A-M Valente-Feliciano

G. Eremeev, C. Reece, J. Spradlin (JLab)
M. Burton, A. Lukaszew (W&M)
A. Aull (CERN)
J. Skuza (NSU)

Multilayer Approach to Increase the Performance of SRF Accelerating Structures beyond Bulk Nb

Outline

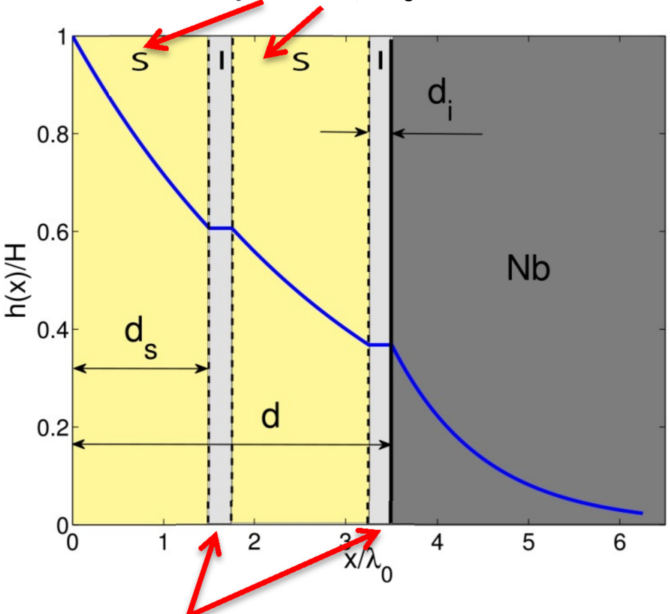
- ☐ Theoretical Proposal: SIS Concept
- ☐ Choice of Materials
- ☐ Experimental Setup
- ☐ NbTiN films
- ☐ AlN Films
- ☐ SRF NbTiN/AlN SIS Structures
- ☐ Concluding Remarks

Beyond Nb: SIS Multilayers

Taking advantage of the high –T_c superconductors with much higher H_c without being penalized by their lower H_{c1}…

Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)
Alex Gurevich, AIP ADVANCES 5, 017112 (2015)
T. Kubo, Applied Physics Letters 104, 032603 (2014)

Higher-T_cSC: NbN, Nb_3Sn, etc



Insulating layers

Multilayer coating of SC cavities:
alternating SC and insulating layers with $d < \lambda$

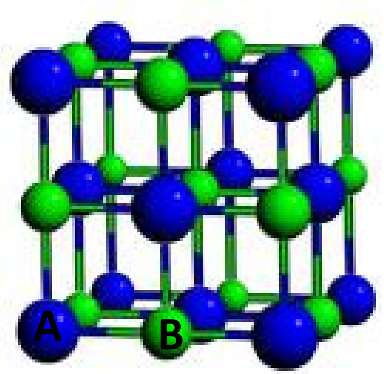
Higher T_c thin layers provide magnetic screening of the Nb SC cavity (bulk or thick film) without vortex penetration

- ☐ 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=> no transition, no vortex in the layer
- ☐ High H_{C1} ,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
- ☐ Strong reduction of BCS resistance (ie high Q_0) because of using SC layers with higher T_c, Δ (Nb_3Sn, NbN, etc)

Possibility to move operation from 2K to 4.2K

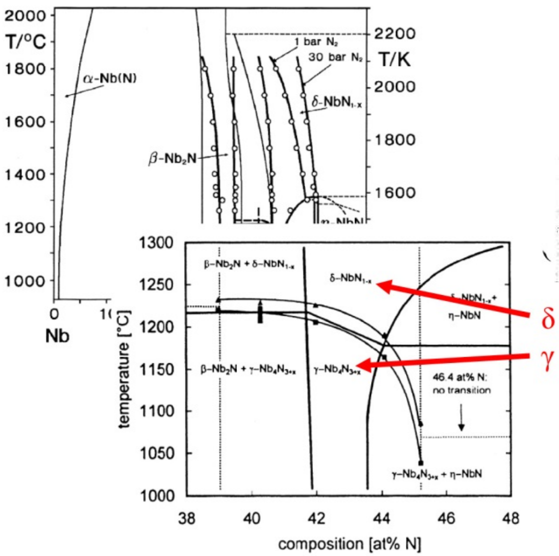
Choice of Materials for S-I-S structures

Ternary Nitride $(Nb_{1-x},Ti_x)N$ (T_c=17.3 K, a= 4.341 Å)



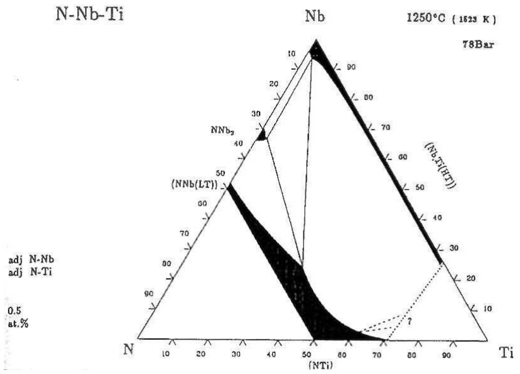
Presence of Ti found to reduce significantly the resistivity
And facilitate formation of a pure cubic structure.
The δ-phase remains thermodynamically stable even at RT.
T_c as high as for good quality NbN, for Nb fraction (1-x)>0.5

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



$\delta - NbN \rightarrow T_c \sim 15 - 17.3$ K

$\gamma - NbN \rightarrow T_c \sim 12 - 15$ K

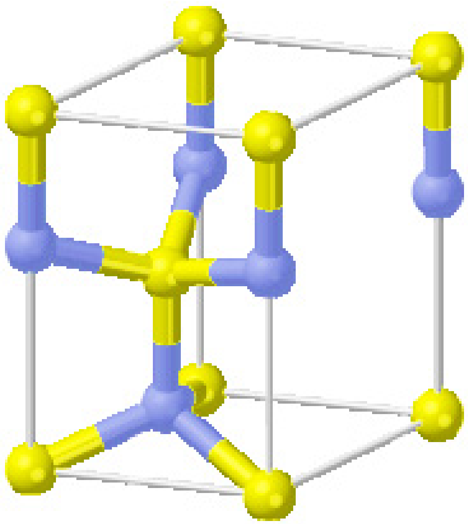


extreme hardness, excellent adherence on various substrates, very good corrosion and erosion resistance, high-sublimation temperature, and relative inertness

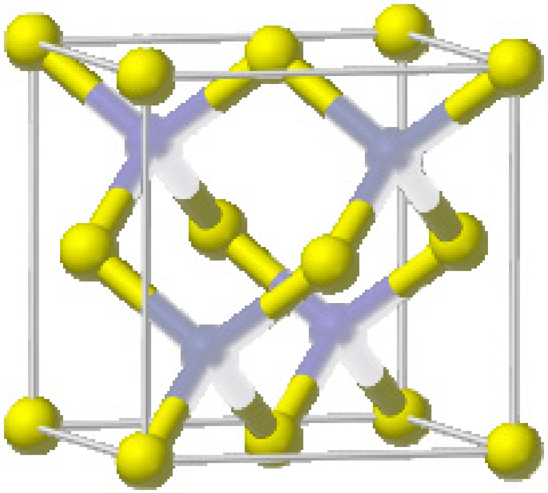
Choice of dielectric for S-I-S structures

AlN is an insulator that :

- can be grown with a wurtzite (hcp, a=3.11Å, c=4.98Å) or sphalerite (B1 cubic, a= 4.08 Å) structure.
- has been found to enhance the properties (T_c) of NbN and NbTiN, in particular for very thin films .
- has a large thermal conductivity (3.19W/cm.K at 300K, comparable with Cu, 4.01W/cm.K)

