SUPERCONDUCTING TECHNOLOGIES

FOR THE NEXT GENERATION OF ACCELERATORS

WORKSHOP

Sergio Calatroni

History and Potential of Thin Film Technology for SC Cavities

Outline

- Why thin films
- Nb sputtering on Cu cavities
  - Technology
  - Advantages and disadvantages
  - State of the art
- Future prospects
  - Energetic condensation
  - Multilayers
  - High(er) Tc

Nb bulk and Nb/Cu

or

?

Basic cost advantages

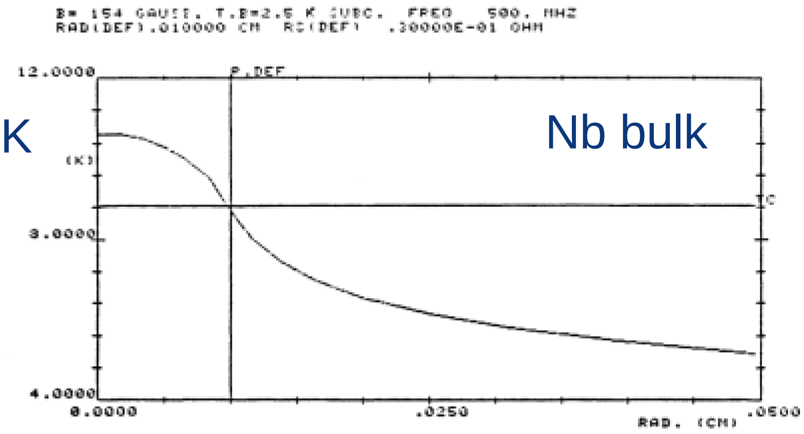
Thin films on Cu OFE cavities

- Cu OFE sheets: 10 EUR/kg
- Nb RRR 300 sheets: 800 EUR/kg

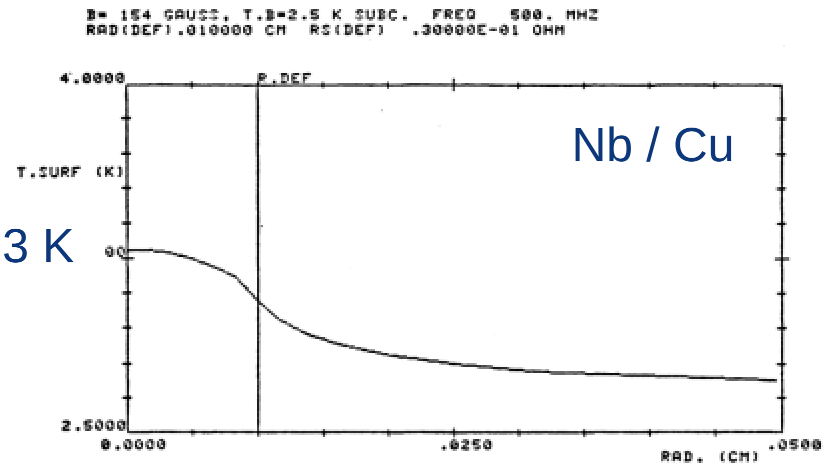
- Simpler cryostats: helium tank can be made of stainless steel instead of titanium
- Conduction cooling is possible

Basic historic motivation

Nb: 10.2 K



Nb/Cu: 3.3 K

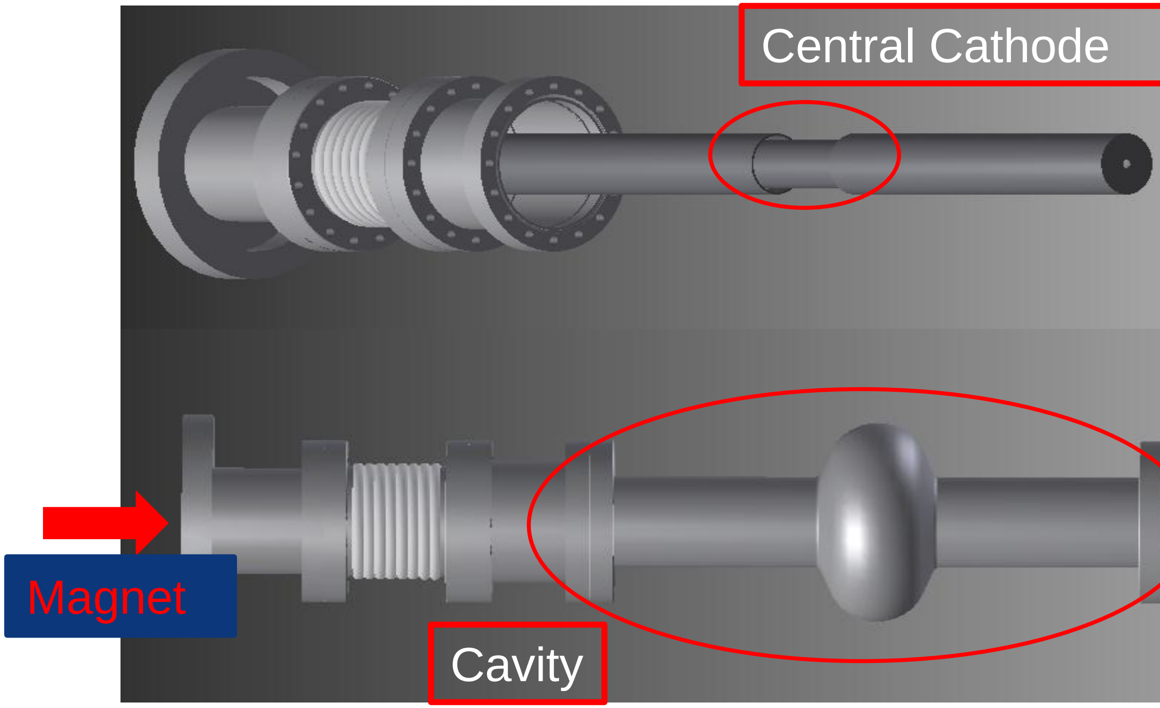


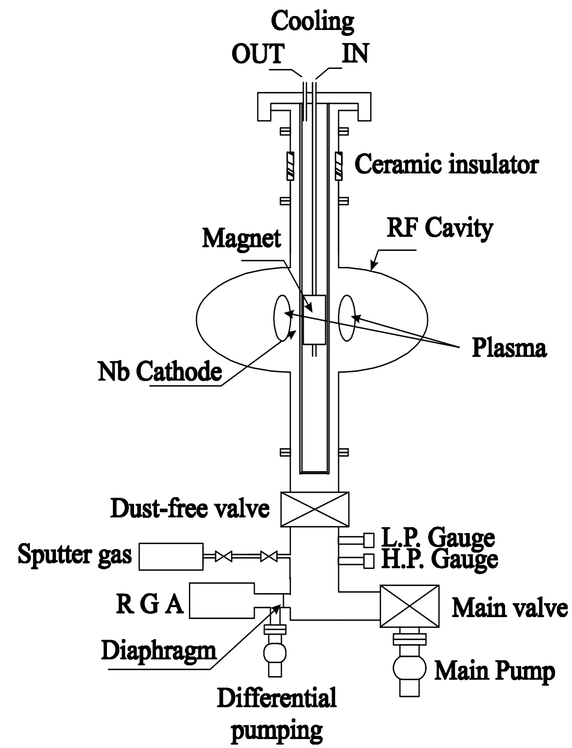
Temperature distribution calculation for a 100 micron radius steel defect embedded either in niobium or in copper

Joachim Tuckmantel - Thermal effects in superconducting RF cavities: some new results from an improved program
CERN-EF-RF-84-6. - 1984.

Quenches cannot happen because of the stabilising effect of the copper with respect to thermo-magnetic breakdown

Niobium Magnetron Sputtering





- Sputtering parameters (1.5 GHz):
  - Sputter gas pressure of 1.5×10^{-3} mbar (Ar or Kr)
  - Plasma current stabilized at 3A - DC
  - Sputter potential ~ -360 V
  - Coating temperature is 150 °C.
  - Thickness: 1.5 µm

- "Standard films" characteristics:
  - RRR: 11.5 ± 0.1
  - Argon content: 435 ± 70 ppm
  - Grain size: 110 ± 20 nm
  - Tc: 9.51 ± 0.01 K
  - Strain: $\Delta a_\perp / a_\perp$ = 0.636 ± 0.096 %

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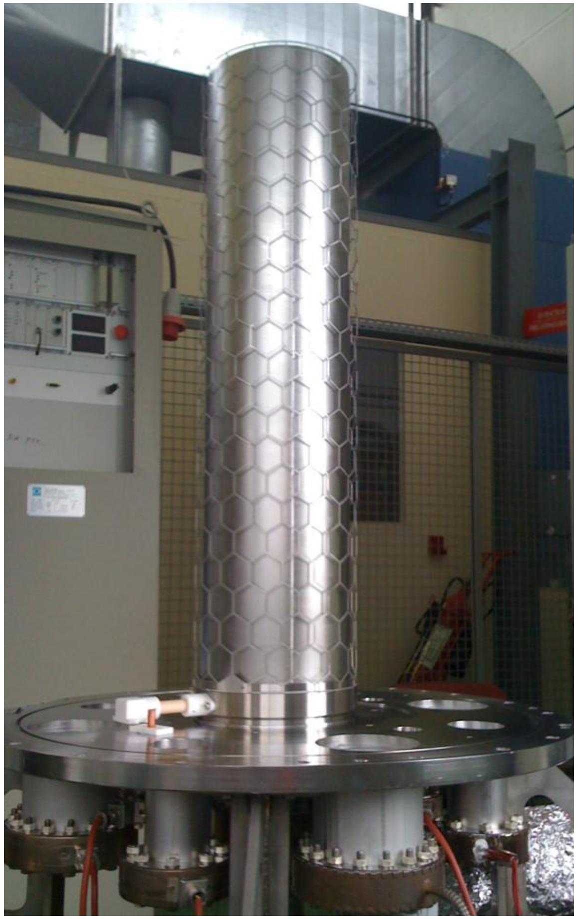
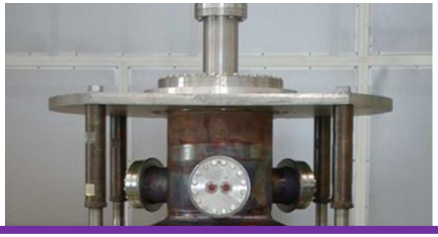
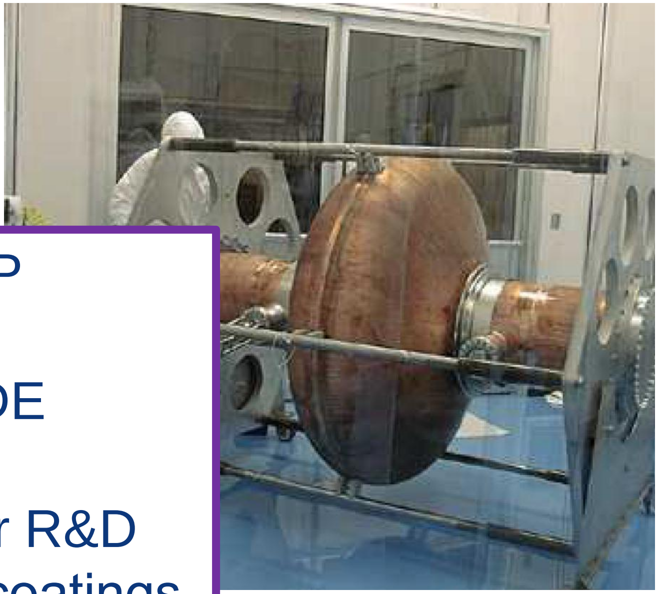
Diode sputtering

