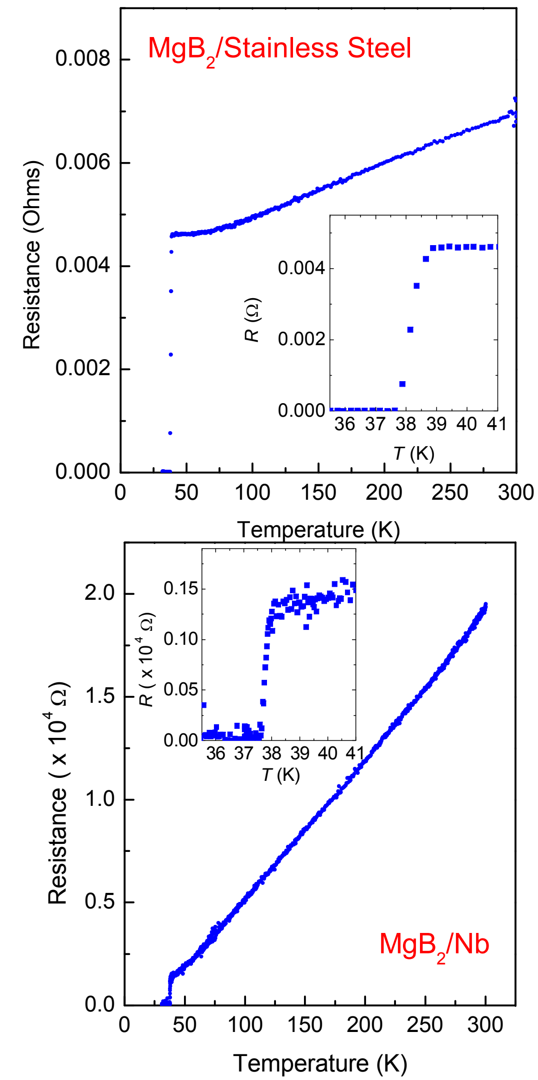
Clean HPCVD MgB2 thin films with excellent properties:

•RRR>80
low resistivity (<0.1 μΩ) and long mean free path
• high *Tc* ~ 42 K (due to tensile strain), high *Jc* (10% depairing current)
• low surface resistance, short penetration depth
• smooth surface (RMS roughness < 10 Å with N_2 addition)
• good thermal conductivity (free from dendritic magnetic instability)

Critical engineering considerations:

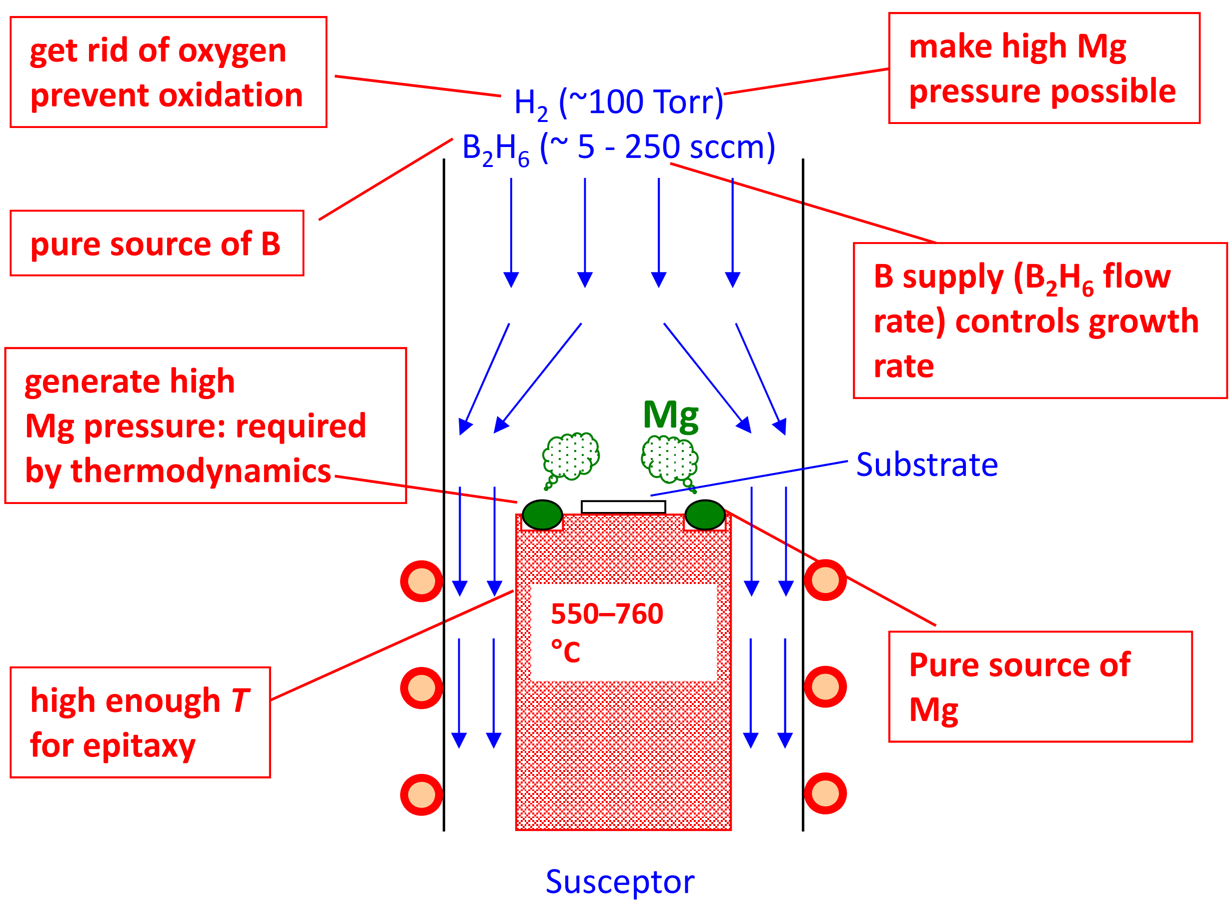
generate high Mg pressure at substrate (cold surface is Mg trap)
deliver di-borane to the substrate (the first hot surface di-borane sees should be the substrate)

X. Xi- TempleUniversity



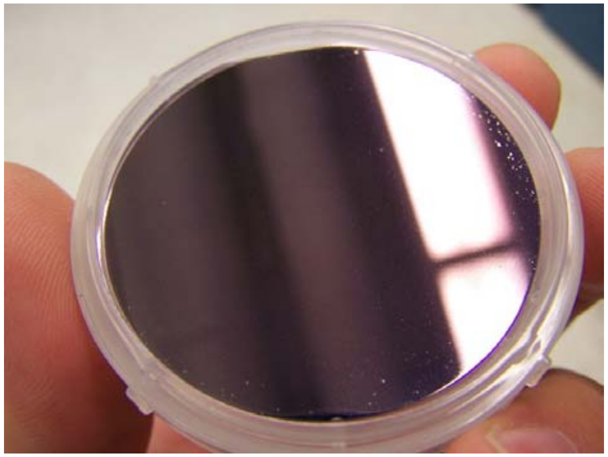
Hybrid Physical Chemical Vapor Deposition (HPCVD) at Temple University