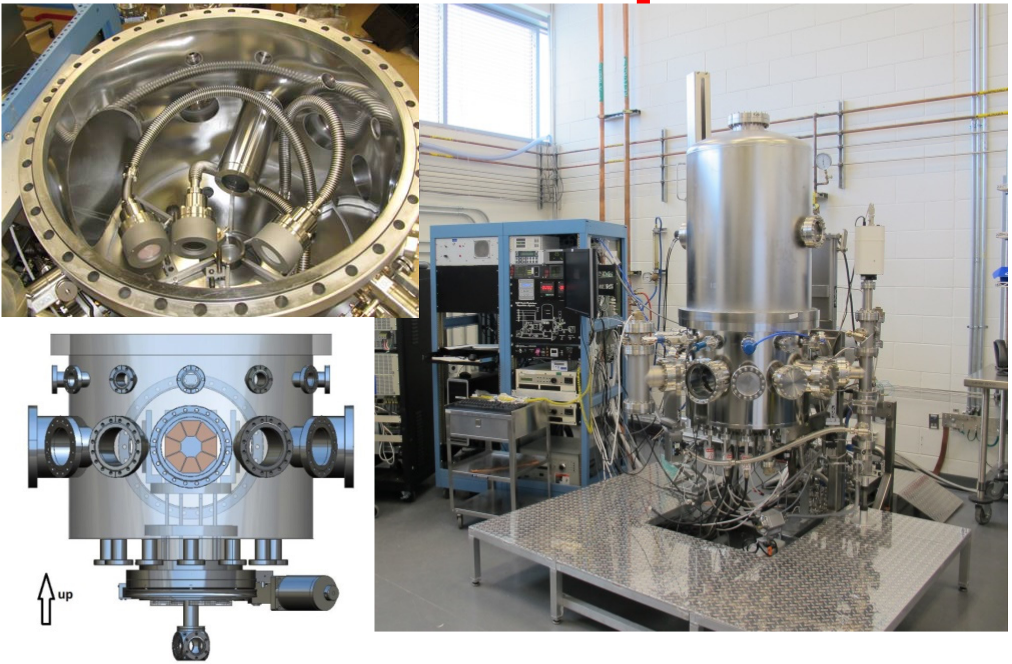


Wurtzite structure



Sphalerite structure

Experimental Setup



Base pressure range: 10^{-10} Torr

- 3 x 2” DC/RF Magnetrons
- Ion source
- dc-Magnetron Sputtering (reactive mode)
- HiPIMS (Huettinger 2000 V, 3000 A)

Substrates:

MgO

AlN ceramic

Bulk Nb

ECR Nb films

CHALLENGES

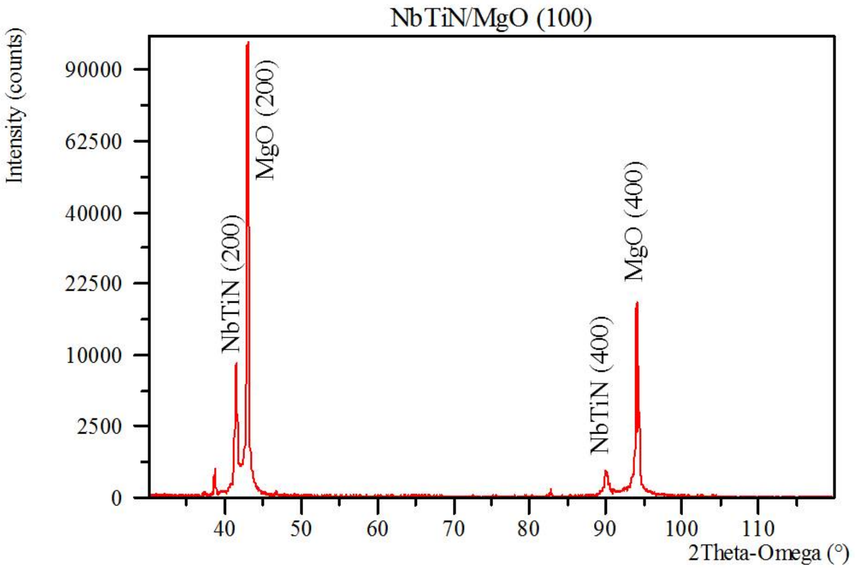
- Develop good quality and uniform thin layers
- Sharp interfaces
- Growth of equally performing S/I and I/S layers

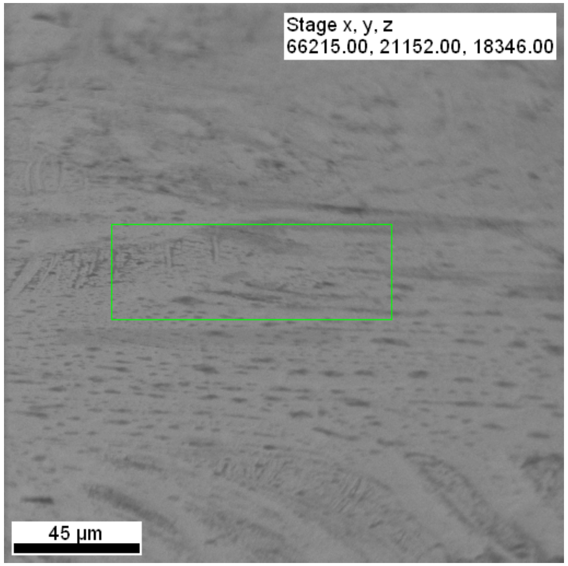
NbTiN film

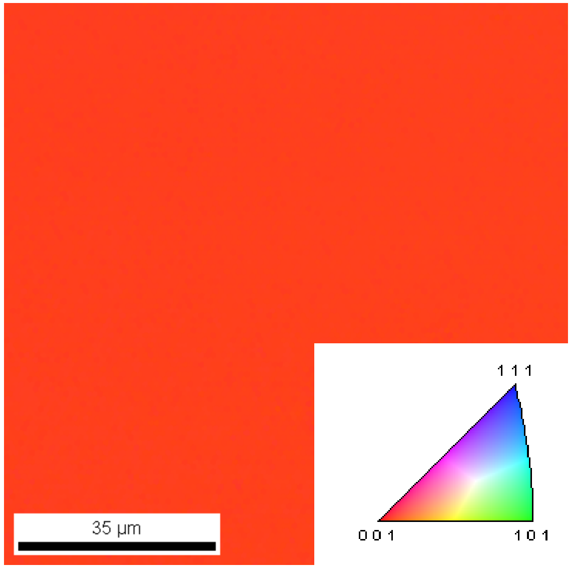
NbTiN are grown on various substrates at 600°C by reactive sputtering with targets of different Nb/Ti weight ratios.