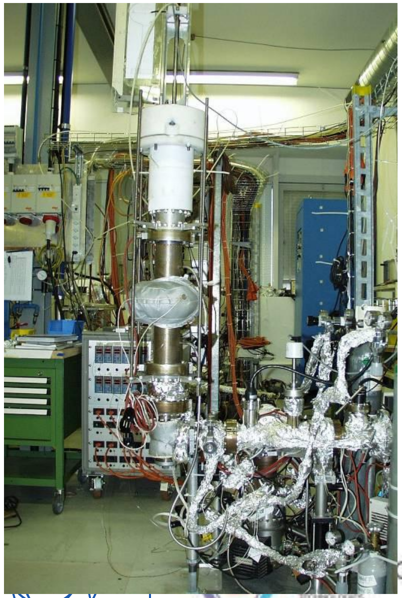


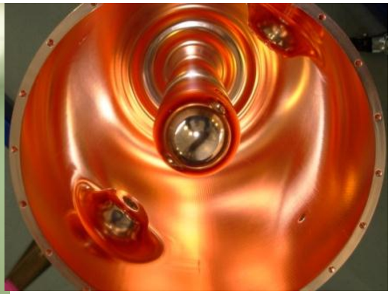
Coating of beta = 1 and lower beta cavities

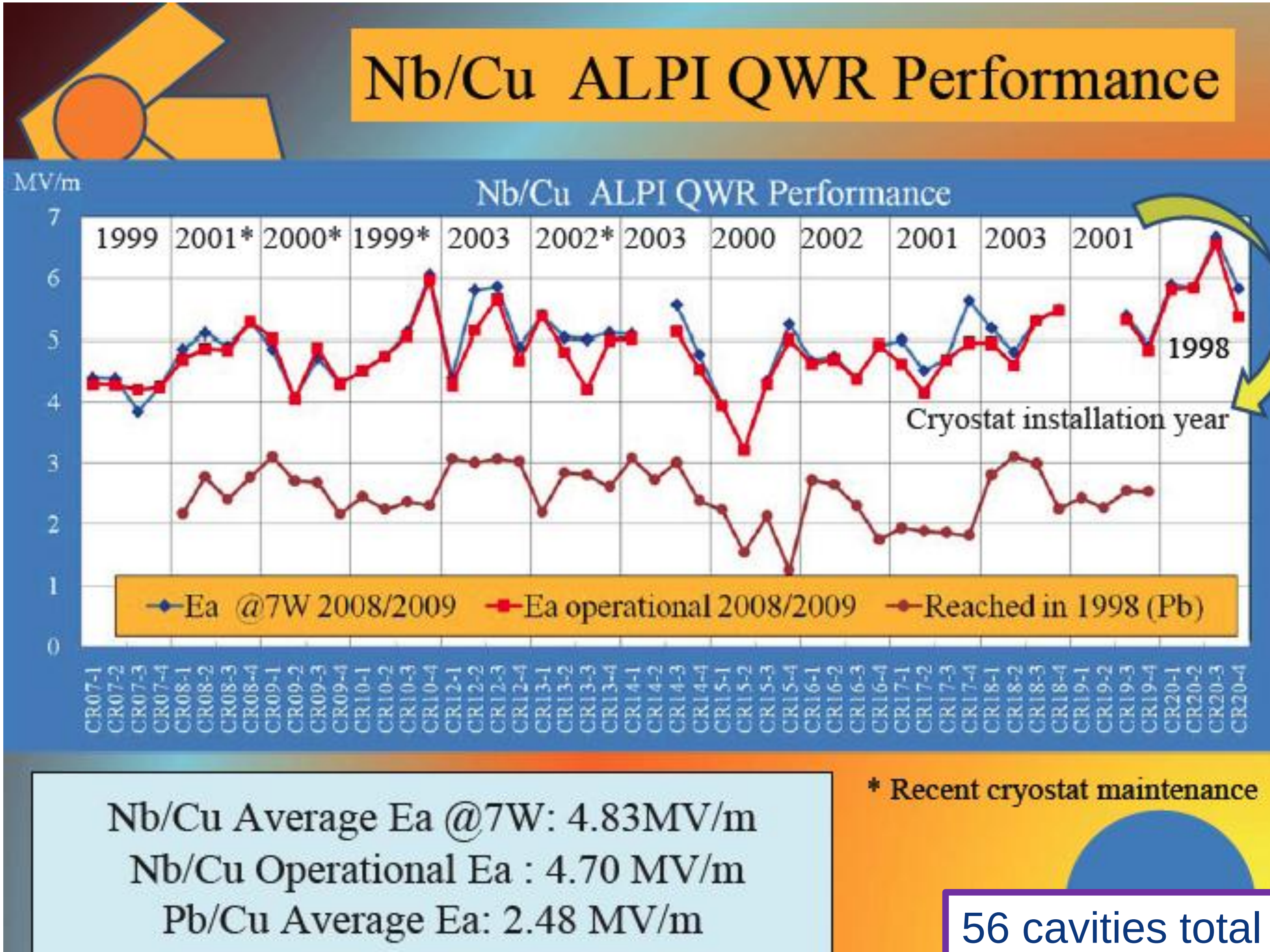
288 Nb/Cu cavities installed in LEP
16 Nb/Cu cavities installed in LHC
32 Nb/Cu projected for HIE-ISOLDE

About 300 coatings on 1.5 GHz for R&D
Low-beta studies, several 10's of coatings
(+ Soleil prototypes, 3HC, 200 MHz
Cornell...)




LNL



56 cavities total

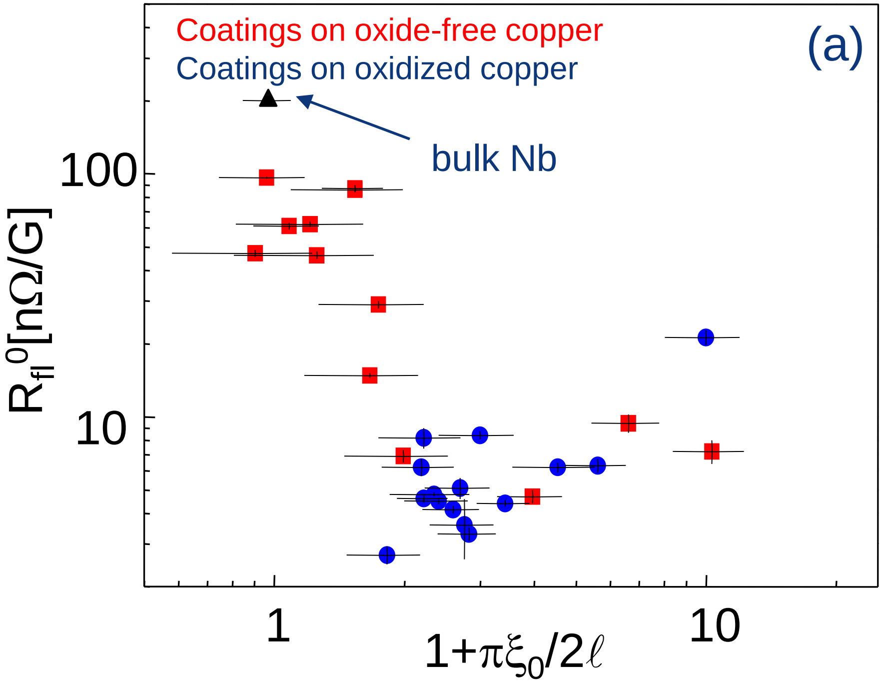
Effect of external magnetic field

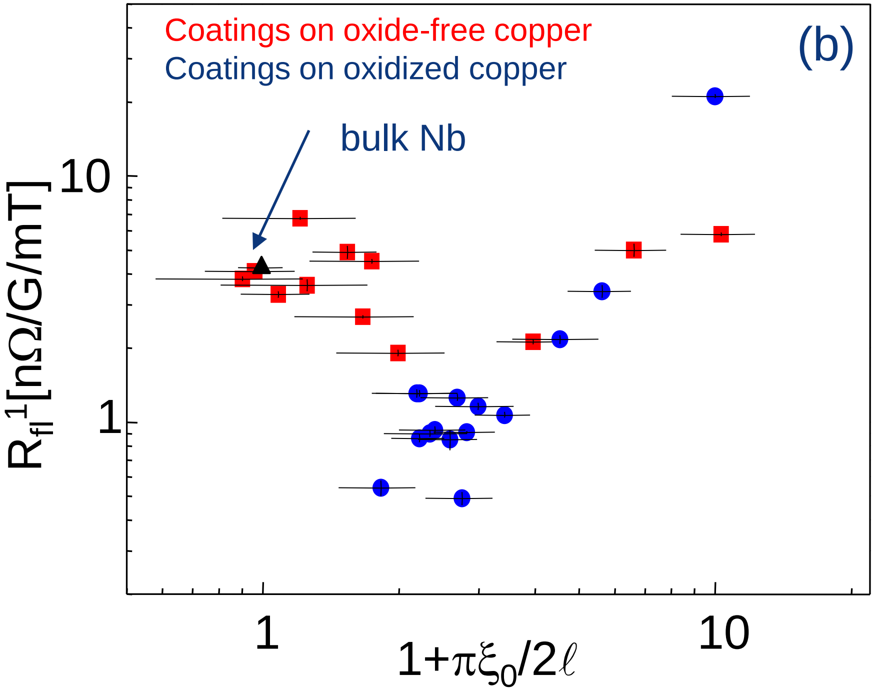
Losses due to trapped external magnetic field at 1.7 K are characterized as

$$R_{fl} = (R_{fl}^0 + R_{fl}^1 H_{RF}) H_{ext}$$

The minimum values are obtained using krypton as sputter gas:

$R_{fl}^0 = 3 n\Omega/G$ $R_{fl}^1 = 0.4\ n\Omega/G/mT$





No need for magnetic shielding considerably simplifies cryostat design

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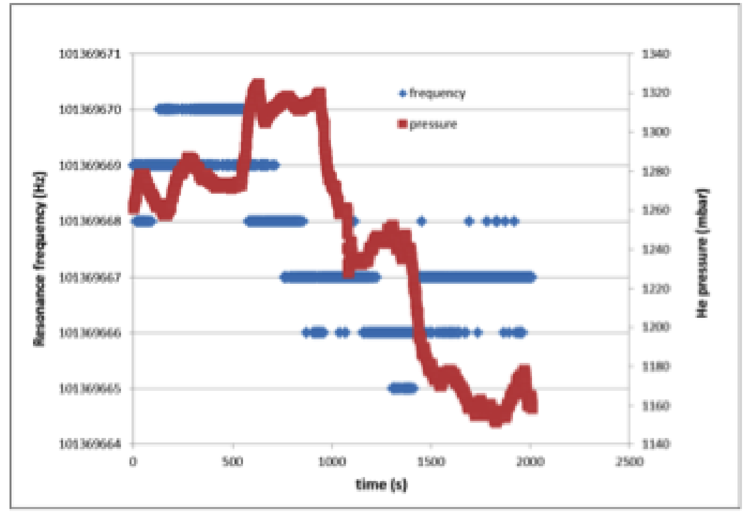
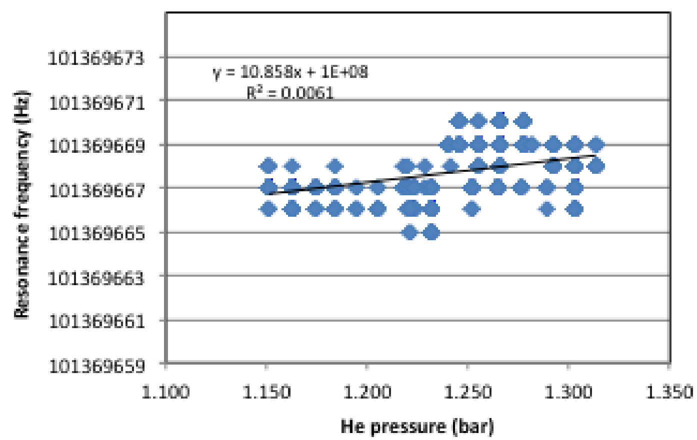
Mechanical stability