Schematic View

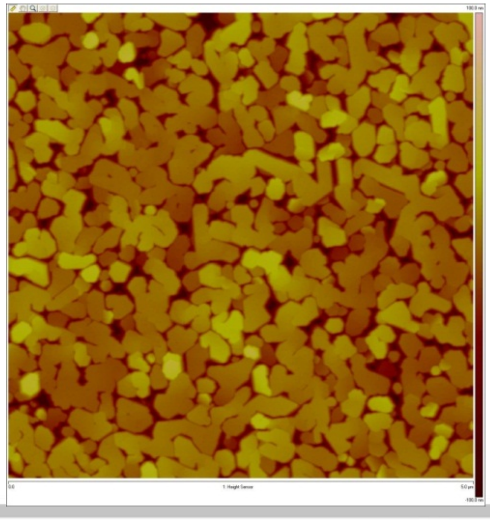


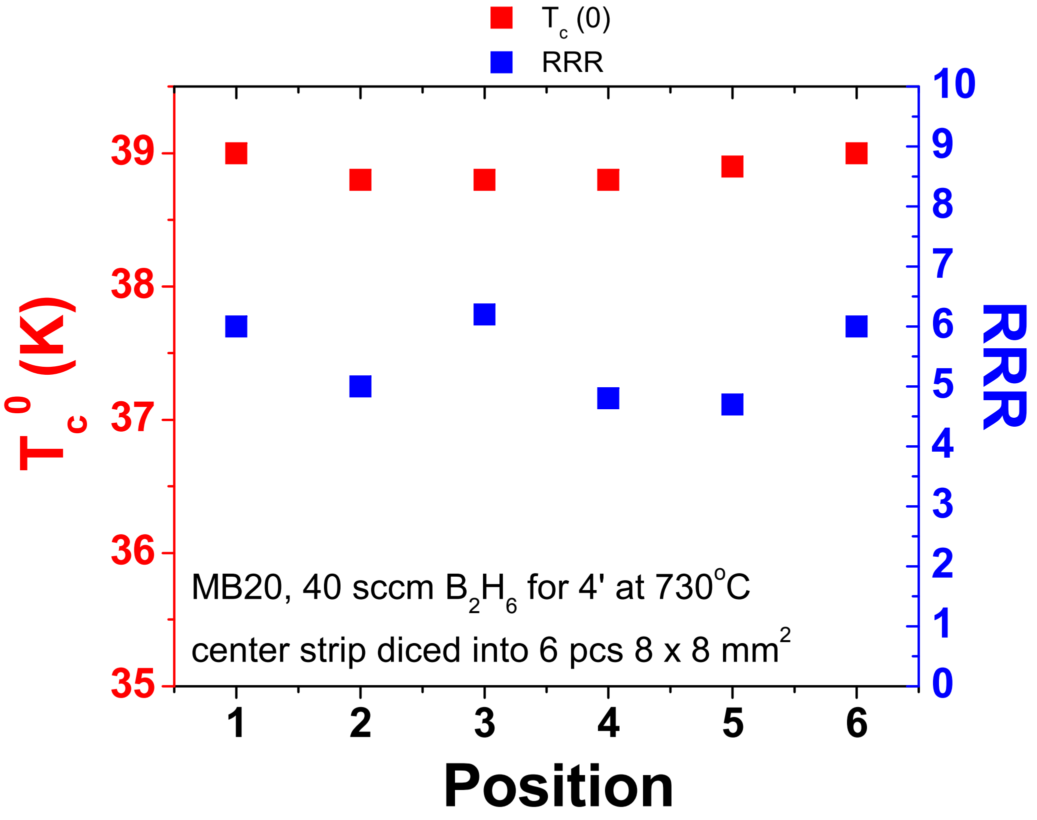
2” MgB_2 Films Grown by HPCVD

200 nm 2’’ MgB_2 film on sapphire

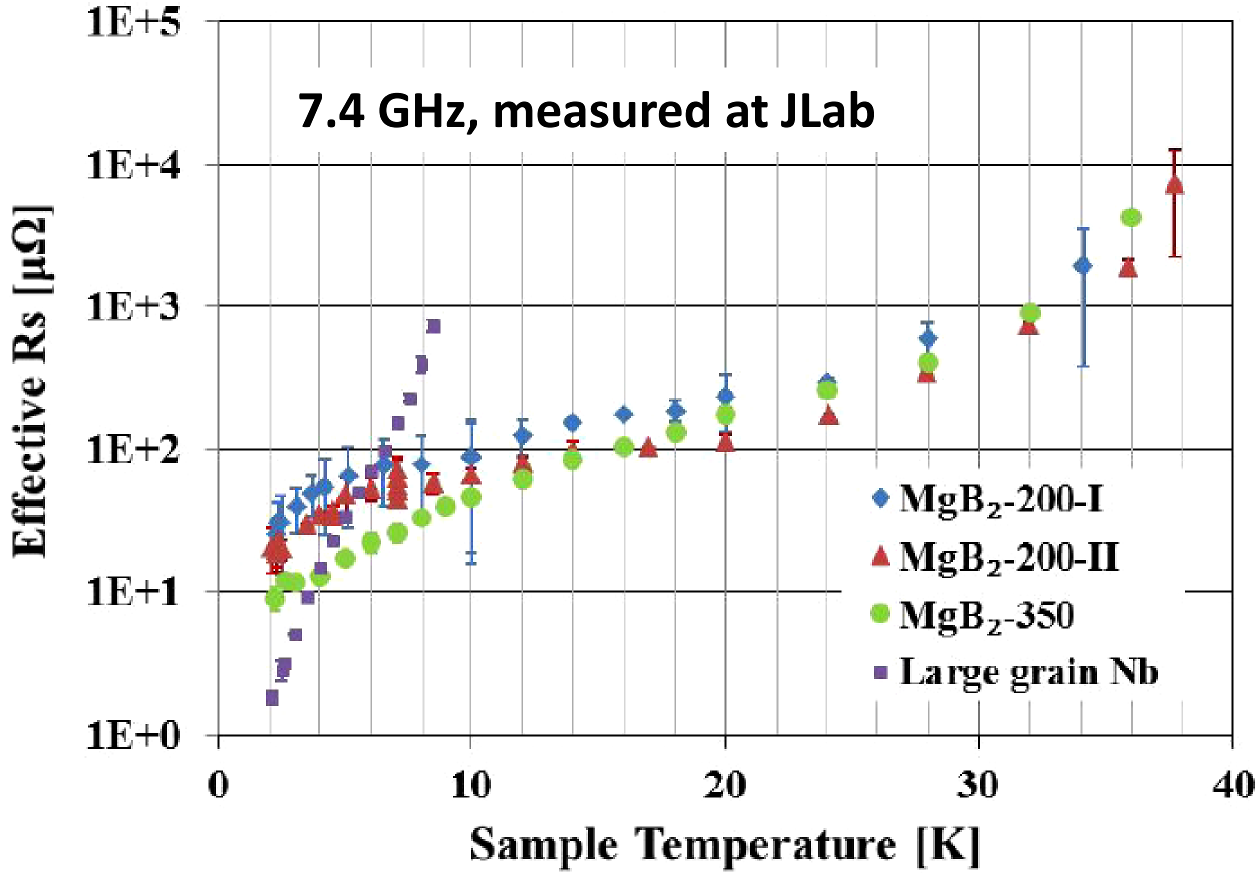


AFM image of film surface





Surface Resistance Compared to Large Grain Nb



Surface resistance of 2” dia. 350 nm MgB_2 film on sapphire comparable to the best large grain Nb at 4 K.

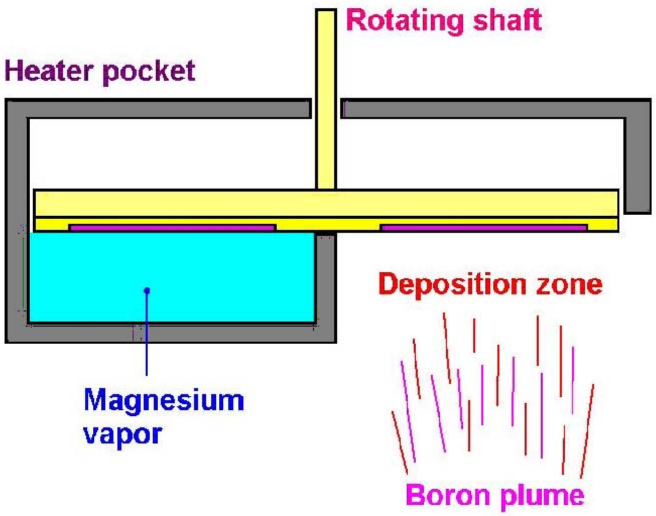
Xiao *et al.*, SUST 25, 095006 (2012)

MgB_2 - Reactive Evaporation

T. Tajima, LANL

RF measurement @ MIT/Lincoln Lab

SuperconductingTechnologies Inc.



In-situ reactive evaporation @ 550˚C

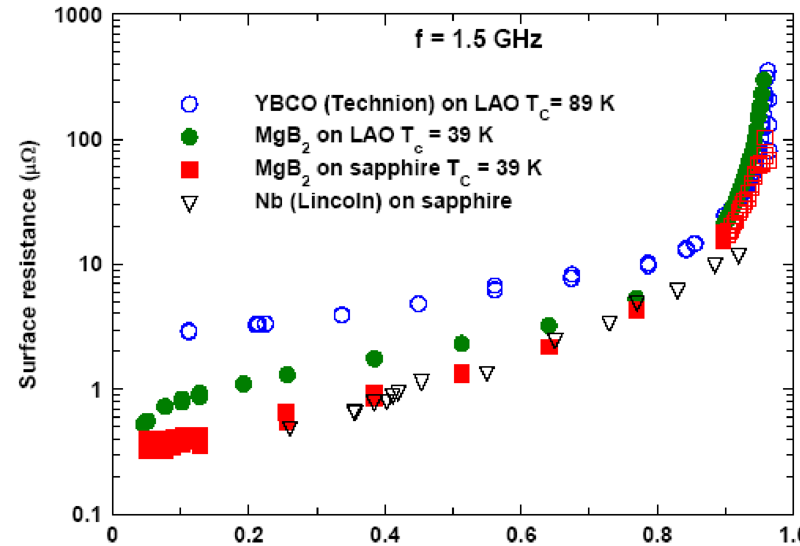
Compared to Nb:

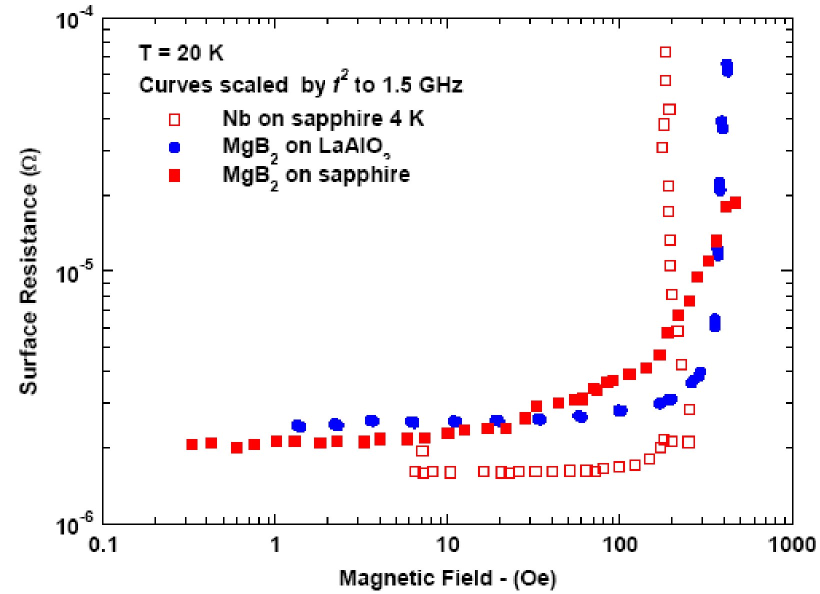
- **Higher T_c**
- **low resistivity**
- **larger gap**
- **higher critical field**

B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.
T. Tajima et al, Proc. PAC05.