Films exhibit good crystalline structure in general

Best results at 600 °C on MgO







NbTiN grown at 600°C on MgO

Thickness = 2µm

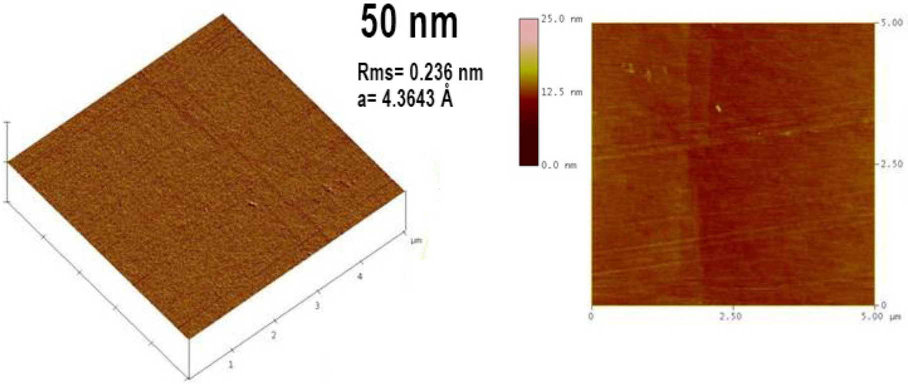
High quality single crystal

T_c= 17.25 K

H_{c1} = 30 mT

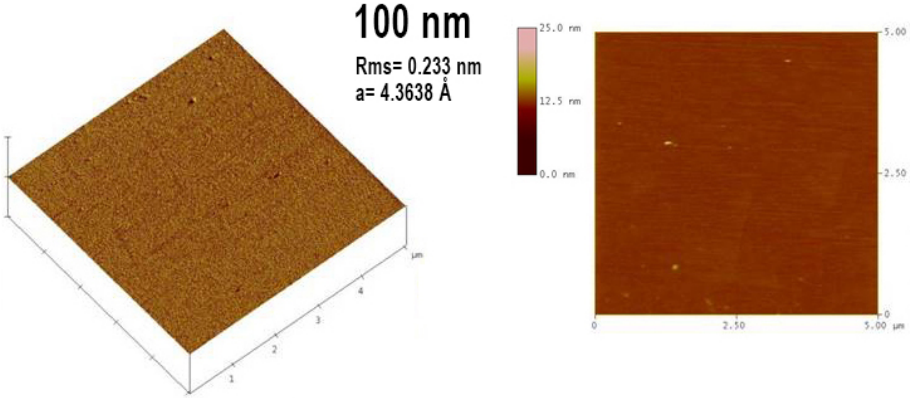
Bulk-like film

NbTiN Films – Influence of Thickness on Tc



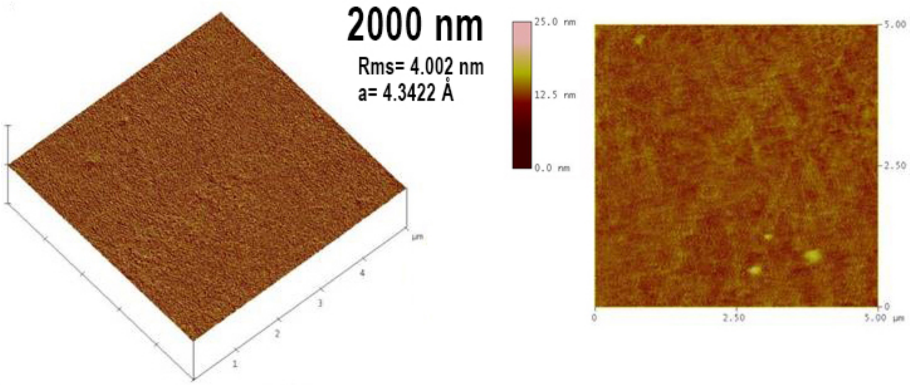
50 nm

Rms= 0.236 nm
a= 4.3643 Å



100 nm

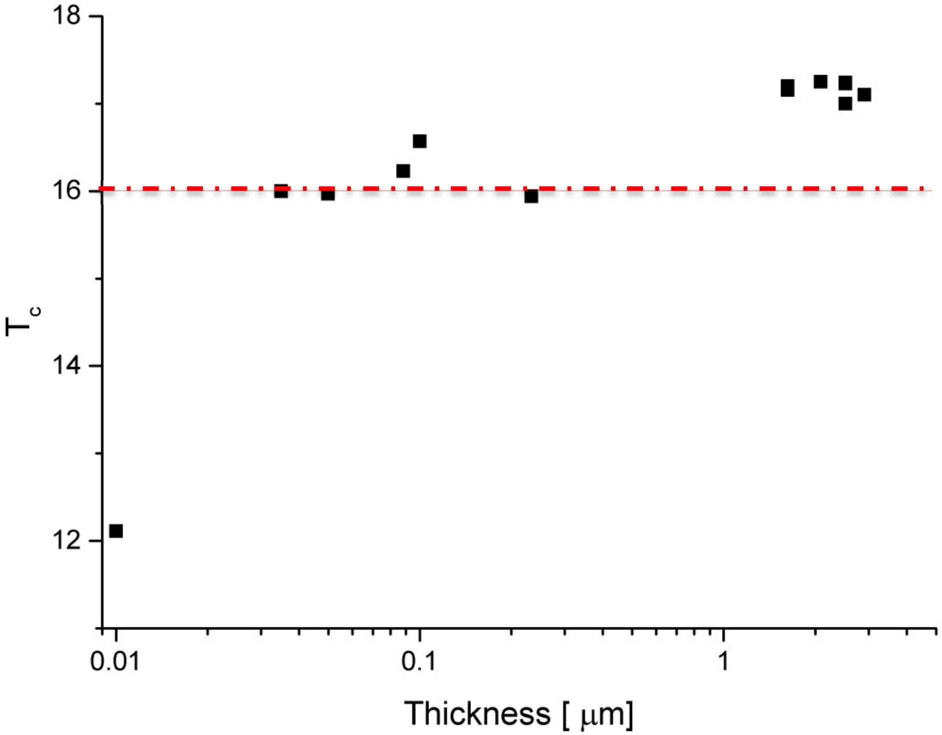
Rms= 0.233 nm
a= 4.3638 Å



2000 nm

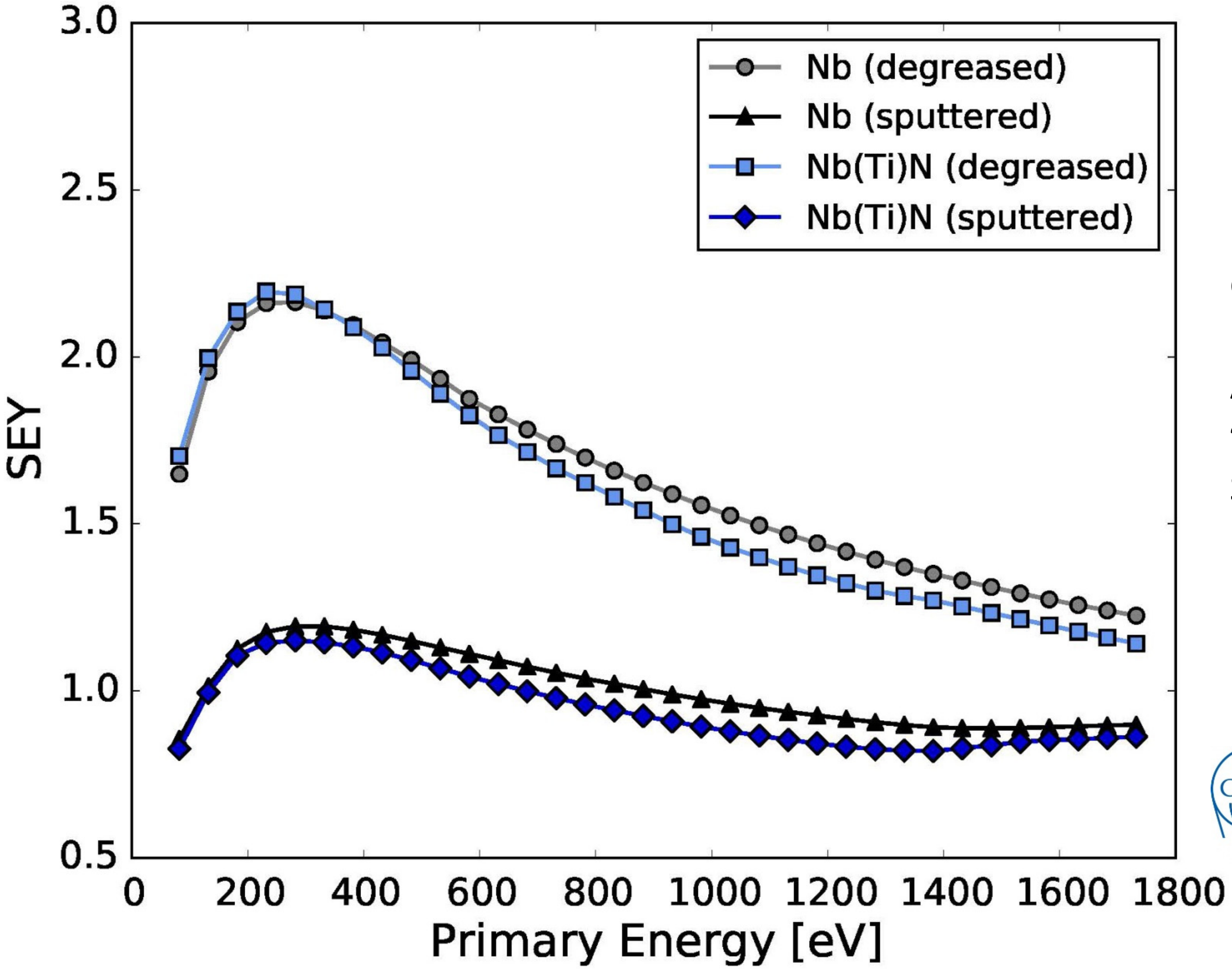
Rms= 4.002 nm
a= 4.3422 Å

Single crystal NbTiN/MgO films (XRD/EBSD)
Very smooth films (~ substrate)