QP1 (new design) ~ 0.01 Hz/mbar

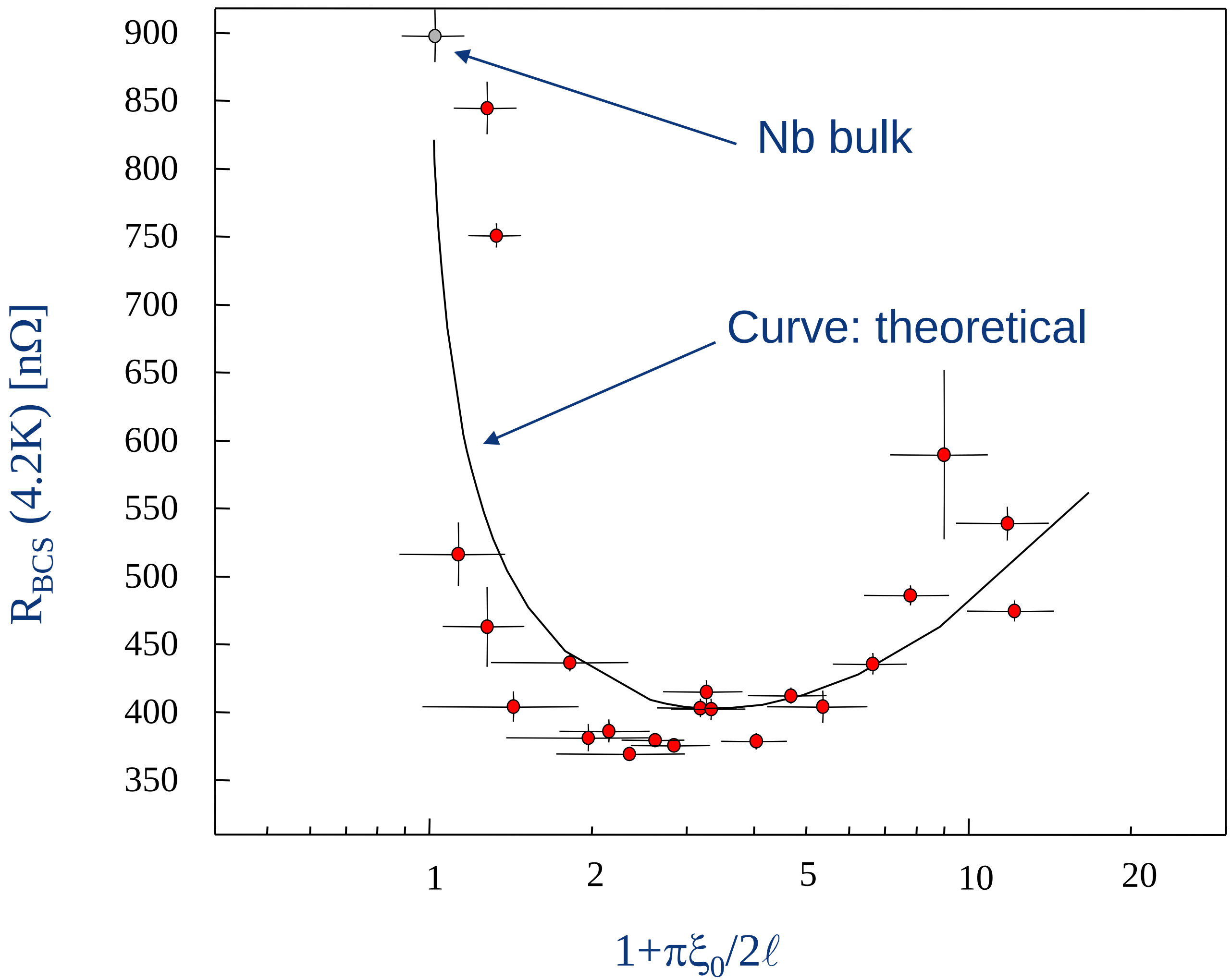




No dynamic tuning needed

Much easier operation compared to bulk:
lower microphonics, feedback systems, etc.

BCS resistance at zero RF field



R_{BCS} at 4.2 K (1.5 GHz)

Nb bulk: ~900 nΩ

Nb films: ~400 nΩ

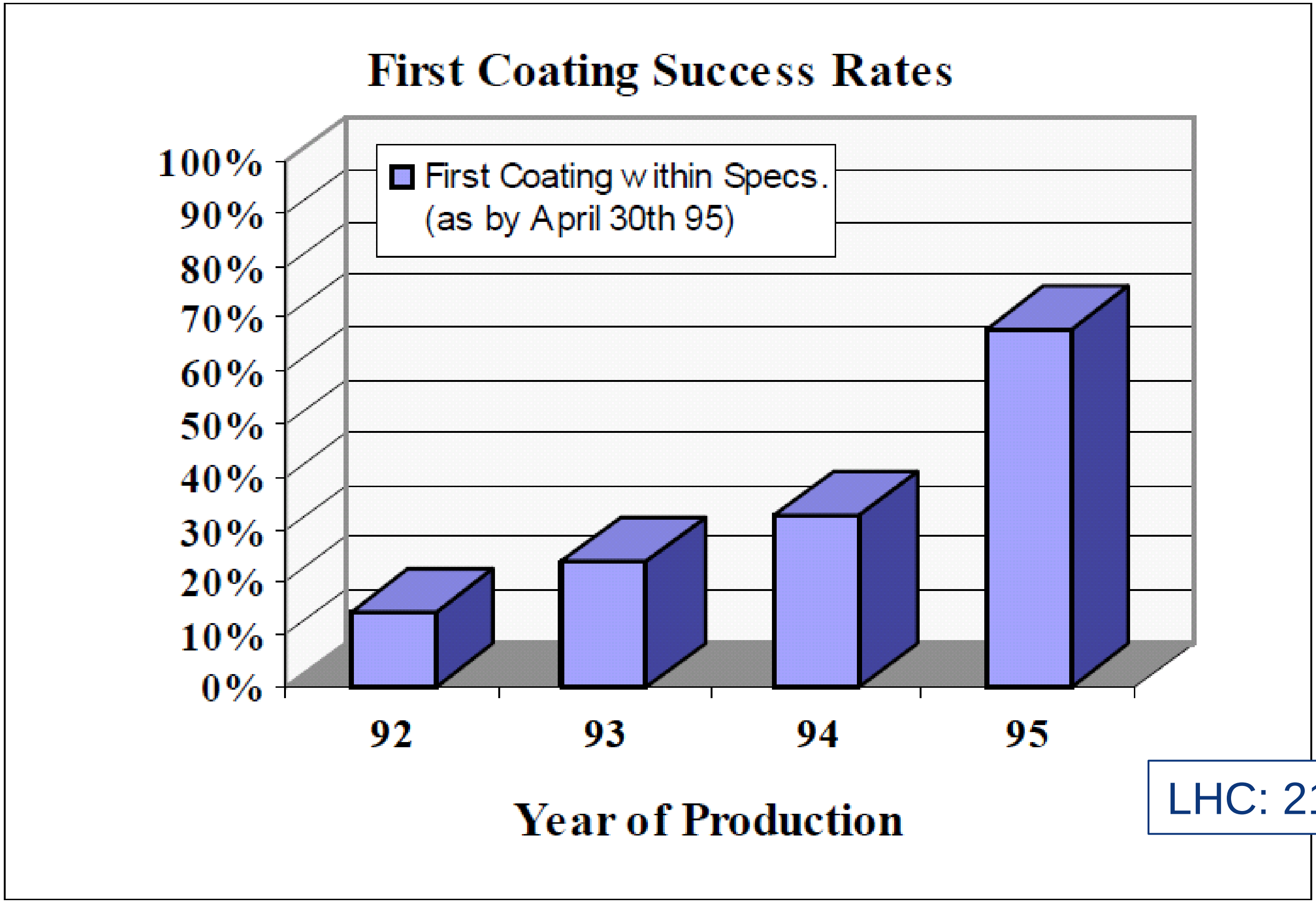
R_{BCS} at 1.7 K (1.5 GHz)