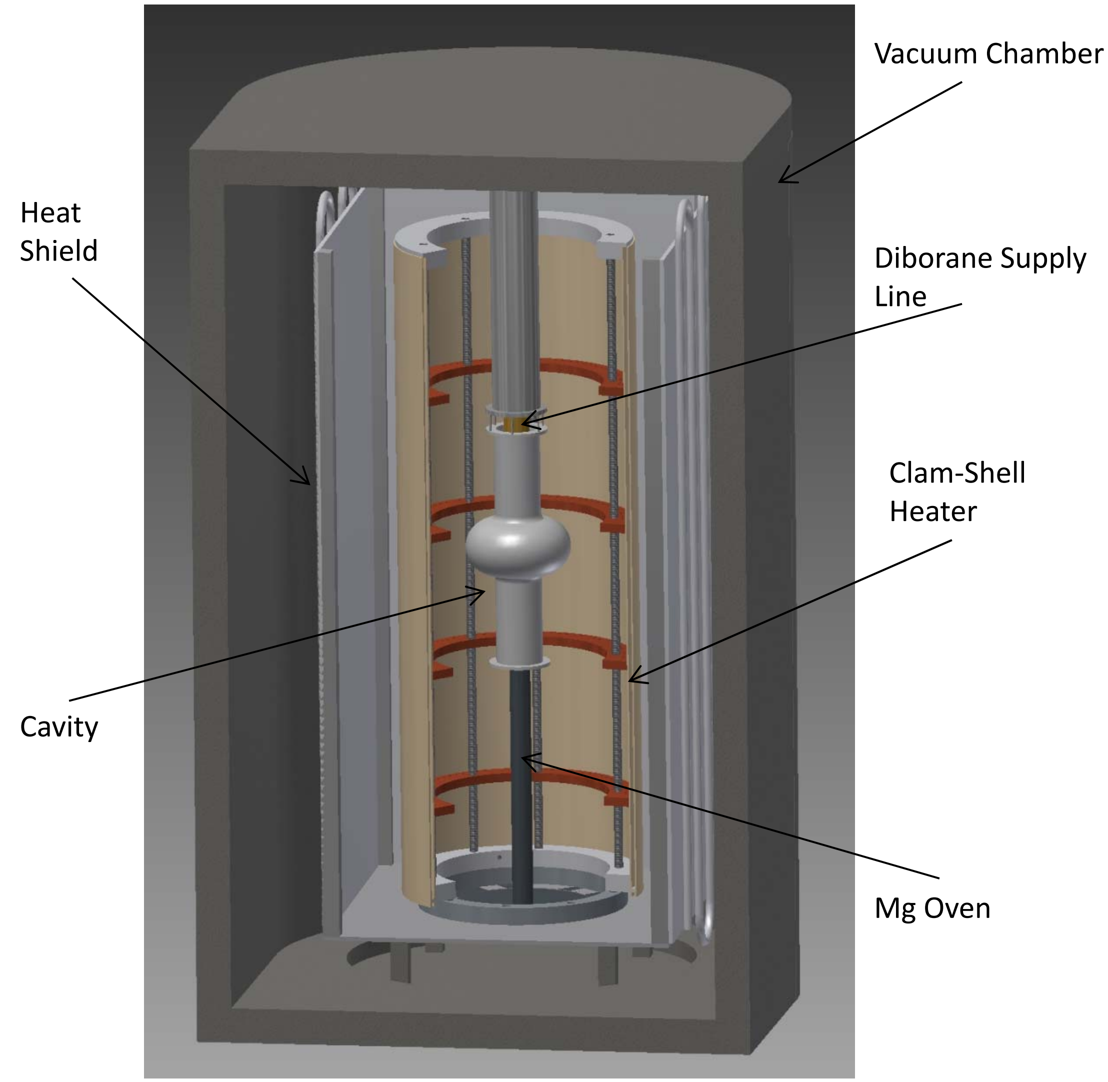
B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005

Oates, Agassi, and Moeckly, ASC 2006 Proceeding





MgB_2 – An Idea for SRF Cavity Coating

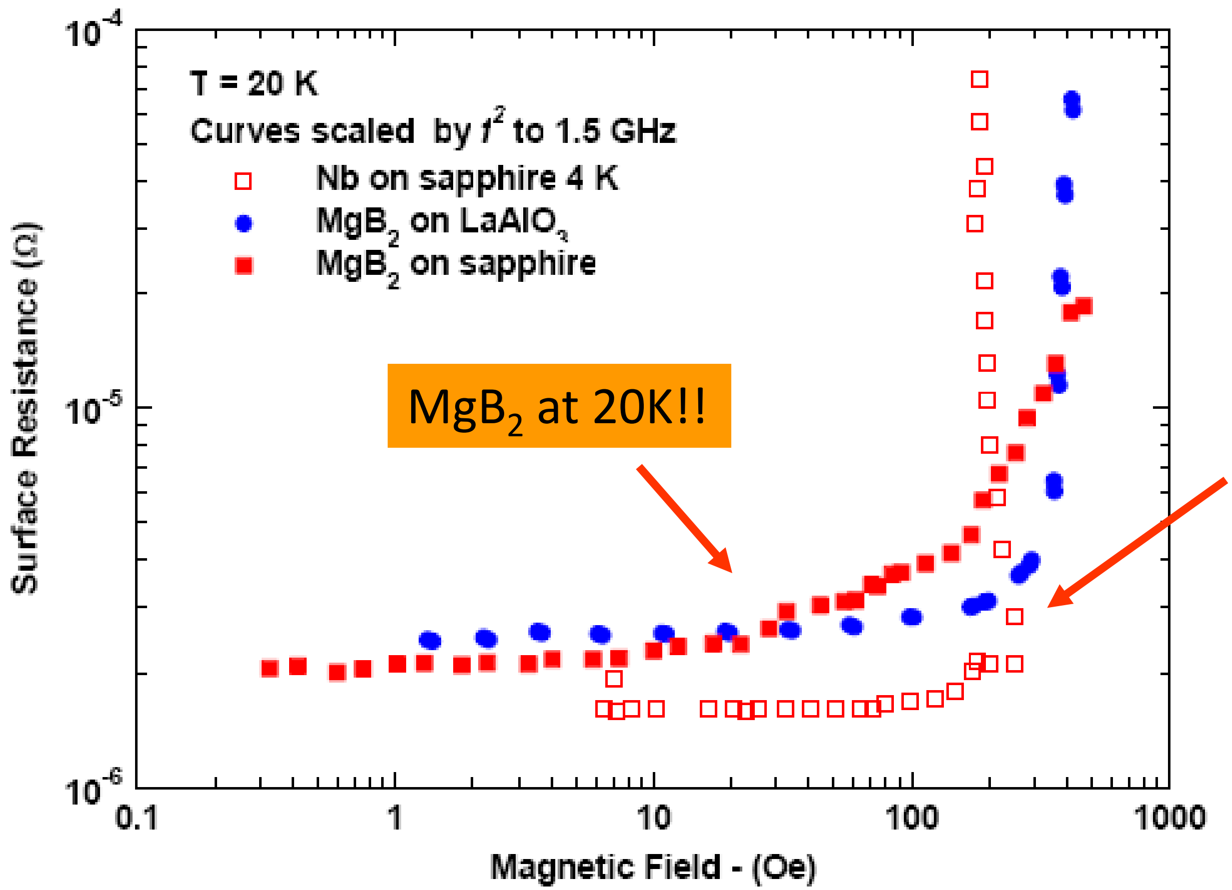


***In-Situ* Coating of MgB_2: 3 GHz Cavity**

- Need enough space between diborane supply line/Mg oven and cavity tubes
- Better control of gas flow inside the cavity
- Largest size that can be accommodated by the existing vacuum chamber

R_s for MgB_2

Results at MIT in 2006 showed R_s comparable to Nb even at 20 K! and the field at which the Rs start to increase rapidly was higher than Nb!!



Coated at STI with reactive evaporation
Thickness: 500 nm

Nb at 4.2 K, Enhanced field at the edges may have caused this take off at low gradient.

Oates et al., IEEE Trans. Appl. Supercond. 17 (2007) 2871.

MgB_2 – Challenges

Keys to high quality MgB2 thin films:

- **High Mg pressure for thermodynamic stability of MgB_2**
- **oxygen-free or reducing environment**
- **clean Mg and B sources**

Challenges

Film properties degrade with exposure to moisture: resistance goes up, T_c goes down

Clean cavity surface leads to degradation in water and moisture

… need of a cap layer?