T_c ≥16 K for film thickness > 35 nm

Secondary Electron Yield of NbTiN Films

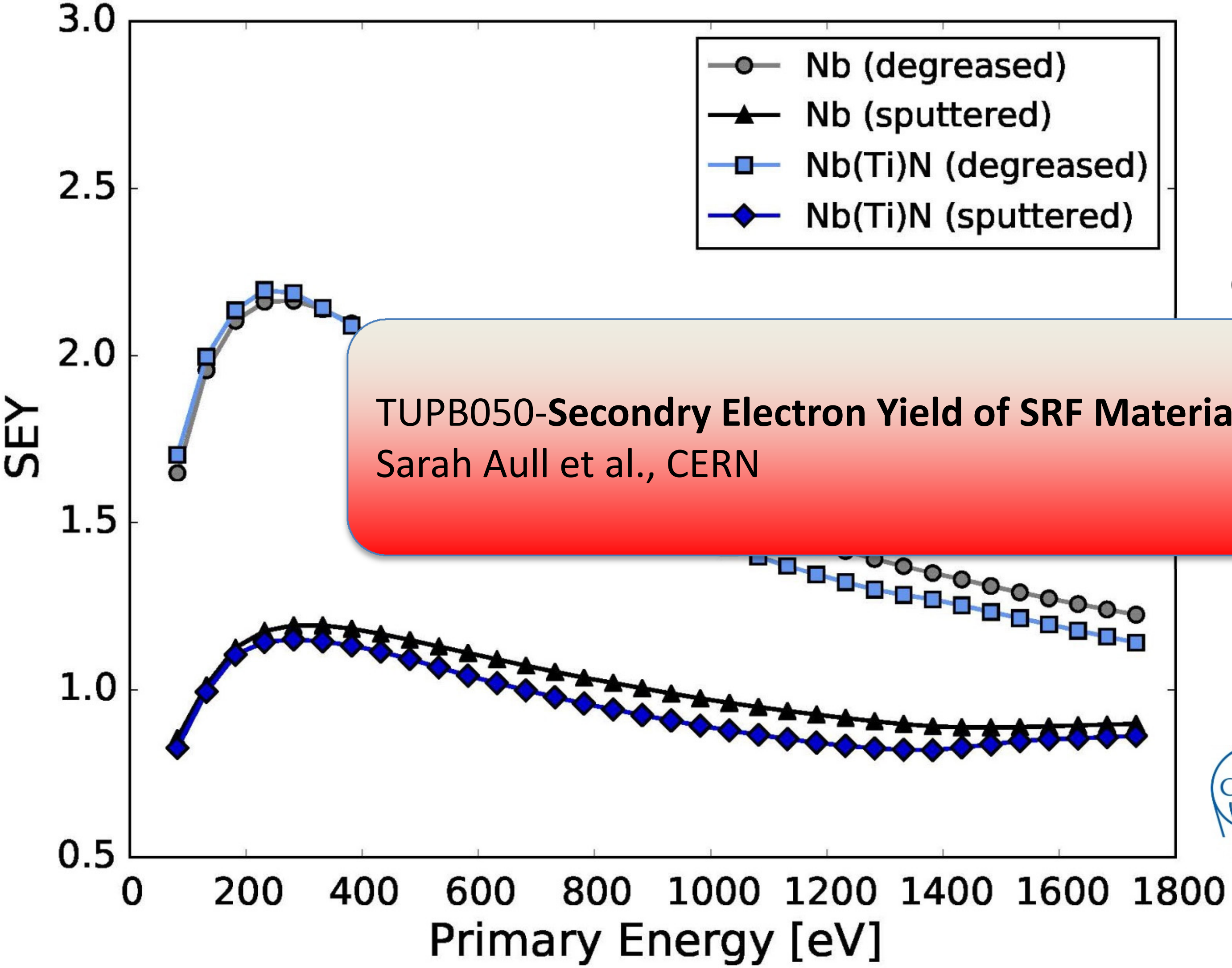


Measurements at
room temperature

Max. SEY =2.2 ± 0.1
comparable to EP Nb

After sputtering away
~ 3 nm,
SEY down to 1.15

Secondary Electron Yield of NbTiN Films



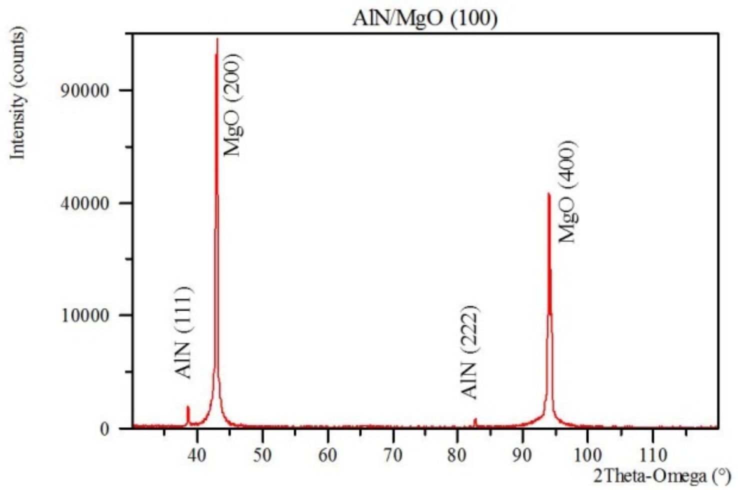
TUPB050-**Secondry Electron Yield of SRF Materials**
Sarah Aull et al., CERN

Measurements at room temperature

Max. SEY =2.2 ± 0.1 comparable to EP Nb

sputtering away
m,
lown to 1.15

AlN Films



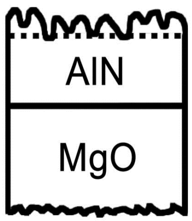
Structure

AlN films were coated by reactive sputtering with different parameters. They were found to become fully transparent for N_2/Ar ratios of ~33%.

Good quality AlN are readily produced at 600 and 450°C by dc-reactive magnetron sputtering.

The films exhibit the cubic structure (single crystal) at 600 °C and the hexagonal structure (polycrystalline) at 450 °C .

Dielectric Behavior



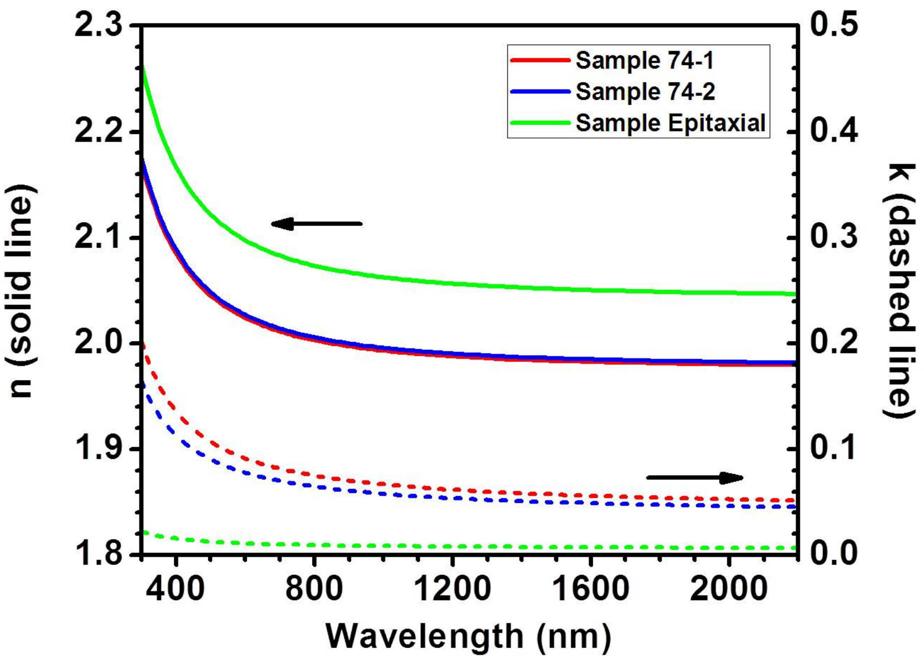
Roughness - EMA with 50% Void (XRR thickness used)

Film - Cauchy w/ Urbach Absorption (XRR thickness used)

Substrate - Palik bulk optical constants; 0.5 mm

At 450 °C, 30 nm AlN films exhibit dielectric properties of polycrystalline AlN films

n in the range of 1.98- 2.15



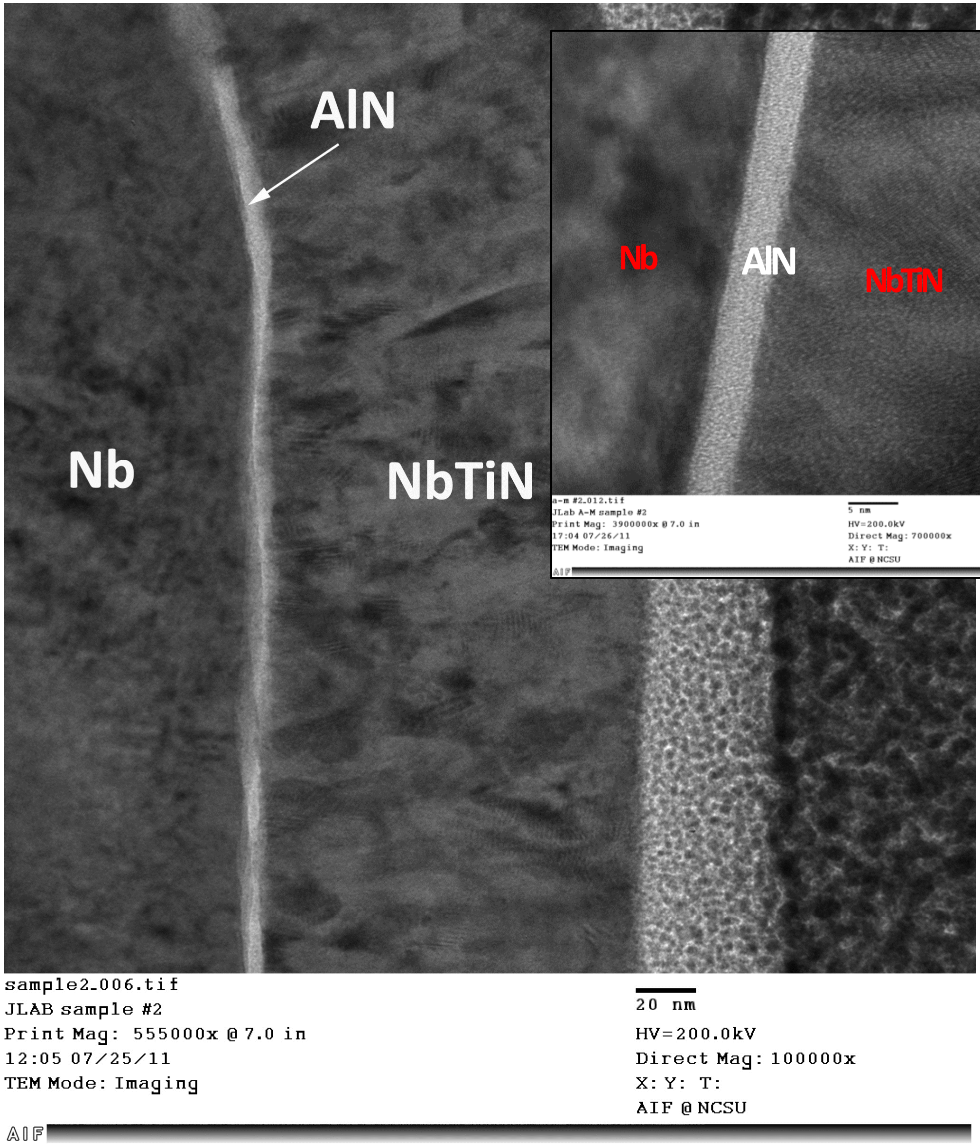
SRF Multilayer Structures Based on NbTiN
Influence of coating temperature