Nb bulk: ~2.5 nΩ

Nb films: ~1.5 nΩ

Lowest R_{BCS} allows achieving highest Q values even at 1.7 K

LEP success rate



LHC: 21/29=72%

Fig.5: Total first coating success rates in industry

E. Chiaveri, SL-95-038

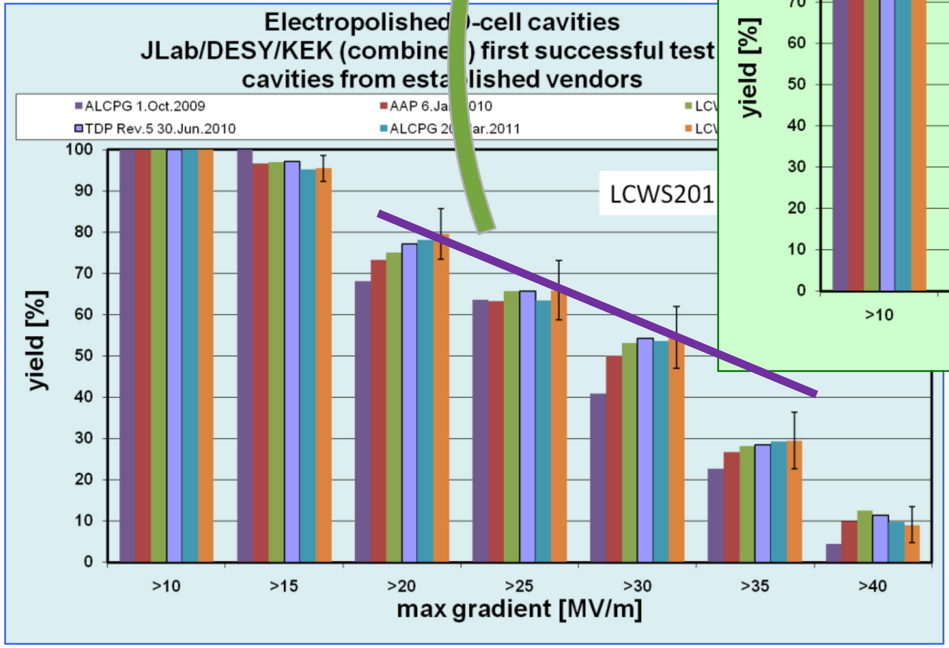
ILC success rate

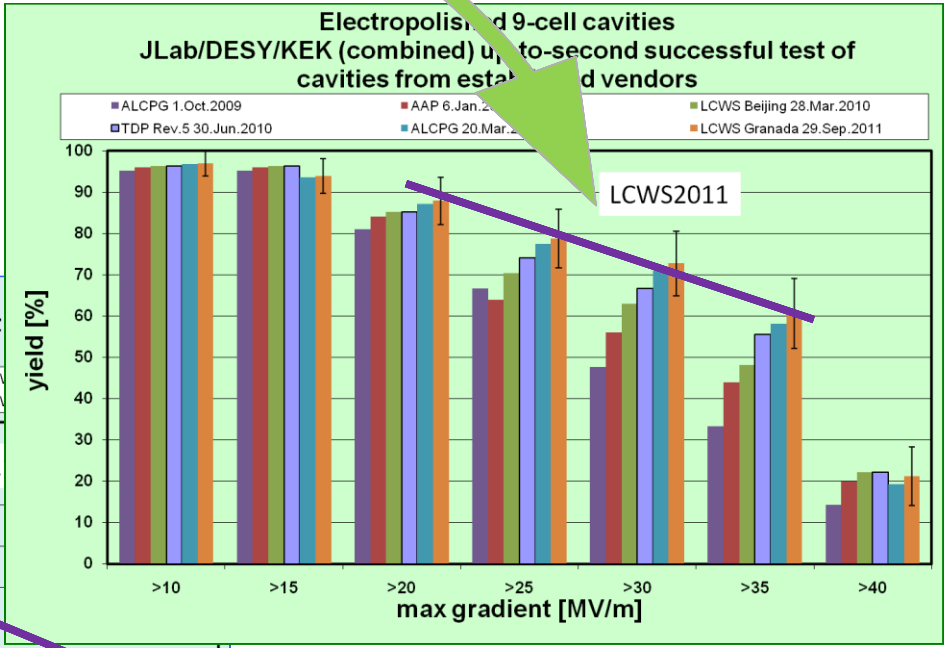
Gradient Yield: Time Progression

with most recent update, Sept. 2011

1st pass

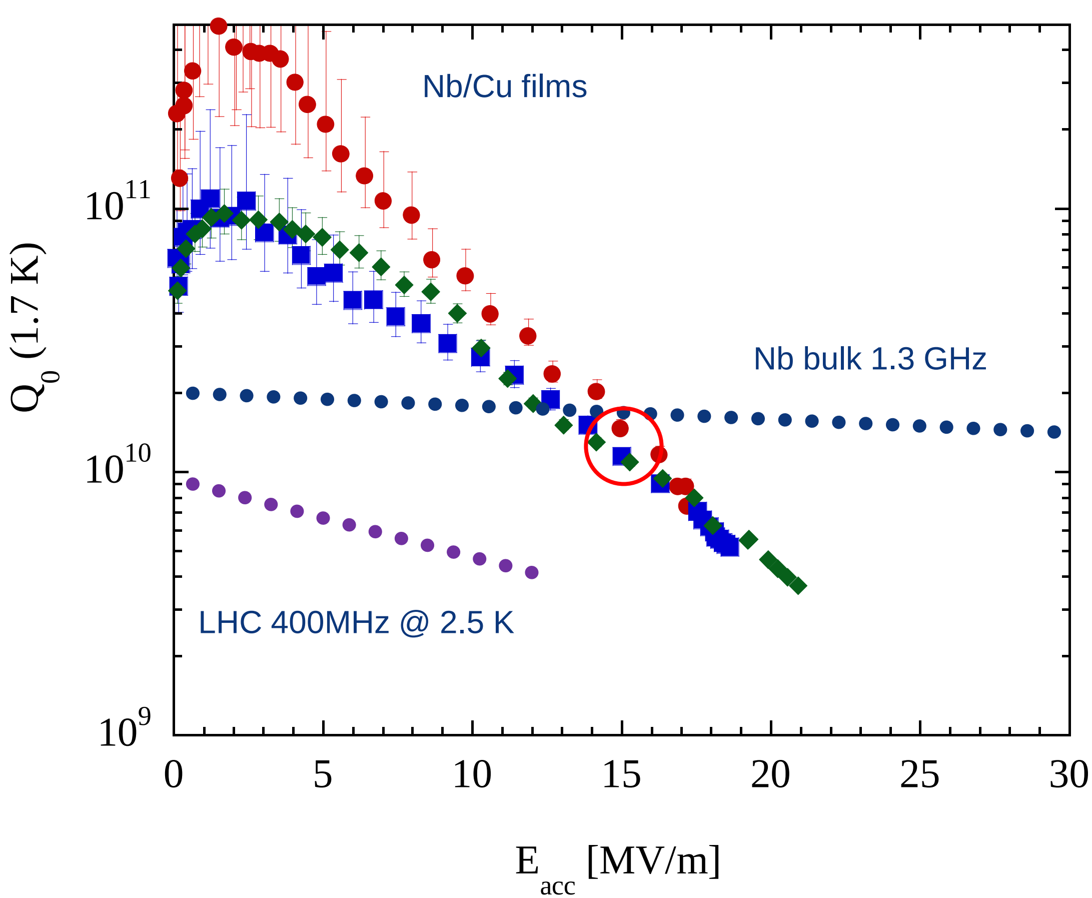
2nd pass





State of the art

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



Q = 1x10^{10} @ 15 MV/m is a value that would make film cavities a competitive option for new high energy proton accelerators

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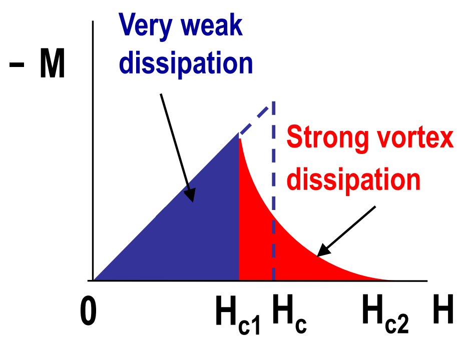
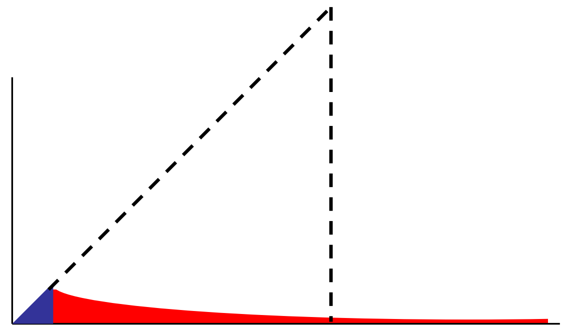
Limitation of H_{c1}: from A. Gurevich

Superconducting Materials



Nb



Higher-H_c SC

Very weak dissipation at $H < H_{c1}$ (Q = 10^{10}-10^{11}) Q drop due to vortex dissipation at $H > H_{c1}$

Nb has the highest lower critical field H_{c1}

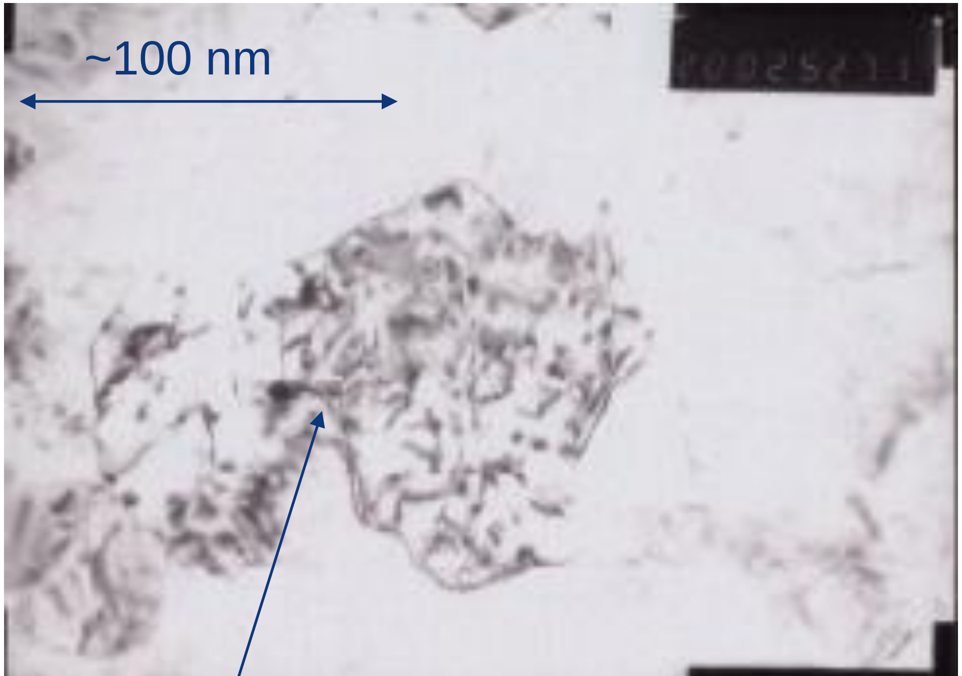
$$H_{c1} = \frac{\phi_0}{4\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right)$$

Thermodynamic critical field H_c (surface barrier for vortices disappears)

$$H_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi}$$

Material	T_c (K)	$H_c(0)$ [T]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	$\lambda(0)$ [nm]
Pb	7.2	0.08	na	na	48
Nb	9.2	0.2	0.17	0.4	40
Nb_3Sn	18	0.54	0.05	30	85
NbN	16.2	0.23	0.02	15	200
MgB_2	40	0.43	0.03	3.5	140
YBCO	93	1.4	0.01	100	150
Nb films	9.45	0.2	0.03÷0.05	0.8÷1.2	40

TEM view – film defects



Crystallographic defects can be at the origin of reduced H_{c1} compared to bulk Nb

$$\frac{1}{\ell_{total}} = \frac{1}{\ell_{\mathrm{int}\,ragrain}} + \frac{1}{D}$$