Diffusion of Mg into substrate (Cu…), need of a buffer layer

Safety … procedures for use of diborane

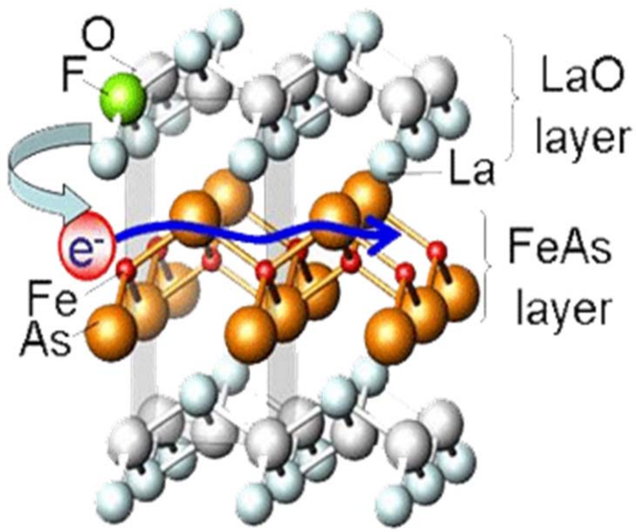
OXYPNICTIDES

A new superconducting family

Oxypnictide base

ReOMP$_n$

- **M = Fe, Co, Ni**
- **Pn = As or P**
- **Re = La, Nd, Sm, Pr**



Iron-Based Layered Superconductor La[$O_{1-x}F_x$]FeAs (x = 0.05−0.12) with T_c = 26 K

Yoichi Kamihara,*,† Takumi Watanabe,‡ Masahiro Hirano,†,§ and Hideo Hosono†,‡,§

ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp

Layered as HTS –superconducting AsFe layers and T_c from <10K to 55K

Superconductivity occurs on the FeAs layer with magnetic pair-breaking Fe^{2+}ions

Another families:$Ba_{1-x}K_xFe_2As_2$

Up to a few thousand compounds

Materials usually brittle

Tests in magnetic fields up to 45 T suggest the H_{c2} of $LaFeAsO_{0.89}F_{0.11}$ may be ~64 T.
A different La-based material ($La_{0.8}K_{0.2}FeAsO_{0.8}F_{0.2}$) tested at 6 K predicts H_{c2} ~122 T.

Can pnictides be useful for TFSRF?

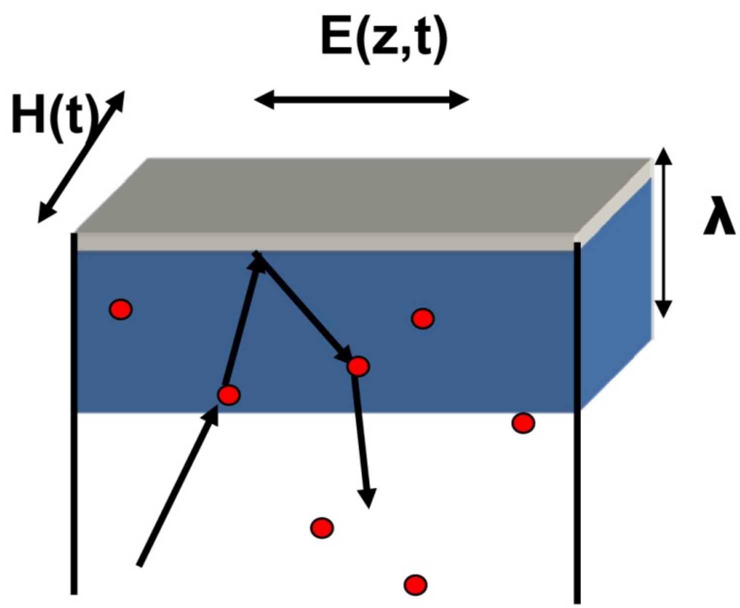
For s-wave members of the pnictide family, one can expect a much lower R_s at 2K because
$\Delta_{oxy} = 5\text{-}10\ meV > \Delta_{Nb3Sn} = 3\ meV$

Normal skin effect($l \ll \lambda$): multiple impurity scattering in the λ-belt:

$Rs \sim (\mu_0^2 \omega^2 \lambda^3 \sigma_n \Delta/T) \exp(-\Delta/T)$

Anomalous skin effect ($l \gg \lambda$)in the clean limit:
Effective $\sigma_{eff} \sim e^2 n\lambda/p_F$
High $\rho_n \sim 1 m\Omega cm \sim 10\rho_n MgB_2$, big$\lambda$= 180-250 nm, low $H_{c1} \sim 10$ mT

R_s can be much lower than R_s of Nb_3Sn, but TF multilayer coating is necessary
First high quality epitaxial films have been grown by C.-B. Eom (UW)

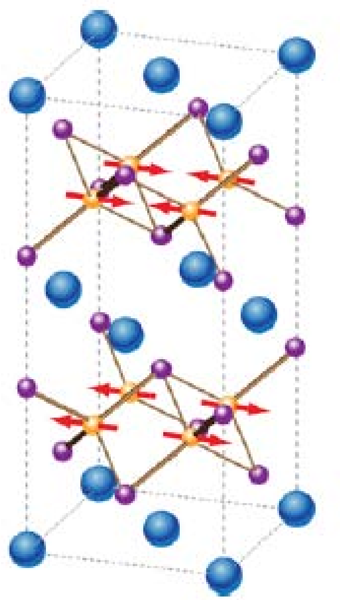


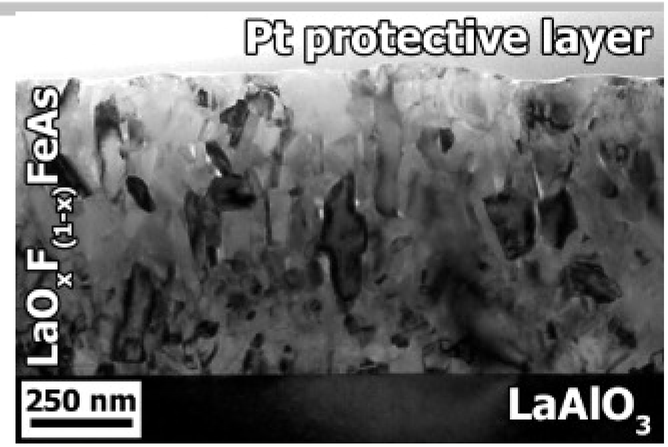
Pnictides Films Deposition

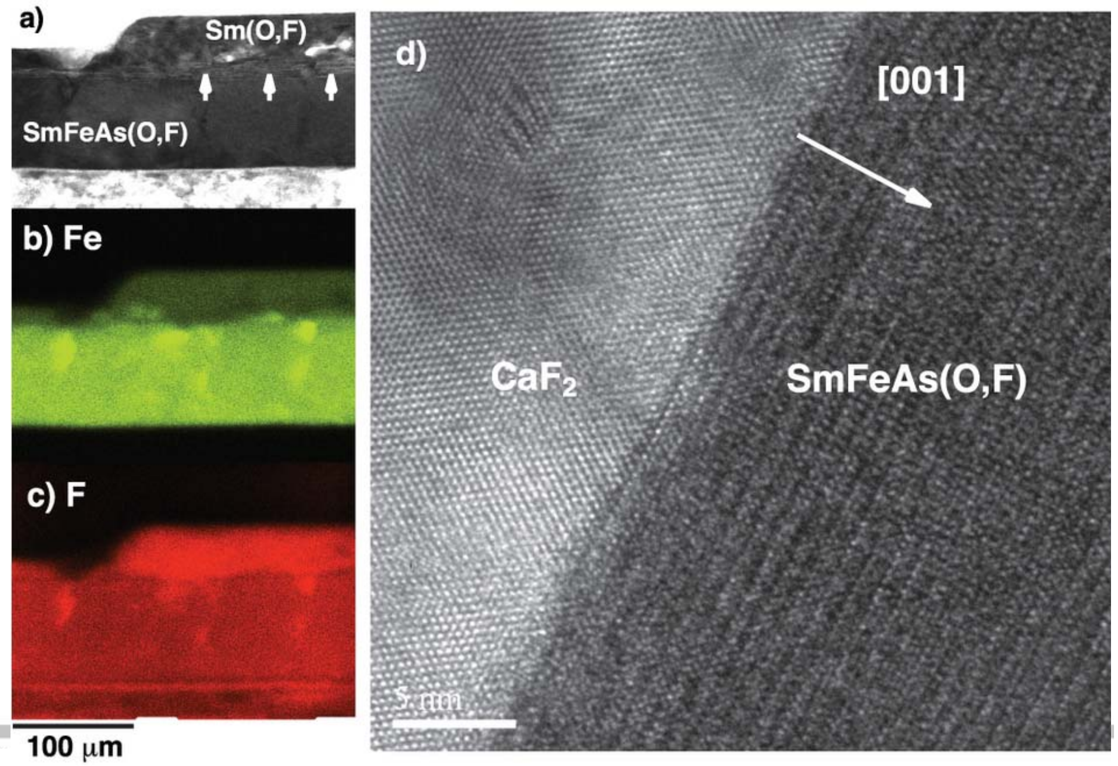
Coating Methods:

Pulse Laser Deposition from stoichiometric target

Ion Beam Assisted - MBE







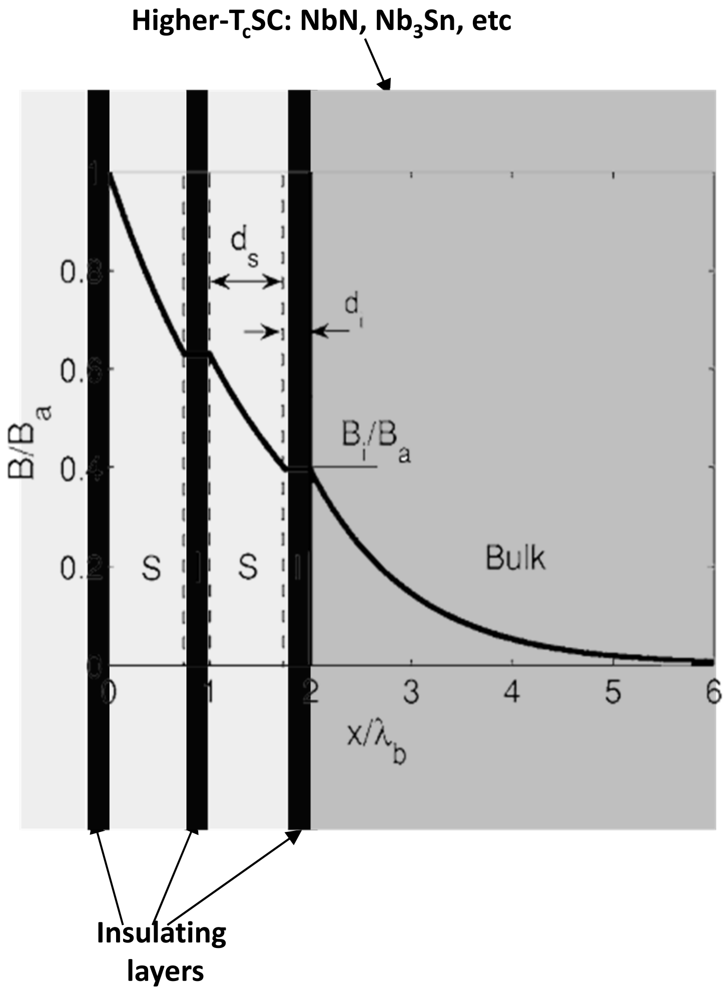
First high quality epitaxial films have been grown by C.-B. Eom (UW)

SIS MULITLAYERS

Beyond Nb: SIS Multilayers

Taking advantage of the high –Tc superconductors with much higher H_c without being penalized by their lower Hc1…

Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)



Multilayer coating of SC cavities: alternating SC and insulating layers with d < λ

Higher T_c thin layers provide magnetic screening of the Nb SC cavity (bulk or thick film) without vortex penetration

No thermodynamically stable parallel vortices due to the enhancement of H_{c1} in thin films with d < λ **(Abrikosov, 1964)**

$$H_{c1} = \frac{2\phi_0}{\pi d^2}\left(\ln\frac{d}{\xi} - 0.07\right)$$

The breakdown field could be increased up to the superheating field Hs of the coating: 450 mT for Nb3Sn

- **Strong reduction of BCS resistance because of using SC layers with higher Δ (Nb_3Sn, NbN, etc)**

  Pushes the accelerating gradient above 100 mV/m

- **Possibility to move operation from 2K to 4.2K**

Screening field in a multilayer

- Solutions of London equation for a layer with the penetration depth λ on a substrate with the penetration depth λ_0

$$h_1(x) = H[(1-c)e^{-x/\lambda} + ce^{x/\lambda}], \qquad 0 < x < d$$

$$h_2(x) = Hbe^{(d-x)/\lambda_0}, \qquad x > d$$

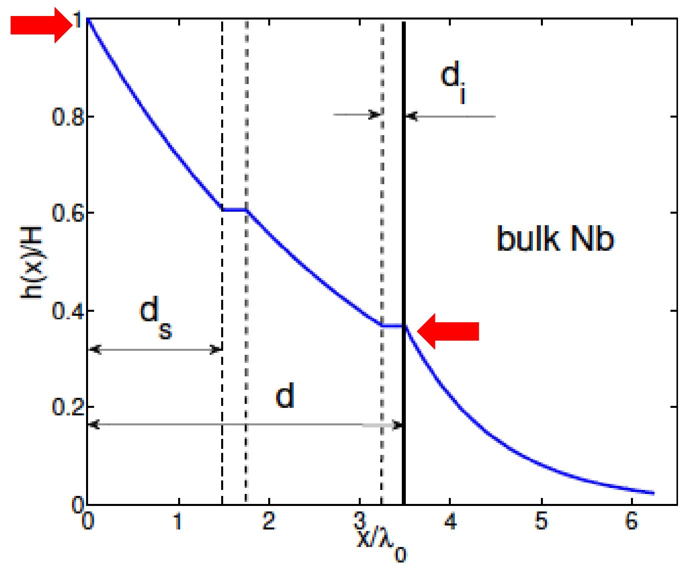
where c and b are given by:

$$c = \frac{k}{k+g^2}, \qquad b = \frac{(1+k)g}{k+g^2}$$

- Important parameters

$$k = \frac{\lambda - \lambda_0}{\lambda + \lambda_0}, \qquad g = \exp(d/\lambda)$$

T. Kubo, Y. Iwashita, and T. Saeki, APL 104, 032603 (2014);
A. Gurevich, AIP Advances, 5, 017112 (2015)



Meissner state breaks down at the surface of either ML or Nb where the current densities J(0) = h'(0) and J(d) = h'(d) are maximum

for the SC substrate (Nb) with $\lambda_0 < \lambda$, both c and k are positive

Current counterflow induced by the Nb substrate

- Current density in the layer J(x) = - h'(x):

$$J(x) = [(1-c)e^{-x/\lambda} - ce^{x/\lambda}]H/\lambda$$

- Current density at the surface J(0) is reduced by the substrate with $\lambda_0 < \lambda$:

$$J(0) = \left[1 - \frac{2k}{k+\exp(2d/\lambda)}\right]\frac{H}{\lambda} < J_d = \frac{H_s}{\lambda}$$

Counterflow induced by the substrate reduces the current density at the ML surface, allowing the Meissner state in the ML to survive up to fields exceeding the bulk superheating field H_s

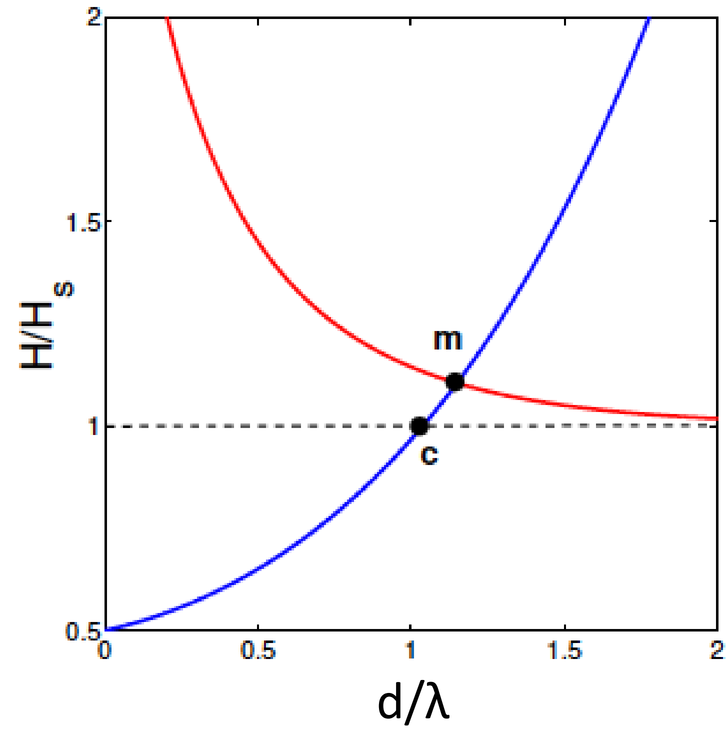
For a thick ML with d >> λ, the maximum field H_m is limited by H_s:
at optimum thickness d_m the field H_m exceeds both H_s and H_{s0}

Optimum thickness

- The Meissner state is stable if the screening current density at the surface of both the ML and the substrate is smaller than the depairing limit:

$J(0) < J_d = H_s/\lambda$ and $J(d) < J_{d0} = H_{s0}/\lambda_0$

$$\frac{(e^{2d/\lambda} - k)H}{e^{2d/\lambda} + k} \leq H_s, \qquad \frac{H(1+k)e^{d/\lambda}}{e^{2d/\lambda} + k} \leq H_{s0}$$



The Meissner state is below both blue and red lines.