NbTiN/AlN/Nb film at 600 °C

	AlN	NbTiN
N_2/Ar	0.33	0.23
Total pressure [Torr]	2x10^{-3}	2x10^{-3}
Sputtering Power [W]	100	300
Deposition rate [nm/min]	~ 2.5	~ 18
Thickness [nm]	5	100
T_c [K]	N/A	14

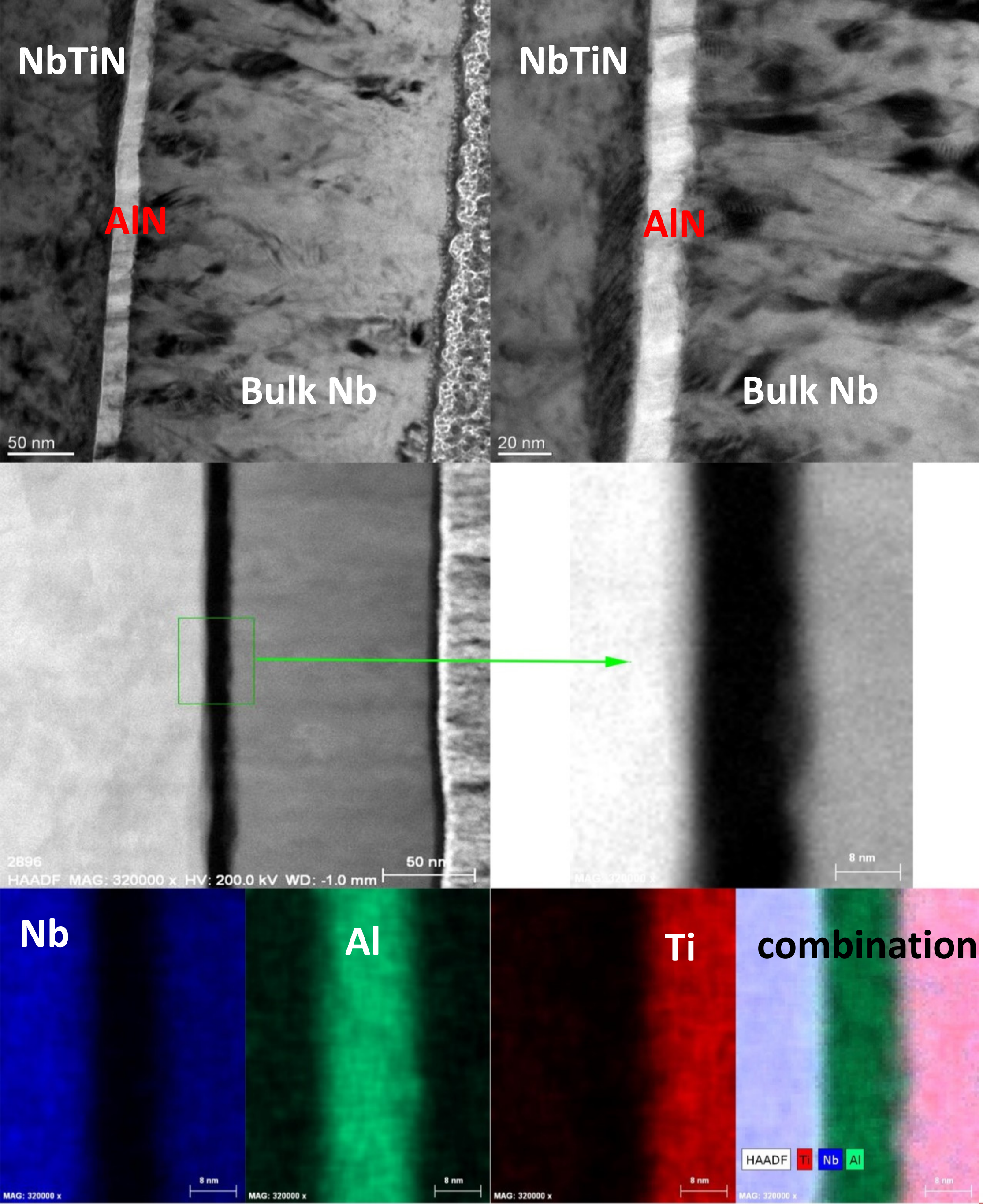
TEM cross-section (FIB cut) of NbTiN/AlN/Nb/Cu structure

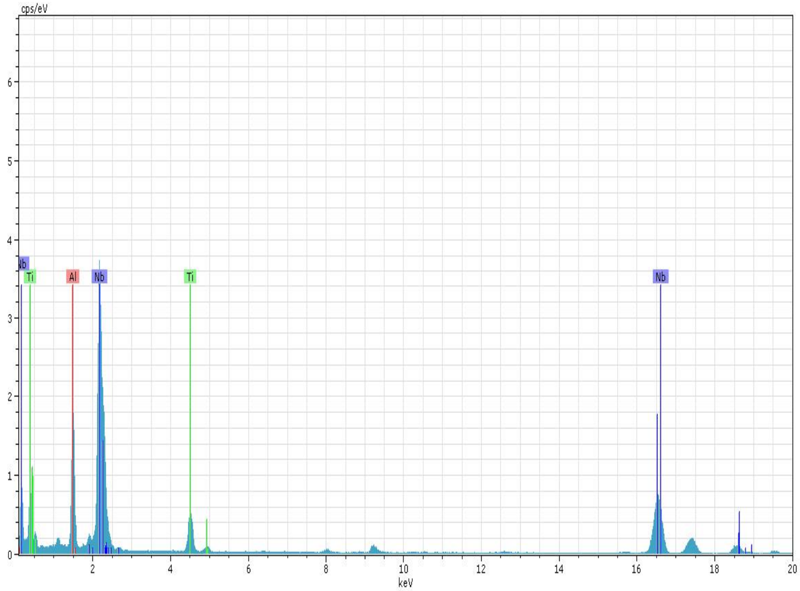
Miscibility of AlN into Nb and NbTiN at 600 °C



NbTiN/AlN on bulk Nb

TEM cross-section (FIB cut) of NbTiN/AlN/bulk Nb structure

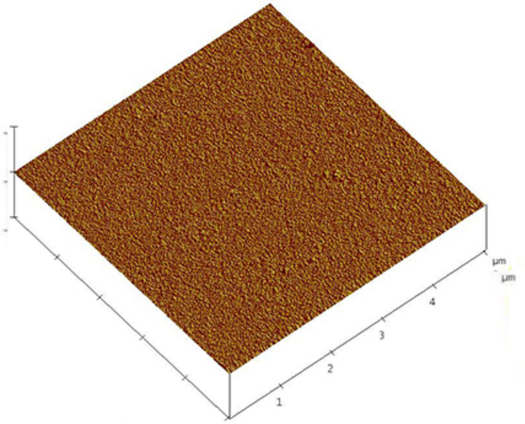




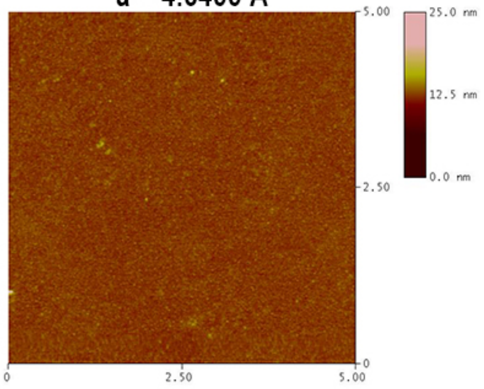
SRF Multilayer Structures Based on NbTiN