RRR of films: 10 ÷ 30

$\Rightarrow$

mfp of films 30 ÷ 100 nm

Grain size of films > 100 nm

$\Rightarrow$

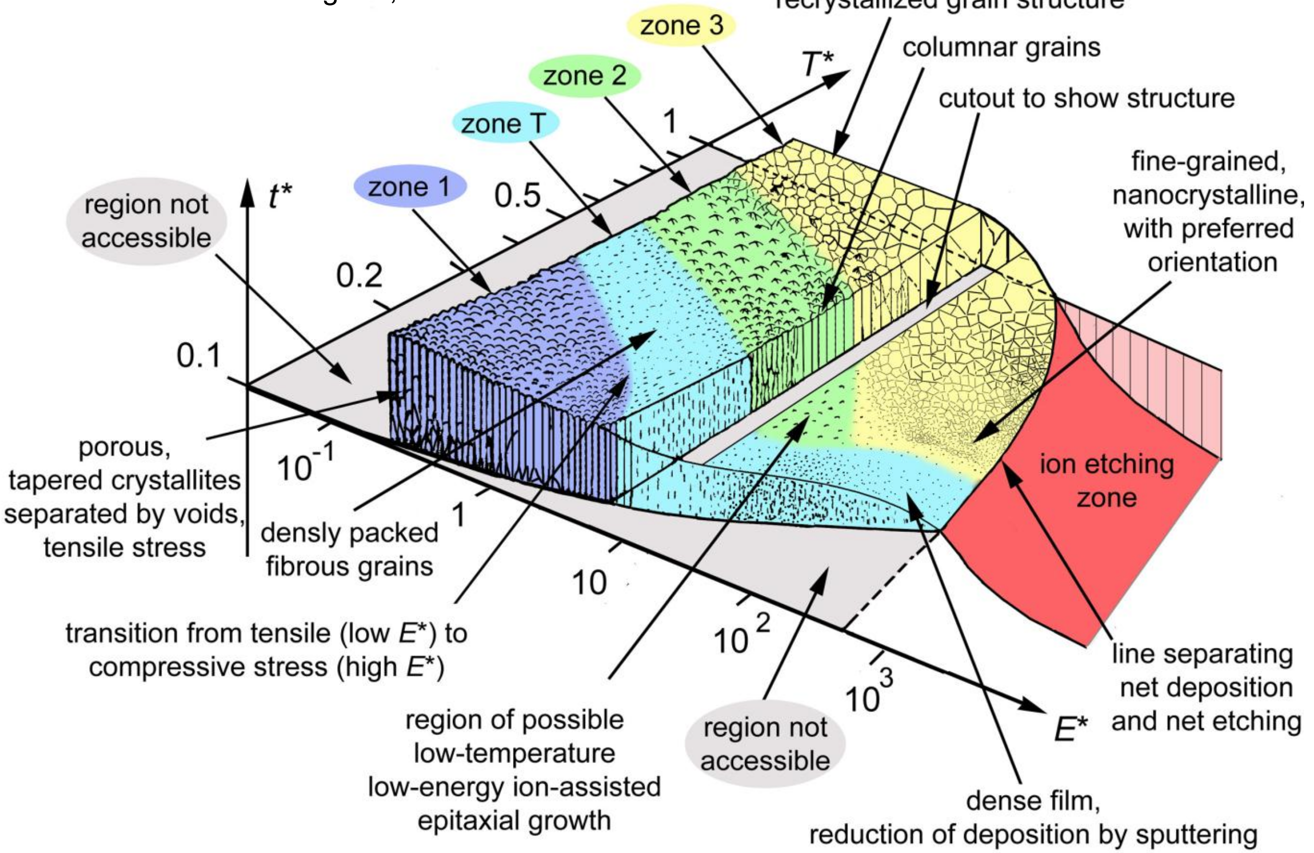
RRR limited by intragrain defects in most cases

The goal is to make films as bulk-like as possible in terms of microstructure structure. The grain size does not seem to be a major issue

Structure zone model from A. Anders

Generalized Structure Zone Diagram

derived from Thornton's diagram, 1974



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

Energetic condensation

Additional energy provided by fast ionised particles arriving at a surface with energy >> eV

⇒Changes in the film growth process:

- ❑ Residual gases are desorbed from the substrate surface
- ❑ Chemical bonds are easily broken, thus affecting nucleation processes & film adhesion
- ❑ Enhanced mobility of surface atoms
- ❑ Arriving Nb ions penetrate 2-3 atomic layers
- ❑ Ions arrive with normal incidence

⇒ Changes in

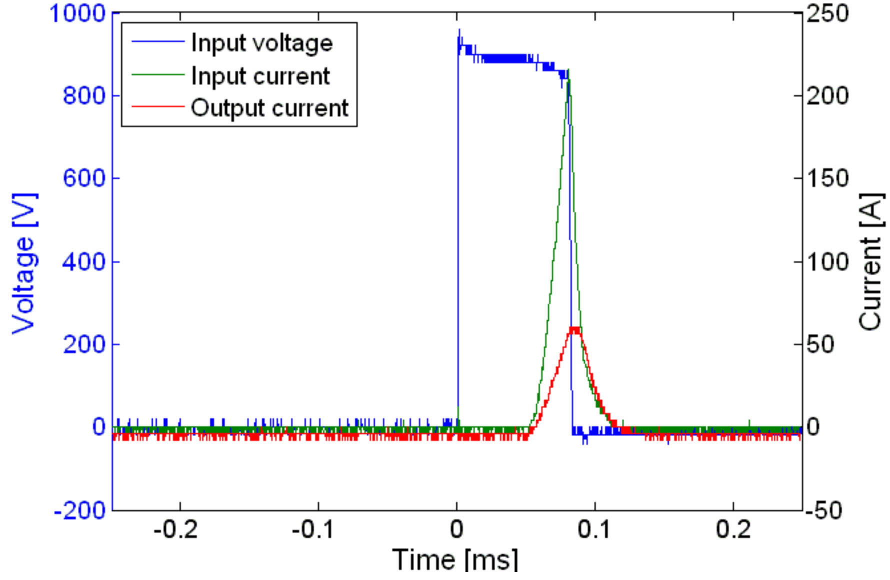
- Morphology
- Microstructure
- Stress

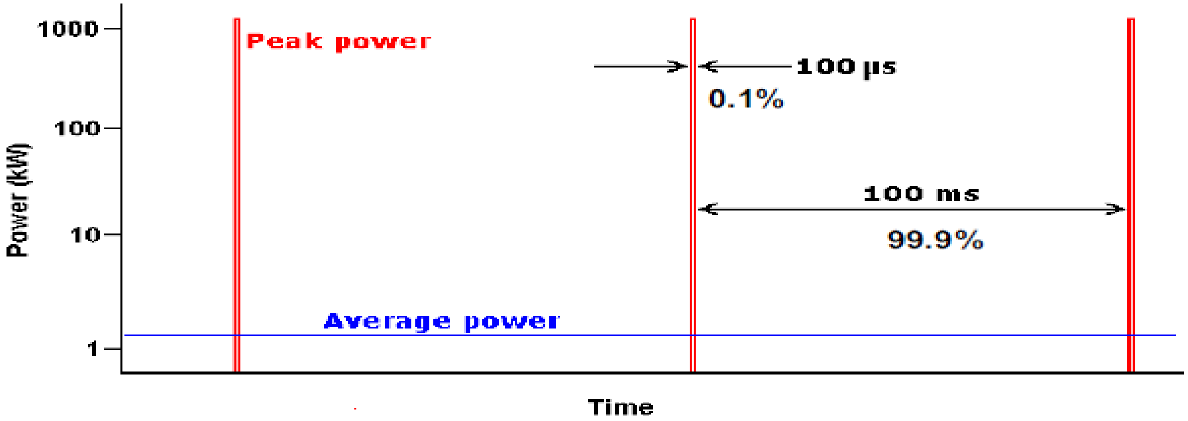
Energetic condensation around the world

	Deposition Methods	Deposition Rate (nm/s)	Ions Energy (eV)	Ion Flux (Nb ions/cm^2-s)	Flux Power (W/cm^2)
1	Magnetron Sputtering, CERN	1.67	<1 (therm.)	~3X10^{15} (neutrals)	2.4X10^{-3}
2	HIPIMS Sputtering, CERN and LBNL	0.1	10-80 (bias)	~3X10^{14}	2.4X10^{-3}
3	UHV Cathodic Arc, INFN + IPJ	10 (no filtered) 2 (filtered)	10-100 (bias)	~1.8X10^{16} (no filtered)	2.9X10^{-1} (DC Mode)
4	Cathodic Arc, AASC CED^{TM}	560 (instant rate, only last 1ms, duty cycle 0.05%) 0.28 (~1 monolayer/s) (avg. rate.)	100-170 (bias)	~1X10^{18} (inst. rate, last 1ms) ~5X10^{14} (avg. rate)	16 (inst. rate, last 1ms) 8X10^{-3} (avg. rate)
5	ECR Nb Plasma, JLAB	2.25[new] 0.5	>63 64-280	~1X10^{15}	~7 X10^{-2} (at 100eV)

Elaborated from a table by C. Reece, JLAB

HIPIMS at CERN

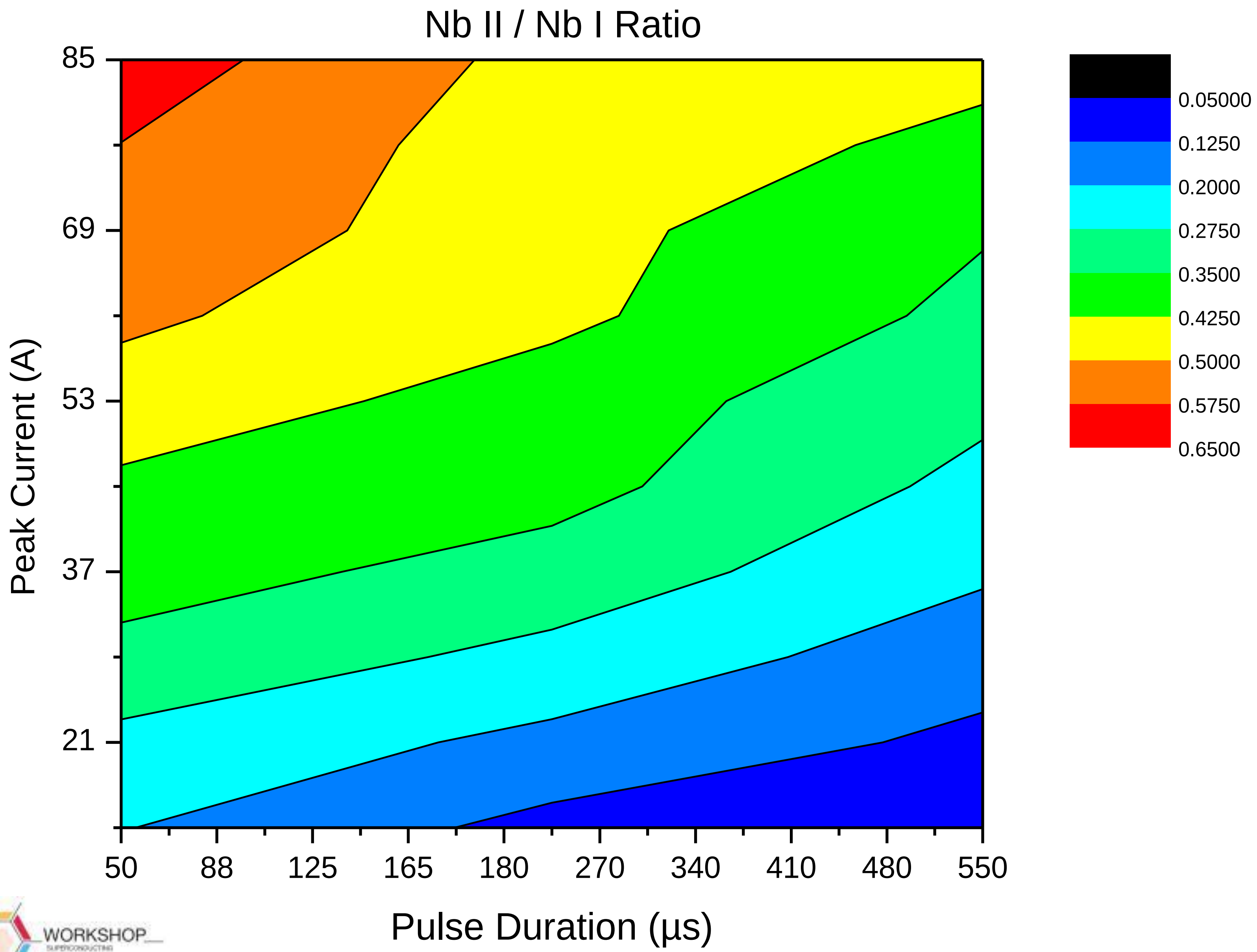




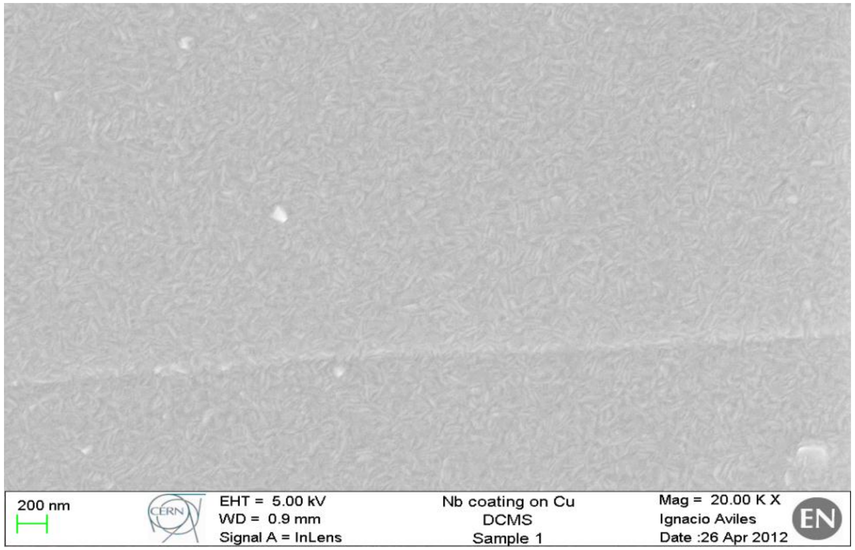
Example of a duty cycle.