The crossing point defines the optimum thickness d_m for maximum H_m which exceeds the superheating fields of both the layers and the substrate

$$d_m = \lambda \ln(\mu + \sqrt{\mu^2 + k}), \qquad \mu = \frac{H_s \lambda}{(\lambda + \lambda_0) H_{s0}}$$

for $H_s = 2H_{s0}$ and $k = ½$,
$d_c = \ln[\mu + (\mu^2 - k)^{1/2}]$

Maximum screening field

- The maximum screening field H_m corresponds to $d = d_m$ for which

$$H_m = \left[H_s^2 + \left(1 - \frac{\lambda_0^2}{\lambda^2}\right) H_{s0}^2\right]^{1/2}$$

H_m at the optimum thickness exceeds the bulk superheating fields of both Nb and the layer material. For $\lambda >> \lambda_0$, practically for $\lambda > 160$ nm for a SC layer on the Nb cavity with $\lambda_0 = 40$ nm, H_m approaches the limit

$$H_m \to \sqrt{H_s^2 + H_{s0}^2}$$

Let us evaluate H_m for a ML on clean Nb with $\lambda_0 = 40$ nm and $H_{s0} = 1.2H_c = 240$ mT (the GL result for clean Nb) and different layer materials, such as Nb_3Sn, NbN, pnictides, and also dirty Nb

A. **Gurevich, AIP Advances, 5, 017112 (2015)**

Estimates of H_m and d_m

- **Nb$_3$Sn:** $H_s = 0.84H_c =$ 454 mT and λ = 120 nm (moderately dirty):

  H_m = 507 mT, $d_m = 1.1\lambda$ = 132 nm

  doubles the superheating field of clean Nb

- **Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$,** T_c = 38 K, H_c = 0.9T, H_s =756 mT, λ = 200 nm

  H_m = 930 mT, $d_m = 1.78\lambda$ = 356 nm.

  almost quadruples the superheating field of clean Nb

- **dirty Nb layer:** H_c = 200 mT, H_s = 170 mT, l = 2 nm, and $\lambda = \lambda(\xi_0 / l)^{1/2}$ = 180 nm

  H_m = 288 mT, $d_m = 0.44\lambda$ = 79 nm.

  20% gain as compared to H_s = 240 mT of clean Nb

SIS Multilayers – The Benefits

- Multilayer S-I-S-I-S coating could make it possible to take advantage of superconductors with much higher H_c, than those for Nb without the penalty of lower H_{c1}
- Strong increase of H_{c1} in films allows using rf fields > H_c of Nb, but lower than those at which flux penetration in grain boundaries may become a problem
- Strong reduction of BCS resistance because of using SC layers with higher Δ(Nb_3Sn, NbN, …)

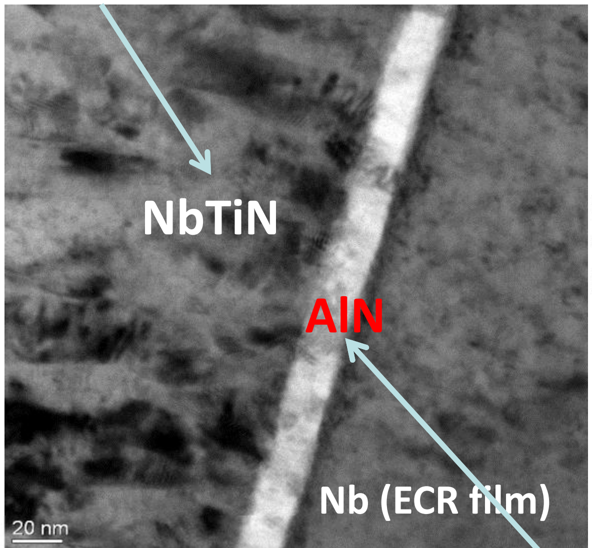
The significant performance gain may justify the extra cost.

… but …

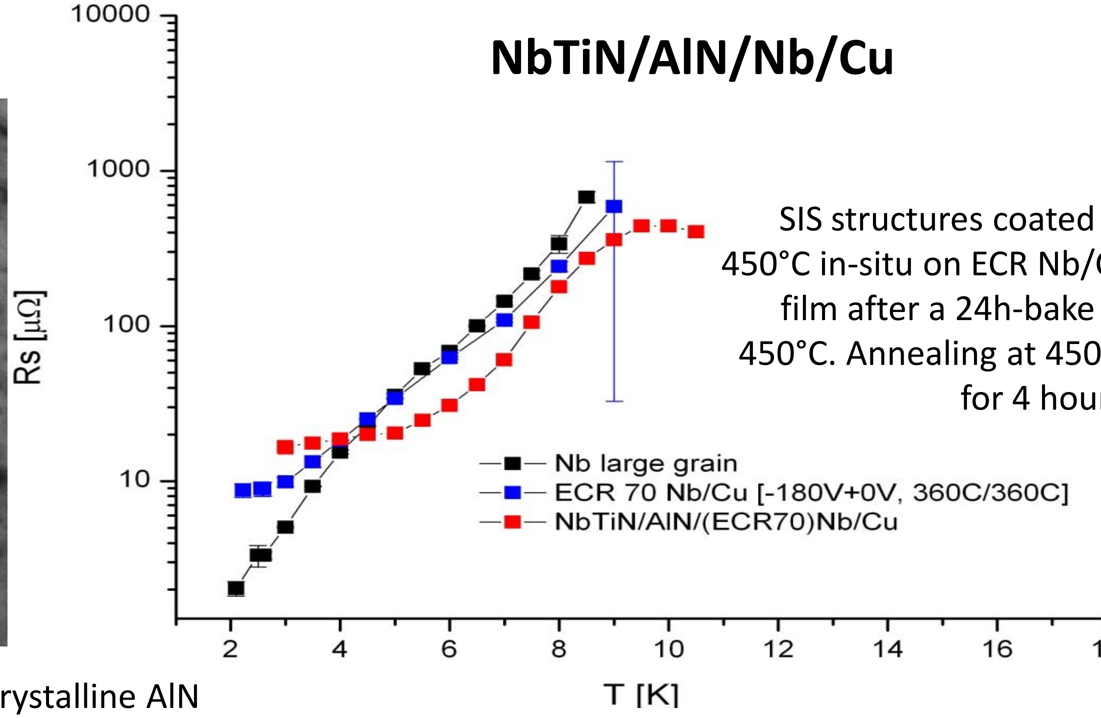
Technical challenges, influence of composition on Hc1 and Hc, influence of the morphology and composition at grain boundaries, …

SIS NbTiN/AlN structures on Nb surfaces

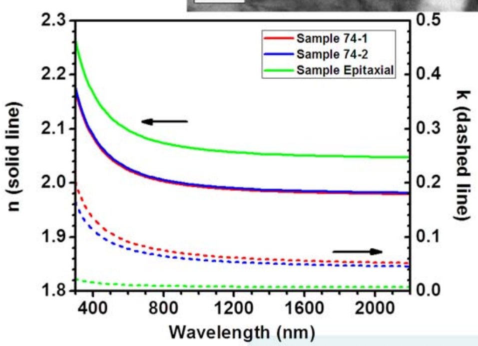
150 nm polycrystalline NbTiN
Tc=16.9K



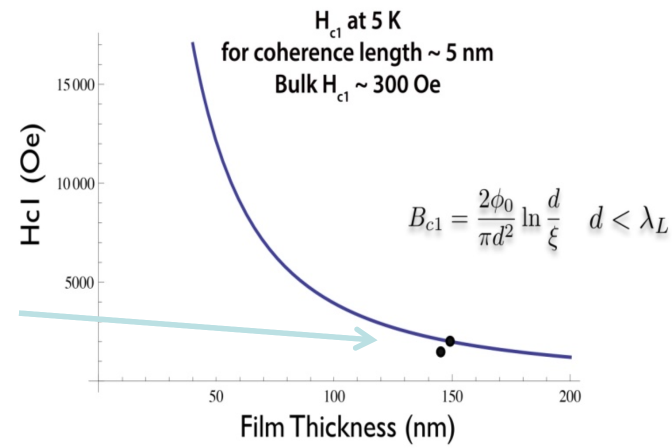
20 nm polycrystalline AlN
n=2.02
(range in Lit. n = 1.9-2.1)



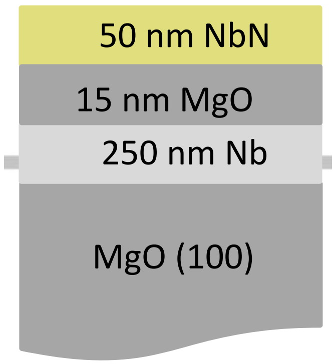
SIS structures coated at 450°C in-situ on ECR Nb/Cu film after a 24h-bake at 450°C. Annealing at 450°C for 4 hours.



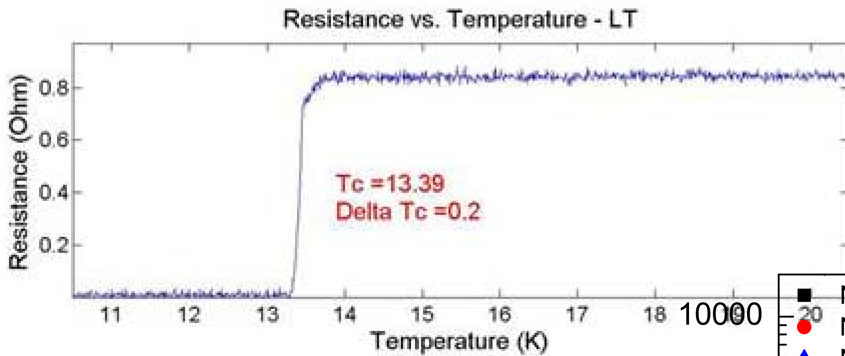
	Thickness [nm]	H_{c1} [mT]	T_c [K]
NbTiN/MgO	2000	30	17.25
NbTiN/AlN/AlN ceramic	145	135	14.84
NbTiN/AlN/MgO	148	200	16.66



Lower BCS resistance beyond 4 K for SIS coated Nb/Cu film compared to standalone film & bulk Nb. Similar effect observed for NbTiN/AlN/bulk Nb.