Influence of roughness & interlayer on T_c

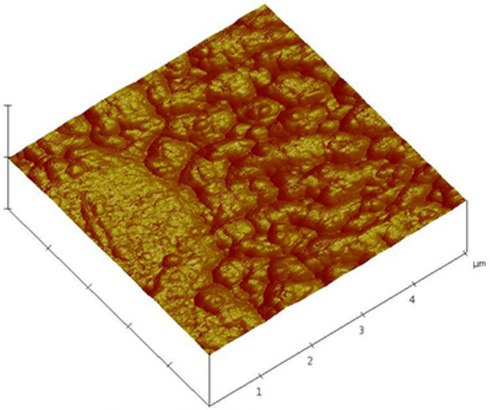
NbTiN/AlN/MgO (100)



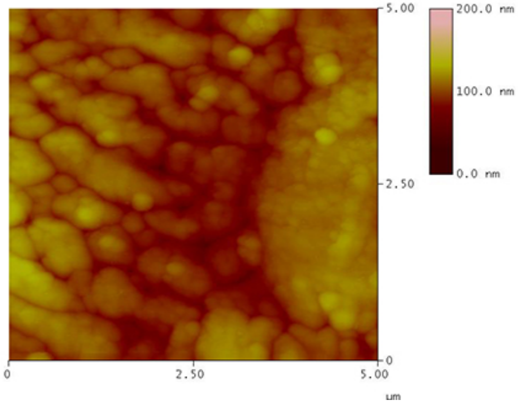
Rms=0.396 nm
a = 4.3455 Å



NbTiN/AlN/AN ceramic

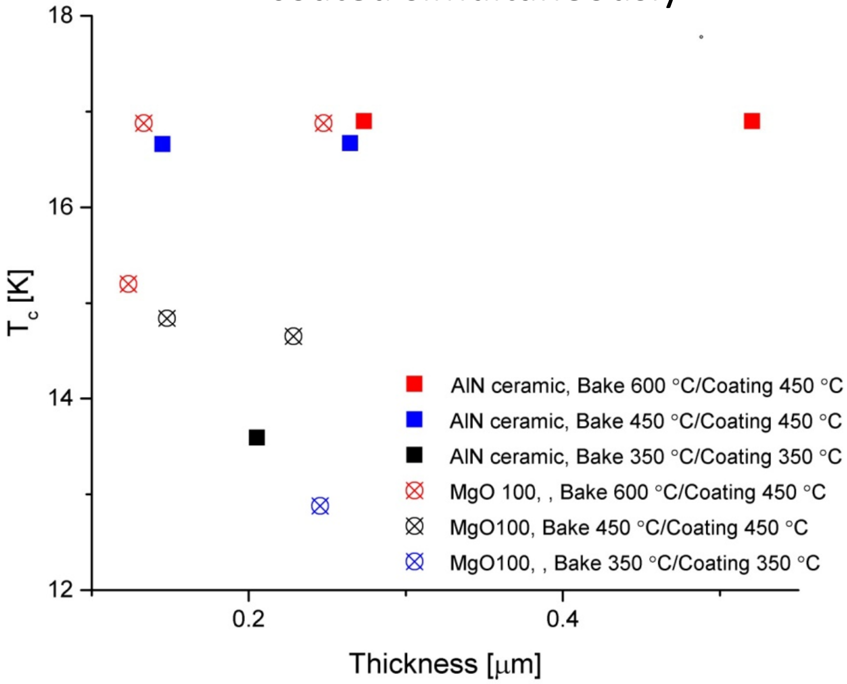


Rms=13.434 nm
a = 4.3584 Å



Quality of underlying AlN dictates
quality of the NbTiN film
Roughness of substrate not detrimental to Tc

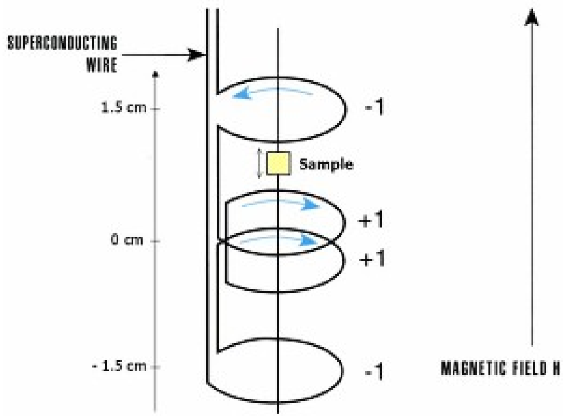
SI layers on MgO and AlN
coated simultaneously

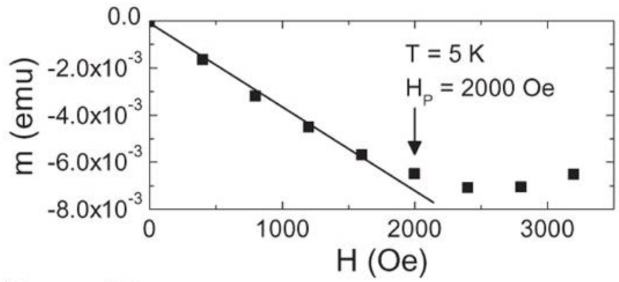


NbTiN Films (SI) – H_{c1} measurement

SQUID Magnetometry

(Prof. A. Lukaszew group, College William & Mary)





150 nm NbTiN/AlN films exhibit

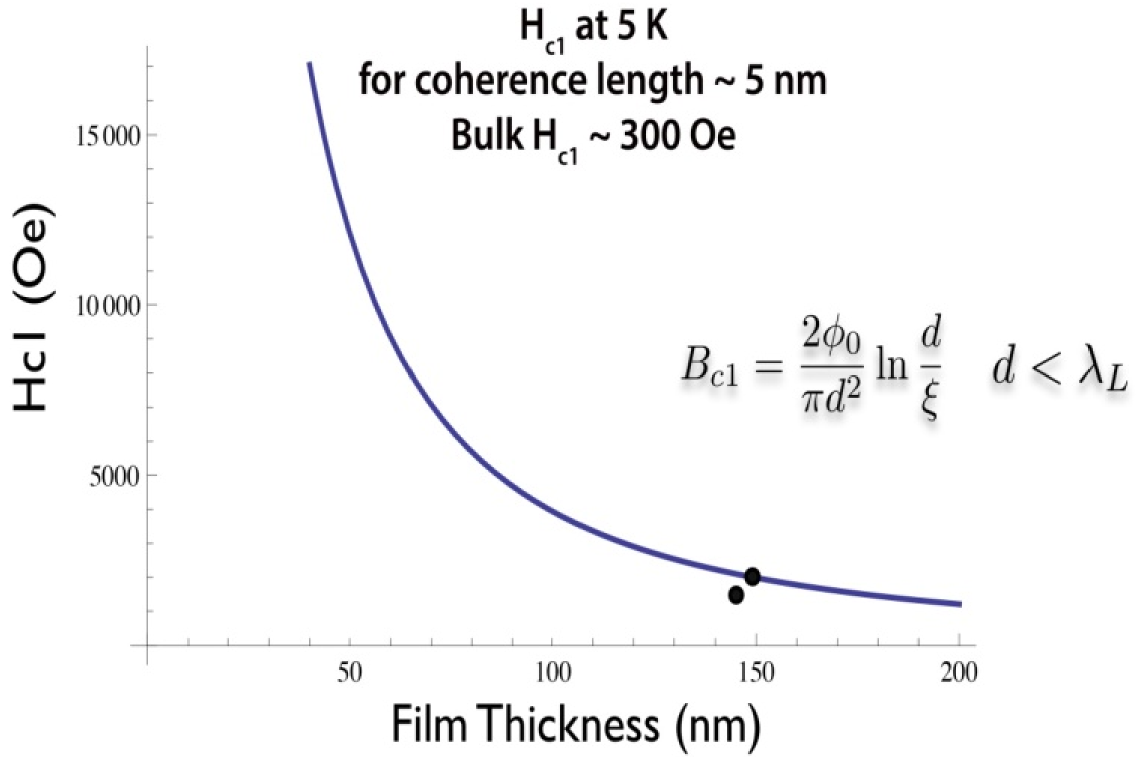
H_{c1} enhancement

compared to

bulk-like NbTiN film

Thickness series study under progress

	Thickness [nm]	H_{c1} [mT]	T_c [K]
NbTiN/MgO	2000	30	17.3
NbTiN/AlN/AlN ceramic	145	135	14.8
NbTiN/AlN/MgO	148	**200**	16.7