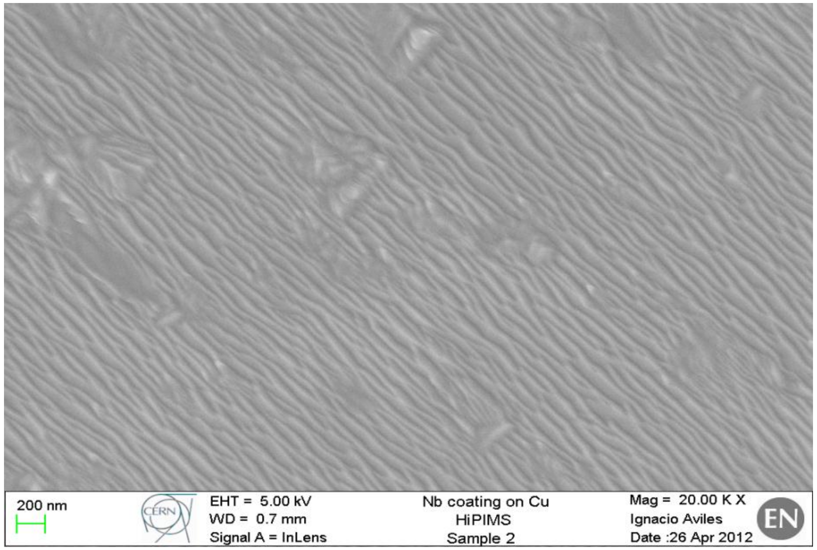
The amount of sputtered Nb in a pulse can be so large that its "pressure" is larger than the noble gas pressure. **As a consequence also the Nb becomes ionized**

Ionisation ratio in HIPIMS

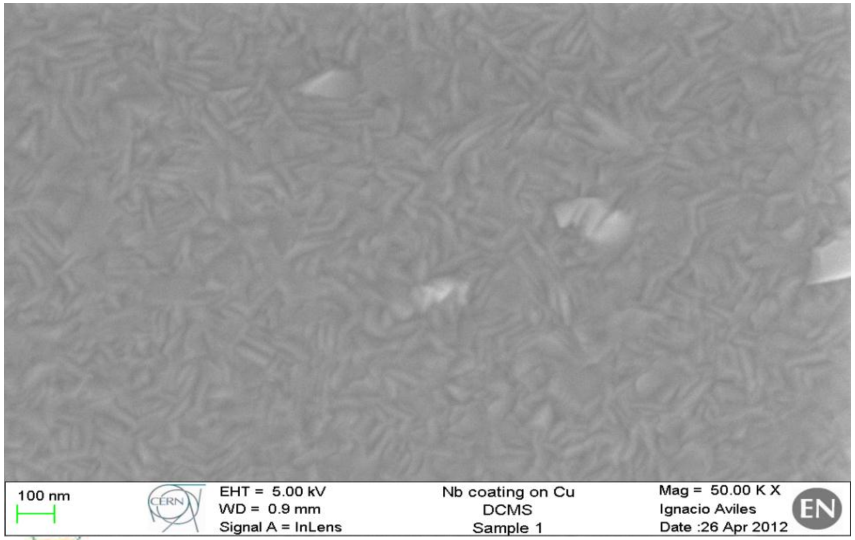


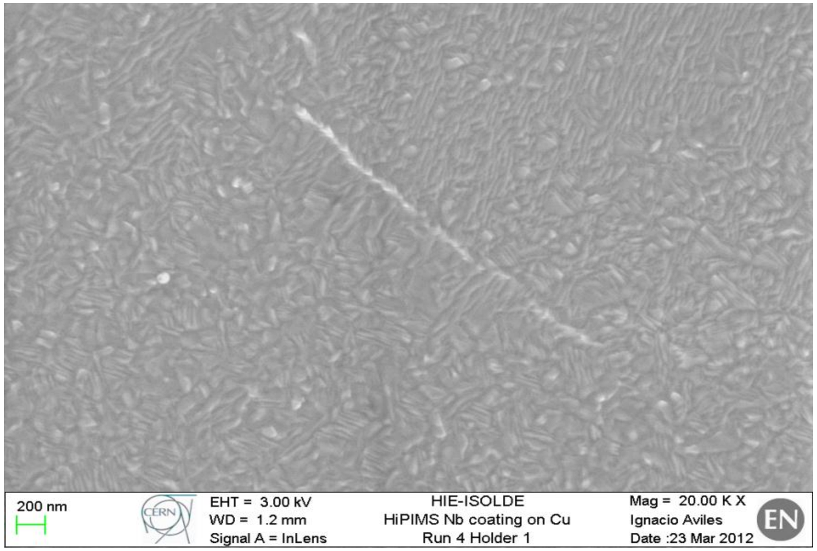
Comparison between DCMS and HiPIMS





HiPIMS High Power (unbiased)





DCMS

HiPIMS Low Power (unbiased)

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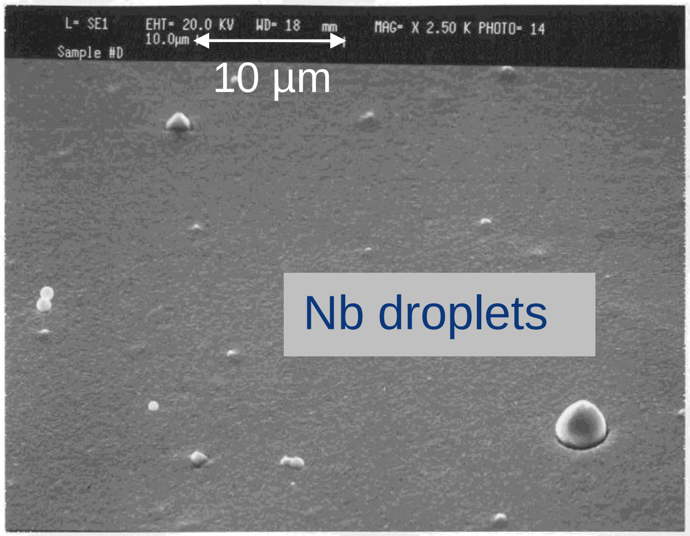
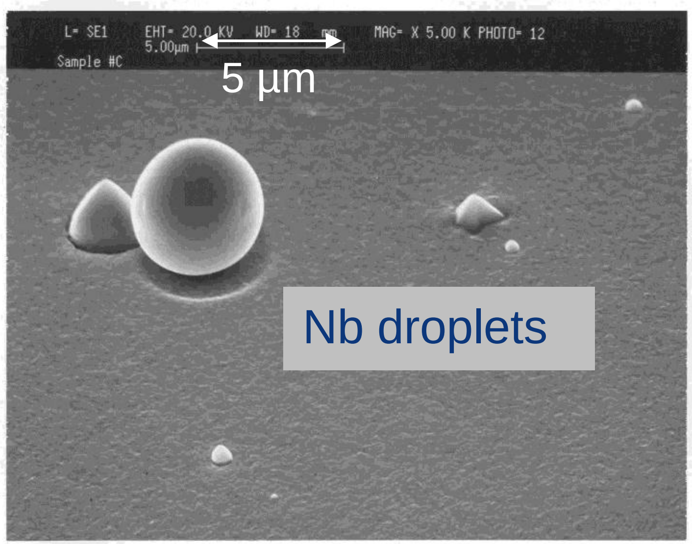
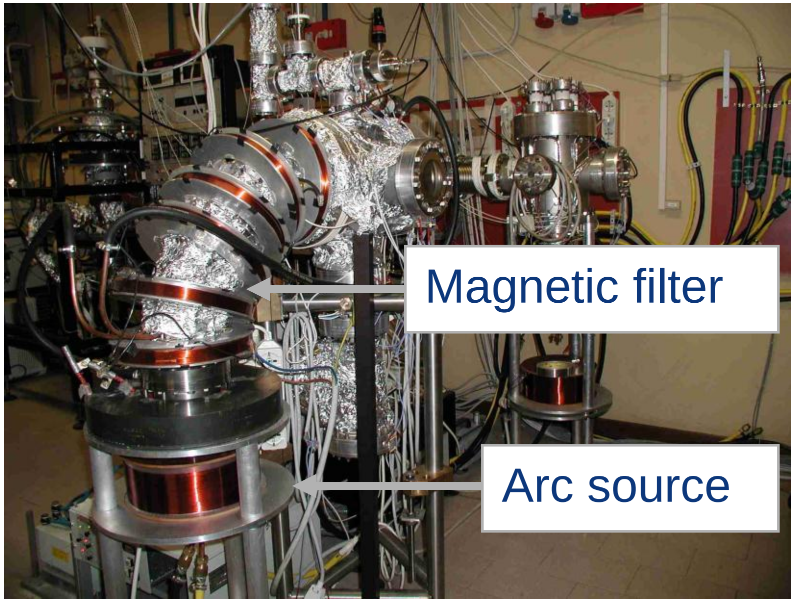
Plasma Arc INFN