NbN based SIS structures

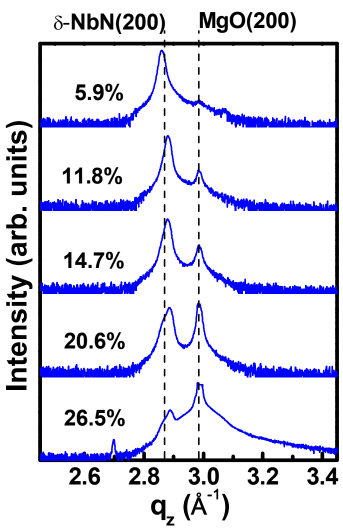


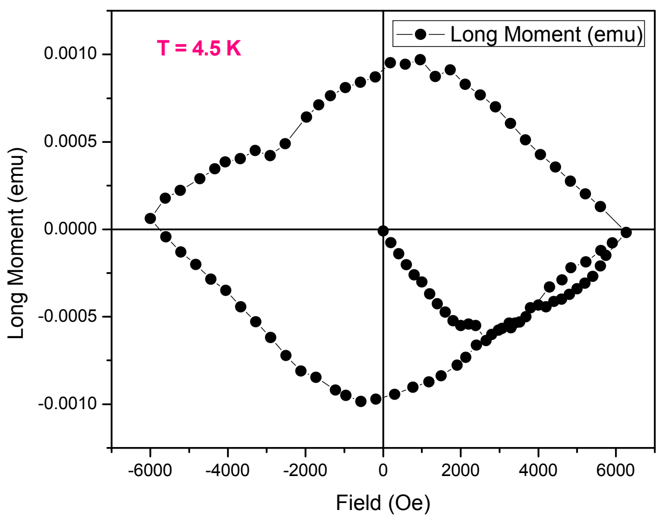
College William & Mary (Prof. Lukaszew)
CEA Saclay (C. Antoine)

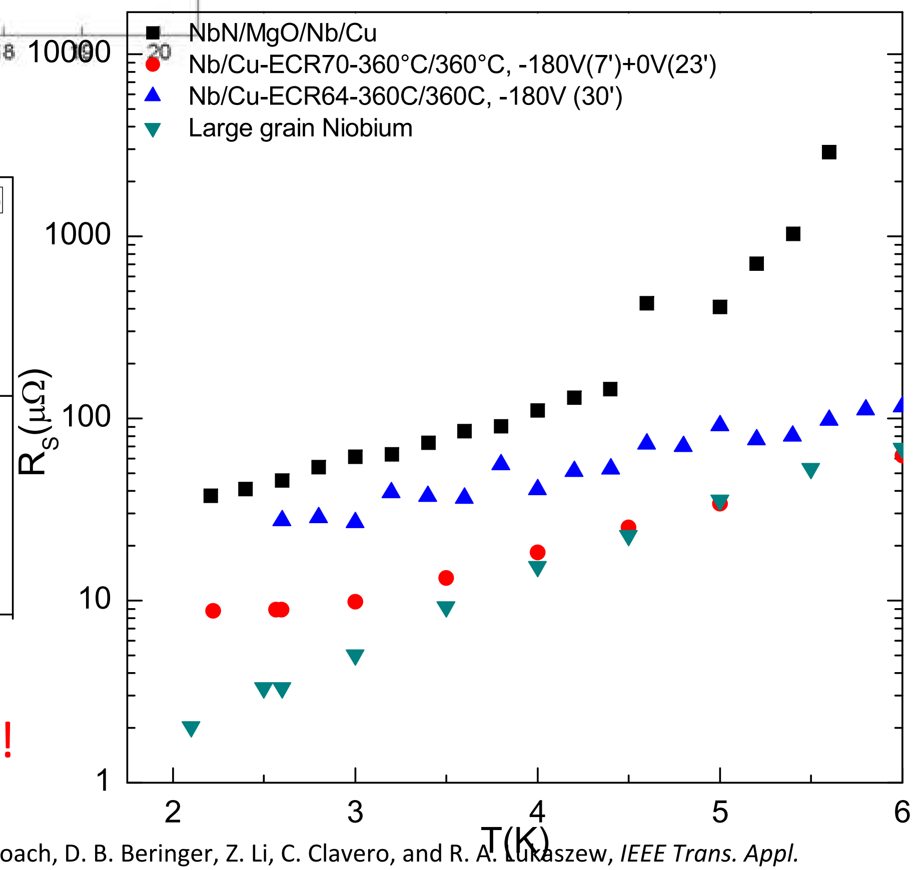
Standalone NbN films T_c ~ 15 K

NbN tri-layer T_c ~ 13.4 K

Single crystal NbN films





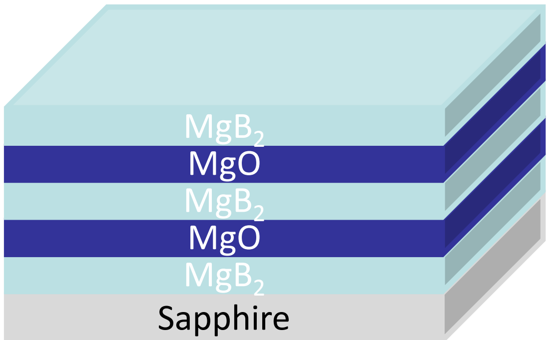


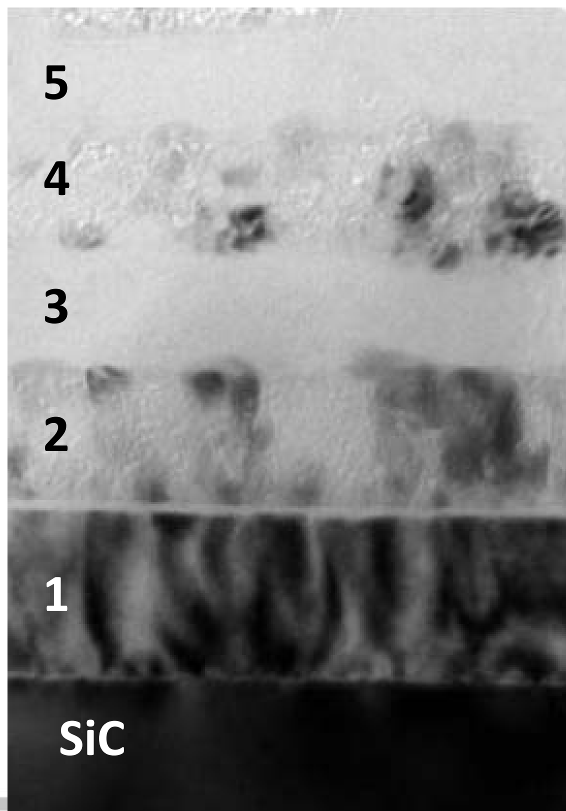
$H_{c1\text{-NbN-based-Multilayer}}$ ~ 220 mT!

$H_{c1\text{-bulk Nb}}$ = 170 mT

"Magnetic Shielding Larger than the Lower Critical Field of Niobium in Multilayers" W. M. Roach, D. B. Beringer, Z. Li, C. Clavero, and R. A. Lukaszew, *IEEE Trans. Appl. Supercond.* **23**, 8600203 (2013).