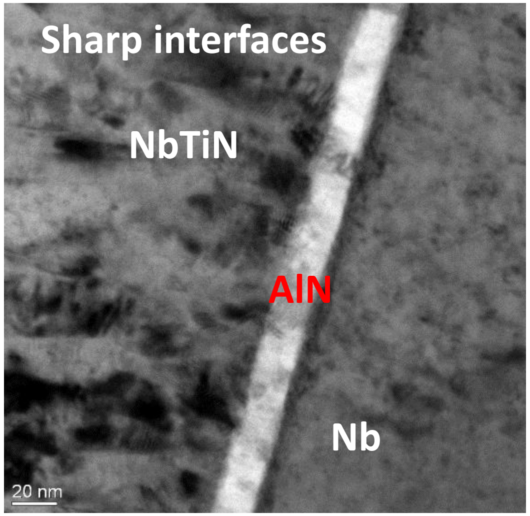


$$B_{c1} = \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\xi} \qquad d < \lambda_L$$

R_s of NbTiN/AlN structures on Nb surfaces

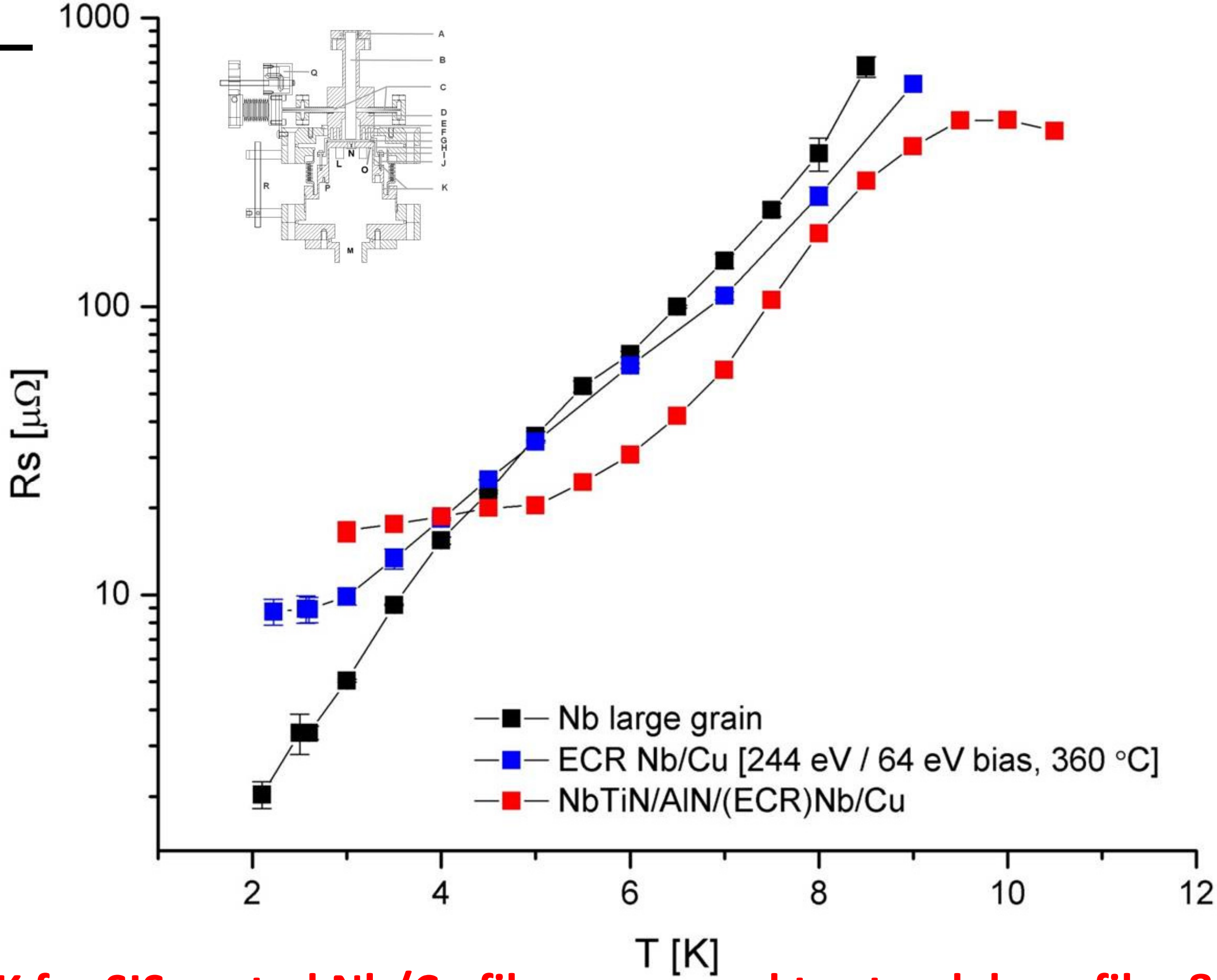
SIS structures coated on ECR Nb/Cu film: 24h-bake, coating and annealing for 4 h at 450°C.

	AlN	NbTiN
N_2/Ar	0.33	0.23
Total pressure [Torr]	2×10^{-3}	2×10^{-3}
Sputtering Power [W]	100	300
Deposition rate [nm/min]	~ 2.5	~ 18
Thickness [nm]	20	150
Tc [K]	N/A	16.9



TEM cross-section (FIB cut) of NbTiN/AlN/Nb/Cu structure

RF Measurement in 7.5 GHz sapphire-loaded TE_{011} cavity



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

Summary

- Good quality standalone NbTiN deposited by reactive DC magnetron sputtering.
  - Bulk, i.e. thicker than 1 micron, NbTiN films readily produced with a T_c of 17.3 K and H_{c1} of 30 mT.
  - Cubic δ-phase and T_c above 16 K for thicknesses larger than 30-50 nm and coating temperatures of 450 ˚C or higher.

- AlN dielectric films with good dielectric properties.

- Good quality SIS NbTiN/AlN layers with a $T_{c,\ \mathrm{NbTiN}}$ between 16.6 and 16.9 K.
  - **Growth conditions for SIS structures** need to be a compromise between optimum conditions for standalone films and minimizing interaction between layers .
  - If the dielectric can be grown as an adequate template, the substrate macro-roughness is not necessarily detrimental to the T_c of the superconducting film.

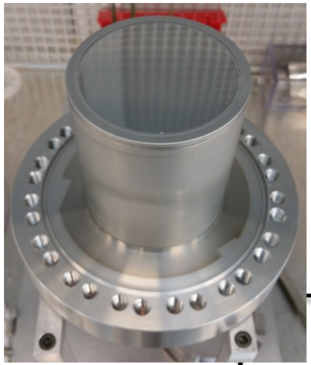
- **H_{c1} enhancement** (SQUID magnetometry) observed for 150 nm NbTiN films. Further studies under way to determine /verify optimum layer thickness.

- **RF characterization of NbTiN/AlN structures coated on Nb surfaces reveal a promise of delaying flux penetration and lower RF losses for SIS coated Nb surfaces, both bulk and thick film** (along with other experiments: cf Antoine C. –CEA, Lukaszew A. - W&M).

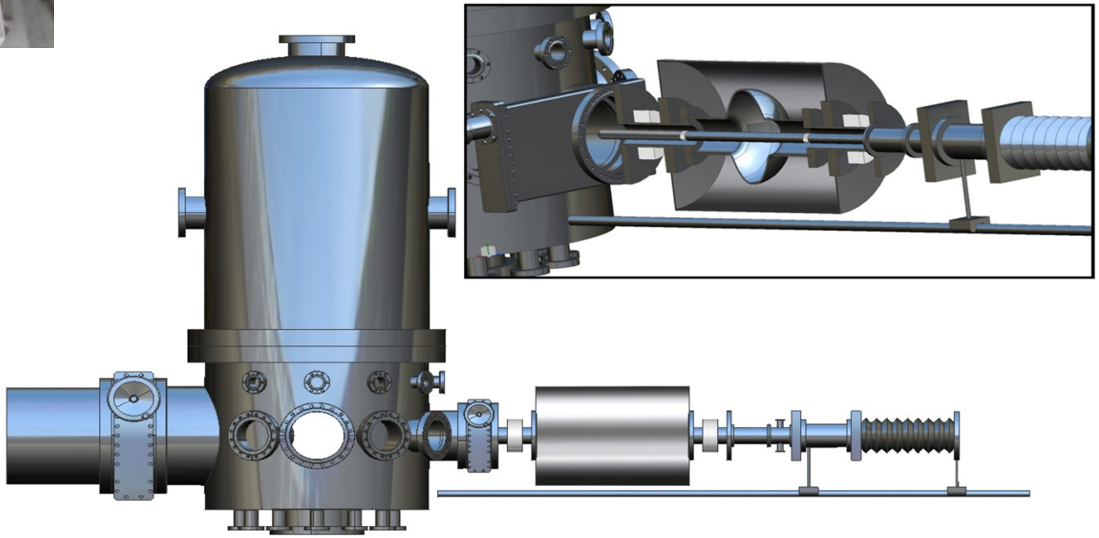
On-going & Future Work

- ☐ Thickness series to **determine/verify optimum layer thicknesses** with H_{c1} measurements
- ☐ **Implementing energetic condensation via HiPIMS (High power impulse magnetron sputtering) will allow to lower the coating temperature while maintaining a good quality δ-phase for NbTiN .**

First depositions of NbTiN films with HiPIMS with reasonable results.