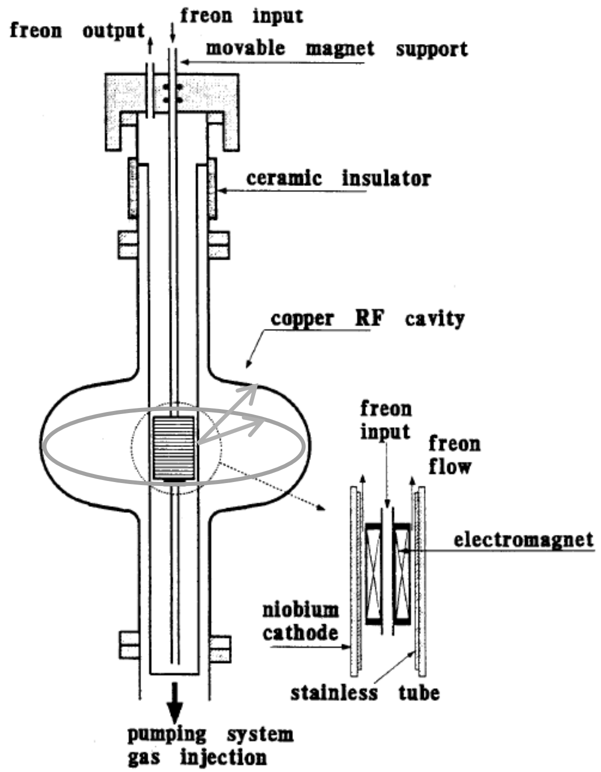




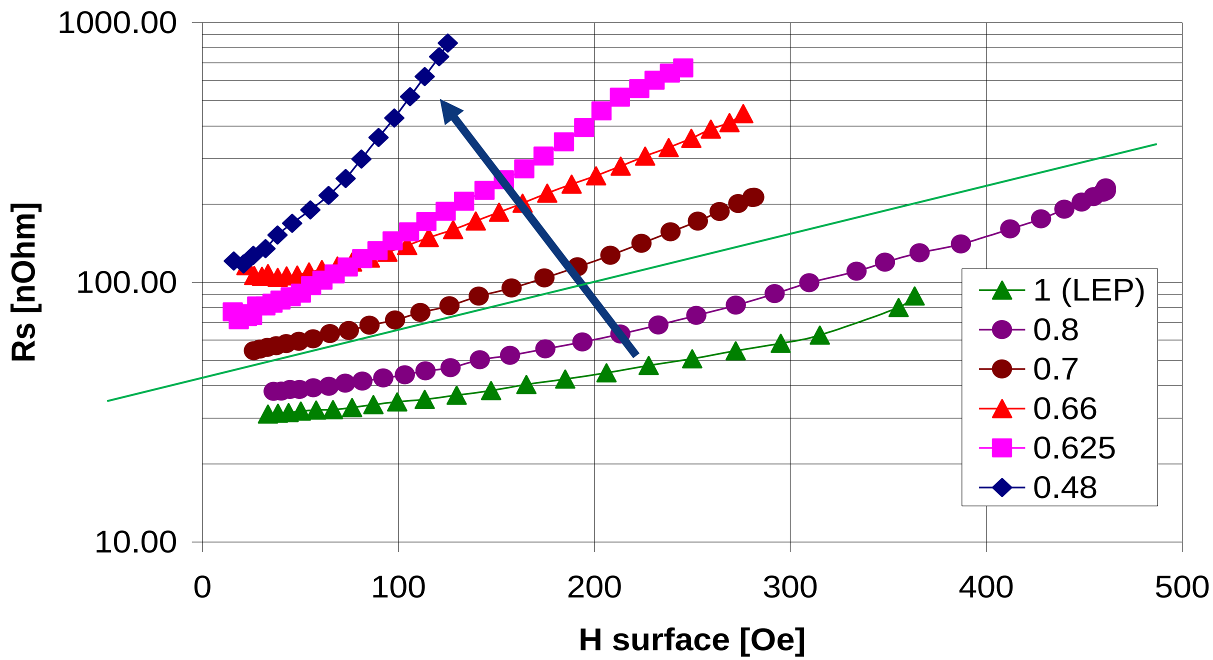


Linear arc with coaxial blind-shutter filter

Angle of incidence of the coating



Average angle of incidence increases

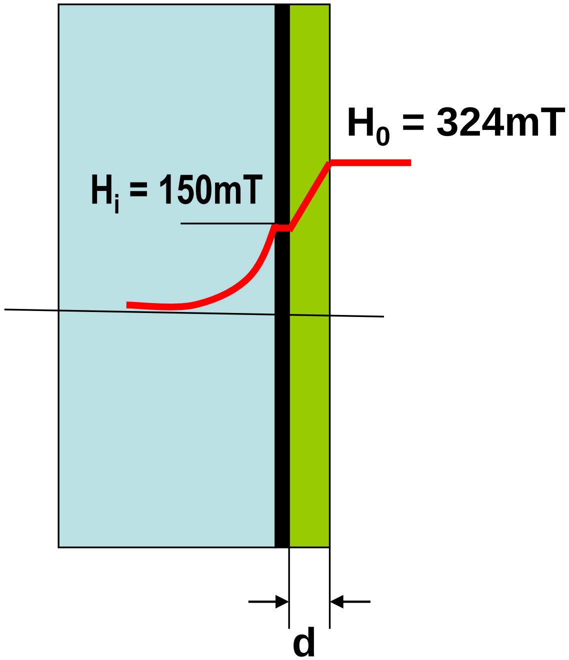


There is a “threshold” effect

Energetic condensation of ions with addition of a bias will likely help solving this problem

Multilayers. From A. Gurevich

A minimalistic solution



A Nb cavity coated by a single Nb_3Sn layer of thickness d = 50nm and an insulator layer in between

If the Nb cavity can withstand H_i = 150mT, then the external field can be as high as

$$H_0 = H_i \exp(d/\lambda_0) =$$
$$150 \exp(50/65) = 323.7mT$$

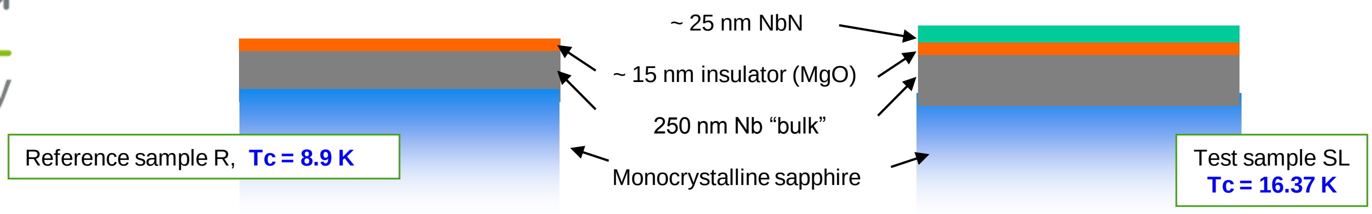
Lower critical field for the Nb_3Sn layer with d = 50 nm and ξ = 3nm: H_{c1} = 1.4T is much higher than H_0

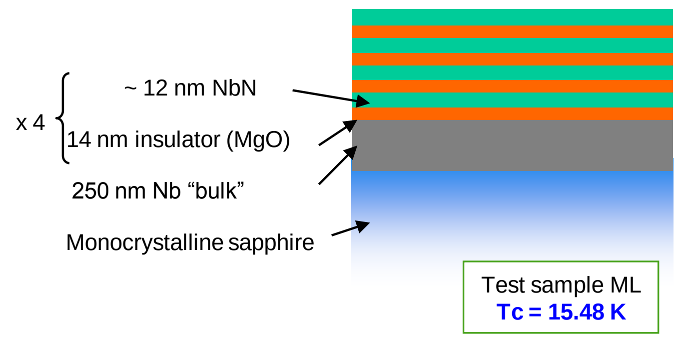
A single layer coating more than doubles the breakdown field with no vortex penetration, enabling E_{acc}~ 100 MV/m

Multilayers by sputtering

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

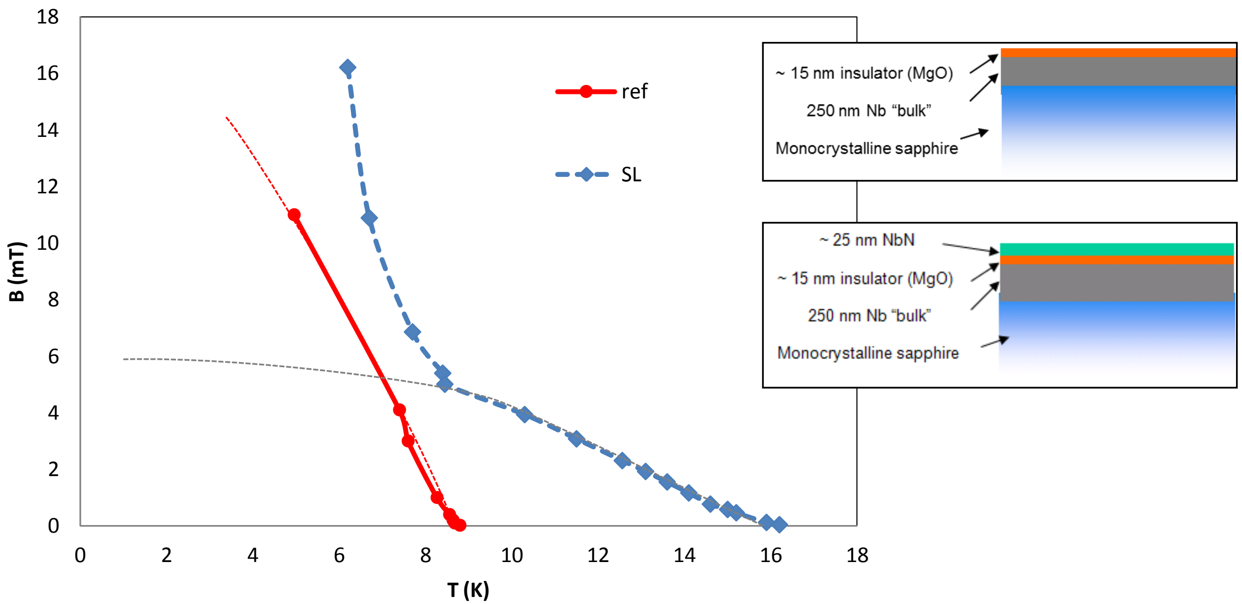




Collaboration with J.C. Villégier, CEA-Inac / Grenoble

NbN / MgO / Nb layers

Local magnetometry (3)

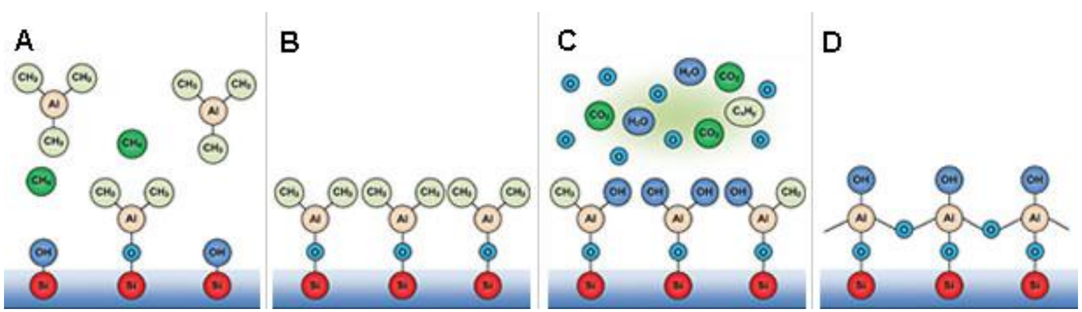


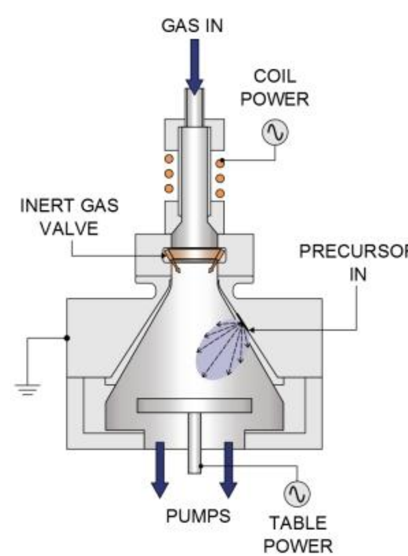
- **SL sample :** 250 nm Nb + 14 nm MgO + 25 nm NbN
- 8.90K < Tp < 16K : behavior ~ NbN alone
- Tp < 8.90K, i.e. when Nb substrate is SC **,** **=> B_{C1}^{SL} >> B_{C1}^{Nb}**

A new idea: ALD

ALD (Atomic Layer Deposition): conformal coatings from gas precursors

- Preliminary investigations (literature survey) done within EuCARD
- Testing going on at Argonne National Lab (USA)