MgB_2-MgO Multilayer Films





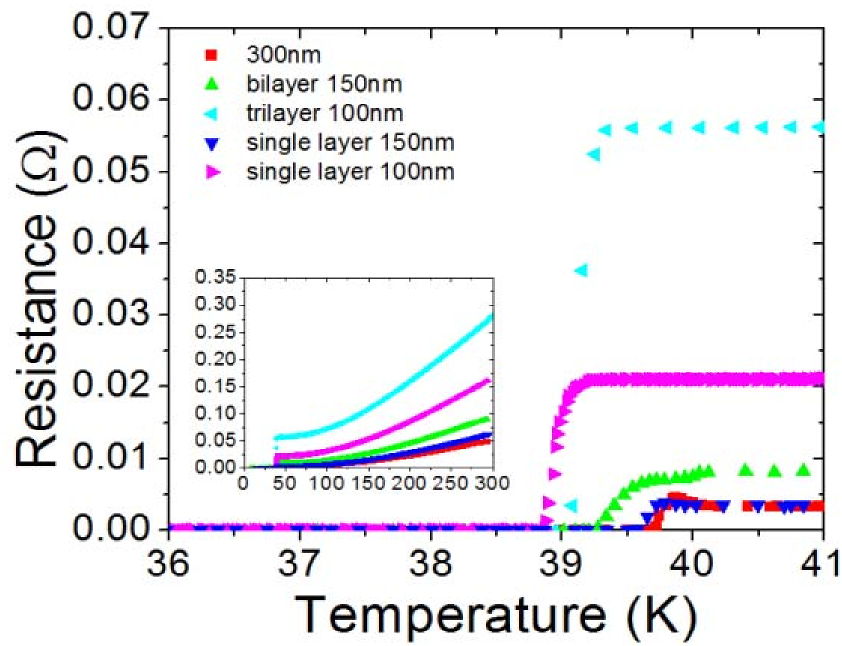
5. a-MgB_2

4. poly-MgO

3. a-MgB_2

2. poly-MgO

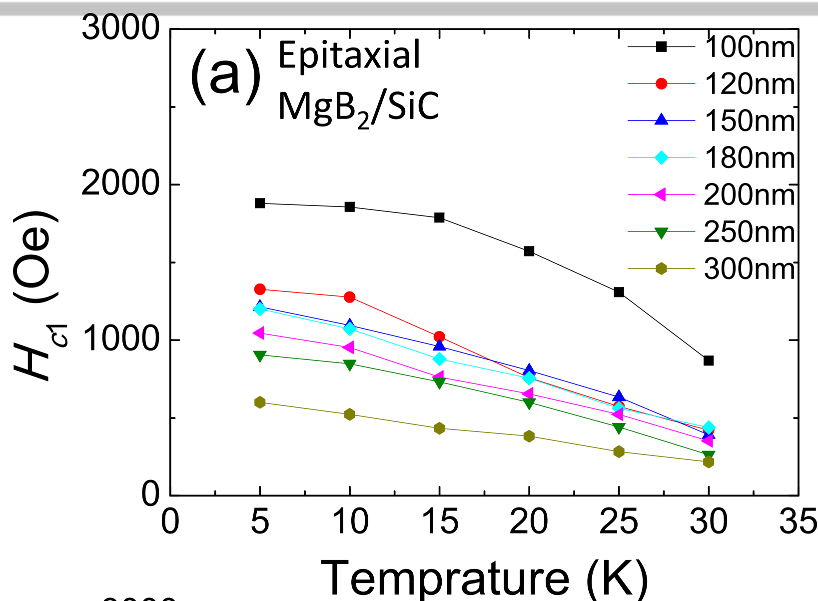
1. Epitaxial MgB_2

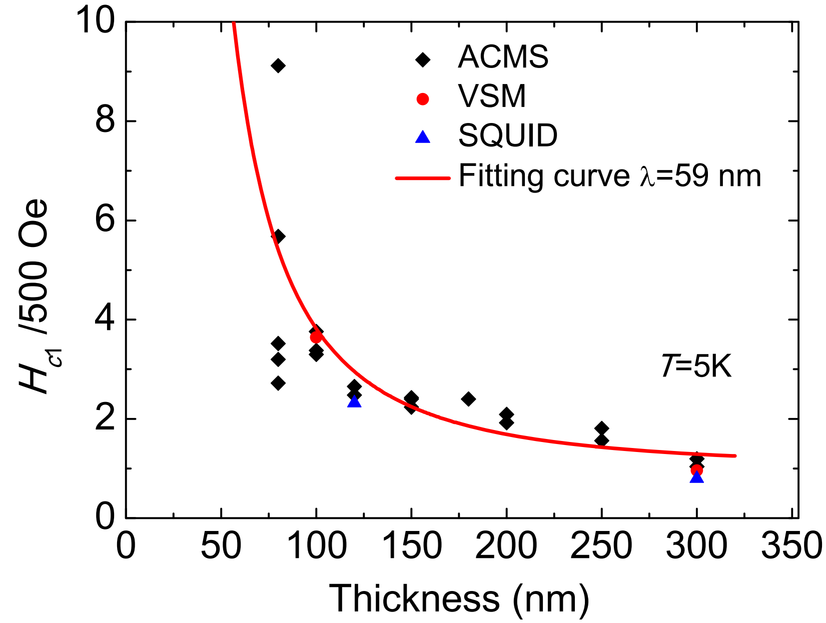


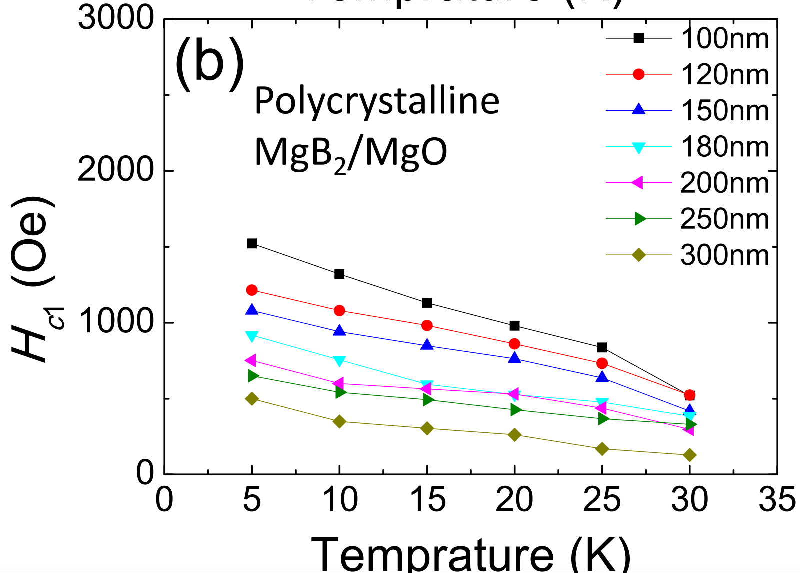
Alternating MgB_2-insulator structures have been fabricated on sapphire substrate. Sputtering MgO are used as insulating layer.

Top MgB_2 layers amorphous.

Epitaxial and Polycrystalline Films: H_{c1} vs Thickness







$$\frac{H_{c1}}{H_{c1b}} = \{1 + \int_0^\infty \frac{(\tanh\sqrt{k^2 + (d/\lambda)^2} - 1)dk}{(\ln\kappa + 0.5)\sqrt{k^2 + (d/\lambda)^2}}\} / (1 - \mathrm{sech}\frac{d}{2\lambda})$$

Epitaxial and polycrystalline MgB_2 films both show increase in $H_{c1}(0)$ with decreasing film thickness.

References

- Experimental evidences of the enhancement of the parallel H_{c1} in thin films

L. Civale, T.K. WoA. Gupta, Phys. Rev. B 48, 7576 (1993).

C. Antoine, et al Phys. Rev. ST-AB 13, 121001 (2010).

T. Tajima, et al. J. Phys. Conf. Ser. 234, 012043 (2010); AIP Conf. Proc. 1435, 297 (2012).

DB Beringer, C Clavero, T Tan, XX Xi, WM Roach, RA Lukaszew IEEE Trans. Appl. Supercond. 23, (2013)

- Increasing the high-field performance and reduction of R_s by a NbN overlayer

C.Z. Antoine, J.-C. Villegier, G. Martinet, APL 102, 102603 (2013).

WM Roach, DB Beringer, Z Li, C Clavero, RA Lukaszew, IEEE Trans. Appl. Supercond. 23 (2013)

CONCLUDING REMARKS

- ✓ Progress in energetic condensation deposition techniques opens the way to high quality Nb/Cu films and the reduction of the Q-slope of Nb/Cu cavities may be in sight.

✓Over the years, some attempts have been made to study alternative materials to Nb for applications to SRF cavities.

✓Most of the sample/cavities using alternative materials have been produced by reactive magnetron sputtering or thermal diffusion.
✓Use of Energetic Condensation Techniques like Vacuum Arc Deposition, ECR, or ALD? (production of very dense films with nm-scale roughness…Some trials with Vacuum Arc @ INFN-Rome, non conclusive)

CONCLUDING REMARKS

✓The multilayer approach opens the door to further potential improvement for SRF cavities, taking benefits from the advantages of higher T_c superconductors without the penalty of lower field onset for vortex penetration and increase the accelerating gradient and Q.

✓Strong reduction of the BCS resistance for superconducting layers with higher Δ(Nb_3Sn, MgB_2, BKBO, NbN … s-wave, fully gapped superconductors)

✓New non-magnetic members of the oxypnictide family with 15K < T_c< 55K or $BaO_{0.6}K_{0.4}BiO_3$ with T_c≈30K: a possibility to greatly increase Q if TF coating can be developed.

CONCLUDING REMARKS cont.

✓Possibility to move from 2K to 4.2K: huge cost saving on refrigeration in LINACS

✓Higher –T_c s-wave materials are often multi-gap superconductors, which do not always have better SRF performance despite higher H_c and T_c

✓First experimental evidence of field enhancement with NbN/MgO/…/Nb, NbTiN/AlN/Nb/Cu samples with SQUID measurement with H // sample plane. Field penetration delayed for NbN , NbTiN layered samples compared to Nb sample.

CONCLUDING REMARKS cont.

✓Many long-standing problems of condensed matter physics and non-equilibrium superconductivity will have to be addressed to understand nonlinear surface resistance under strong rf fields

✓Multi-parameter materials optimization is required to unravel the full SRF performance potential.

✓The effort for new materials research for SRF cavities application has been very limited so far…but interest has been regained. There is still a lot of work ahead!