- ☐ **RF measurement** for SIS NbTiN/AlN structures on previously characterized bulk Nb **QPR samples**.

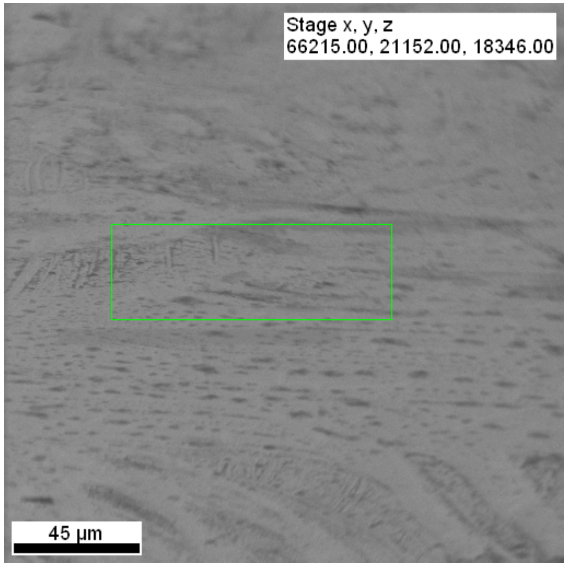


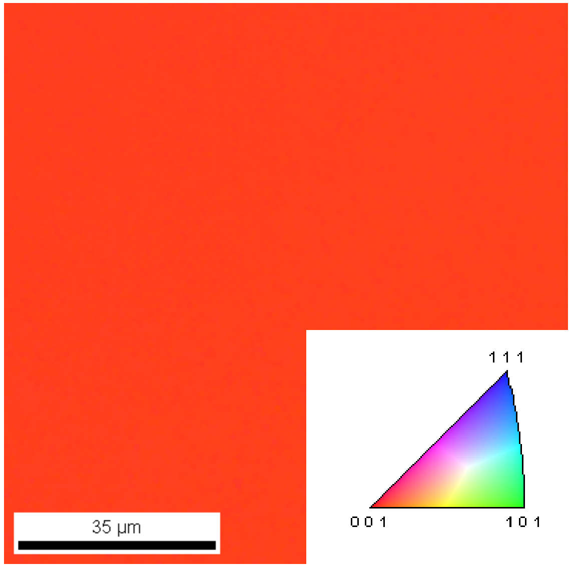
A concept to deposit SIS structures on Nb cavities (bulk of thick Nb/Cu) has already been developed. This will allow the implementation of the SIS proof of concept in form of elliptical cavities using existing infrastructure.

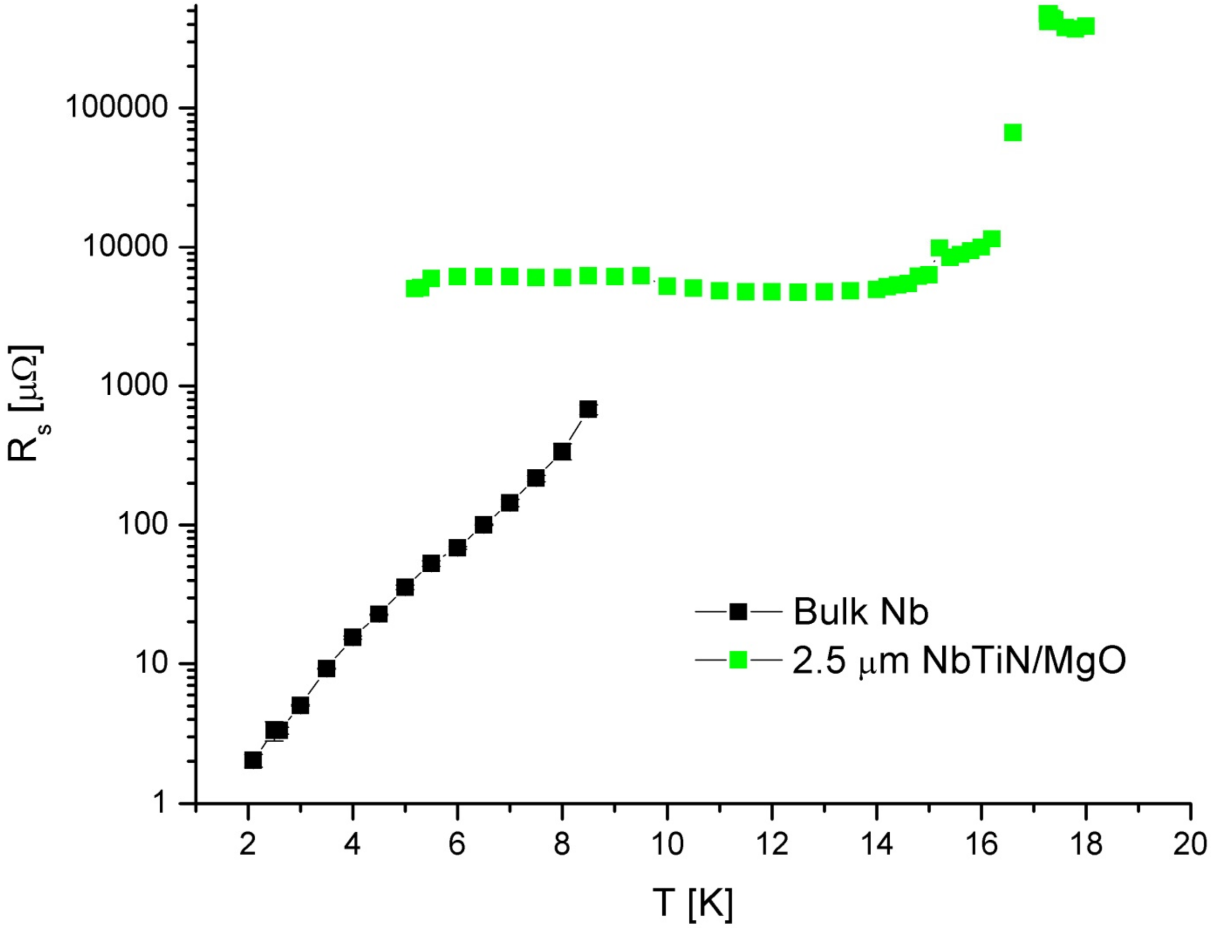
Concept for SIS structure coating on Nb & Nb/Cu cavities

Thank You
for your Attention

R_s of bulk NbTiN film (2 µm)



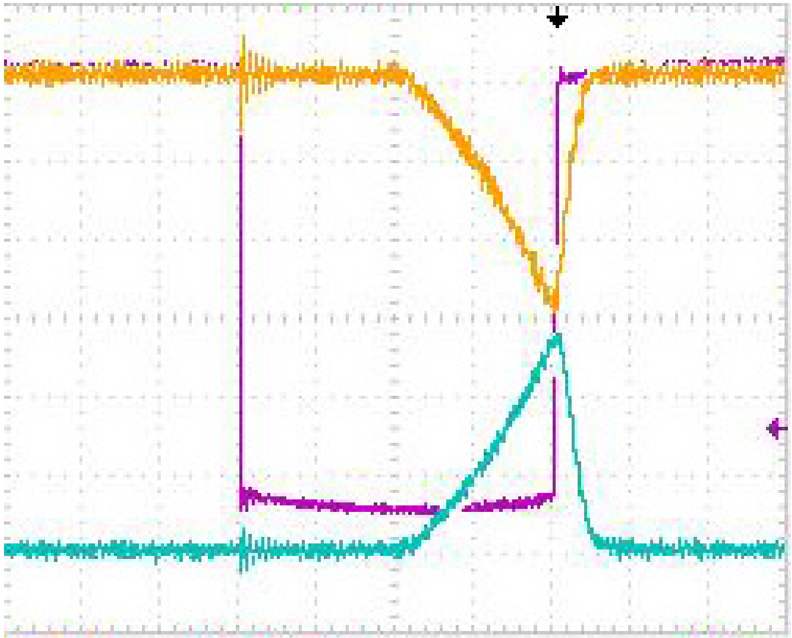




NbTiN Films with HiPIMS

Thickness [nm]	Average Power [W]	Peak current [A]	Pulse width [µs]	Repetition rate [Hz]	Coating time [min]
30	100	115	100	100	120
250	400	140	100	200	120
230	400	100	150	200	30
118	400	150	100	200	30
252	400	150	100	200	60
218	400	150	100	200	120

θ-2θ scans of the first films produced by HiPIMS reveal that only the films produced with an average power of 400 W and repetition rate of 200 Hz have the δ-phase. The measured T_c is 16.6 K for a 250 nm thick film.



Typical pulse for reactive HiPIMS of NbTiN