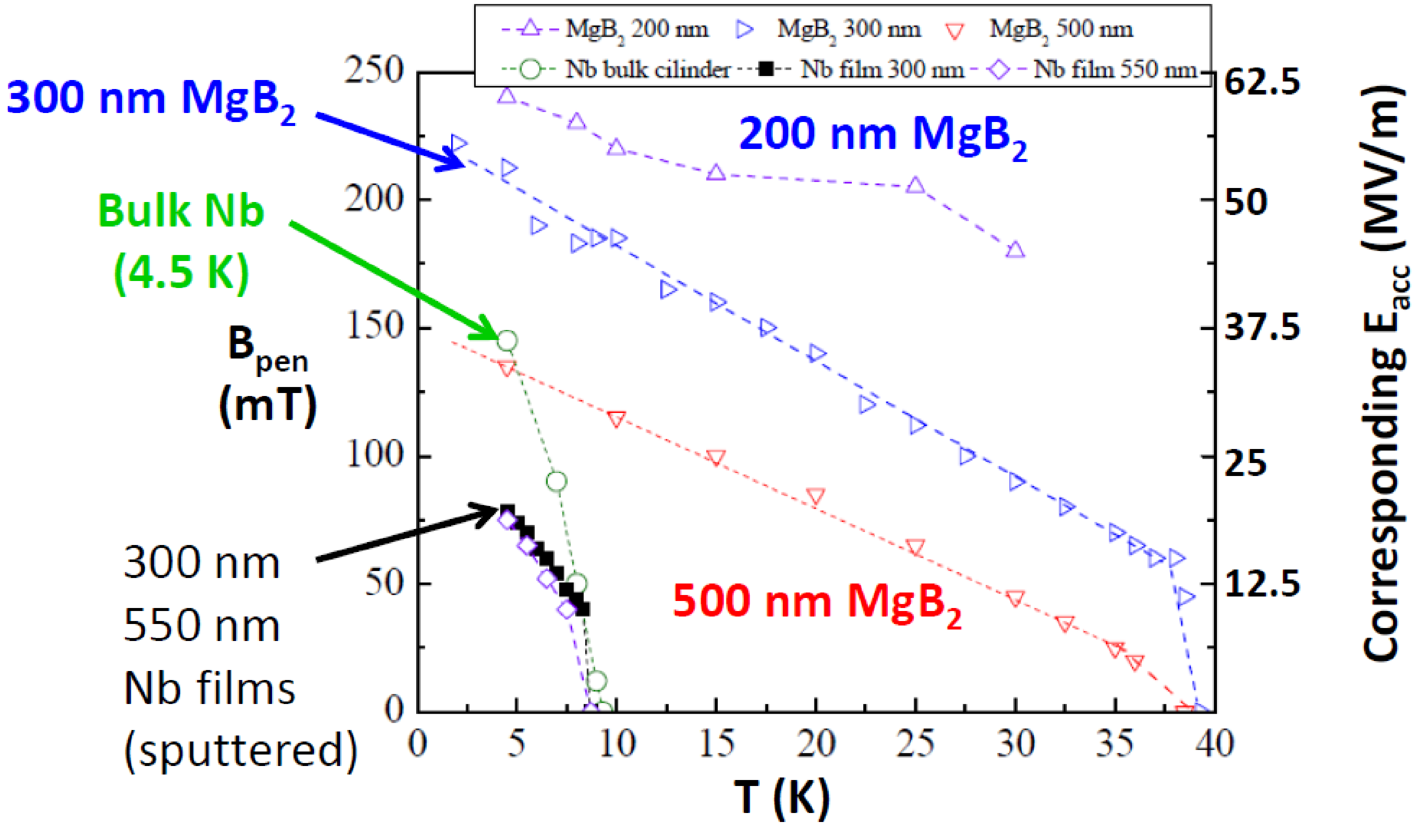




Images: Oxford Instruments

MgB_2 multilayer

DC magnetization measurement results: MgB_2 thin films (<500 nm) prepared by STI show higher B_p than that of Nb

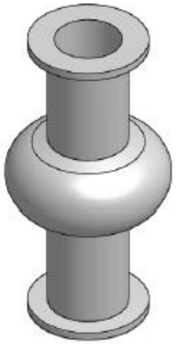


Tsuyoshi Tajima - LANL

MgB_2 thick films, preparing for cavity coating

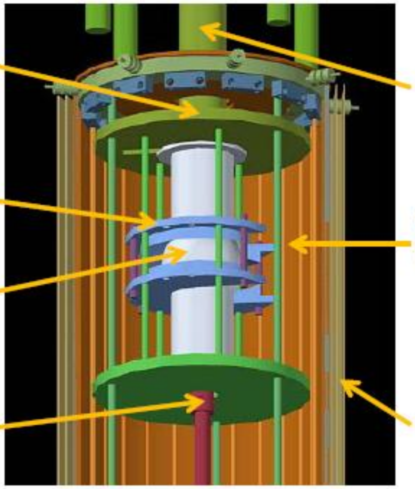
MgB_2 work at Temple – 6 GHz Nb cavity coating system

Integrated HPCVD system for cavity coating



6 GHz Nb cavity
(4″ high, 1.5″dia.)

S.S. Dummy
(4″ high, 1.5″dia.)



Cavity Drive (along z and rotation)

Cavity holding brackets

6GHz Nb cavity

Mg oven

B_2H_6 feed line (with water cooling jacket)

Cavity heater (constitute of two halves)

Thermal shield

Cartoon of cavity coating system

Front view

under test

Top view

- ❑ System for in-situ coating a real 6GHz Nb cavity
- ❑ B_2H_6 and Mg feeding line fixed, the cavity will move vertically in z direction and rotate
- ❑ System is close to completion, heater testing finished, same-size stainless steel dummy will be first coated for uniformity test

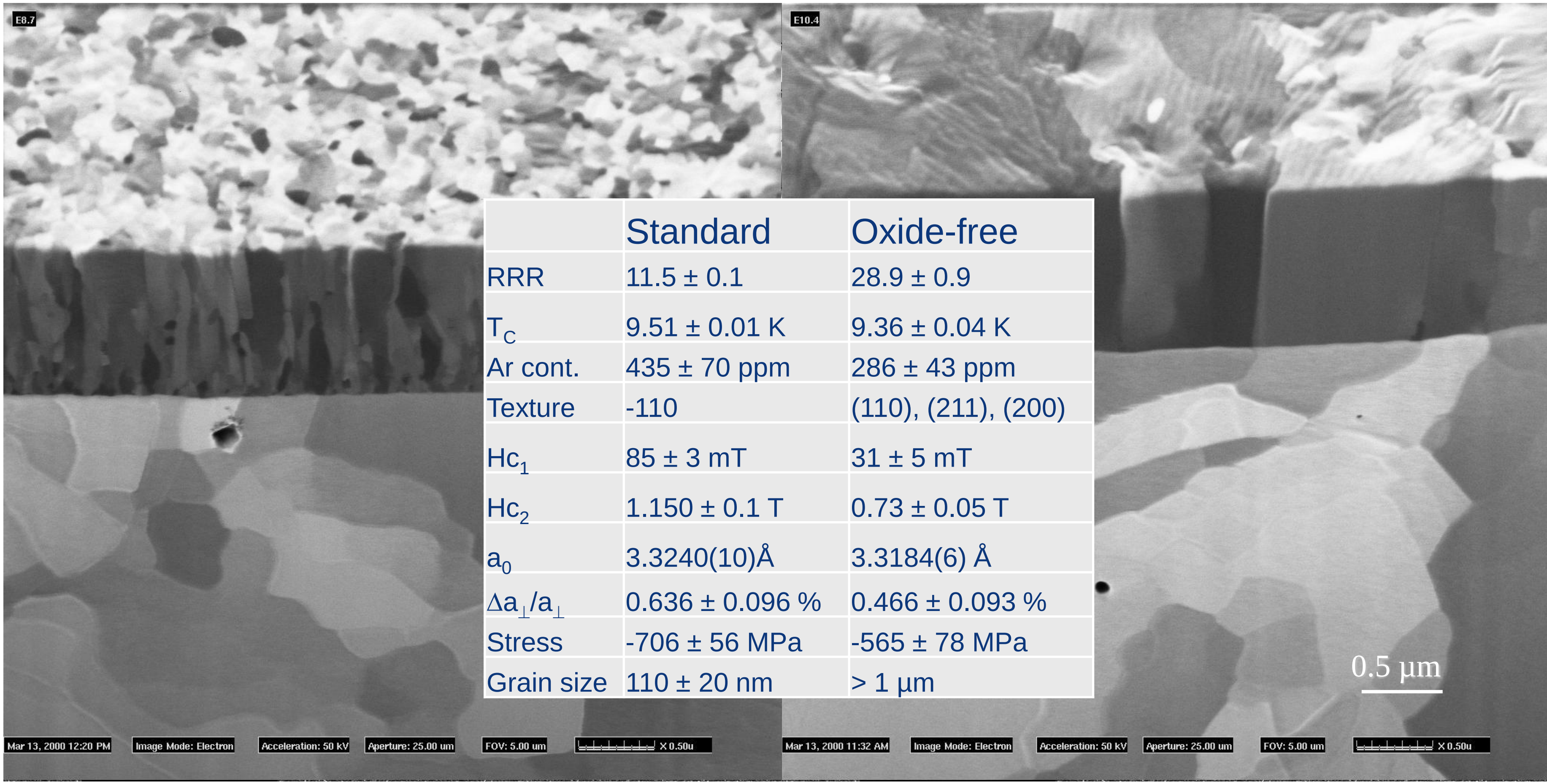
Summary and outlook

- Nb/Cu sputtered films investigated for > 25 years. State of the art results could be compatible with specs for high intensity proton accelerators.
- Nb/Cu cavities have clear advantages for operation stability. RIB facilities could benefit.
- Energetic deposition techniques have promise of improving over standard Nb/Cu -> will see soon
- Multilayers can theoretically improve even the performance of bulk Nb -> need R&D
- Higher Tc materials: potential for higher fields, probable limitation for high Q -> need R&D

Film analyses

Standard films

Oxide-free films

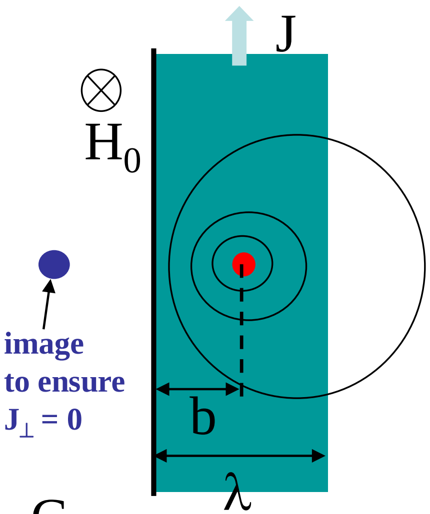


	Standard	Oxide-free
RRR	11.5 ± 0.1	28.9 ± 0.9
T_C	9.51 ± 0.01 K	9.36 ± 0.04 K
Ar cont.	435 ± 70 ppm	286 ± 43 ppm
Texture	-110	(110), (211), (200)
Hc_1	85 ± 3 mT	31 ± 5 mT
Hc_2	1.150 ± 0.1 T	0.73 ± 0.05 T
a_0	3.3240(10)Å	3.3184(6) Å
$\Delta a_{\perp}/a_{\perp}$	0.636 ± 0.096 %	0.466 ± 0.093 %
Stress	-706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

FIB cross sections courtesy: P. Jacob - EMPA

Multilayers. From A. Gurevich

Surface barrier: How do vortices get in a superconductor at $H > H_{c1}$?



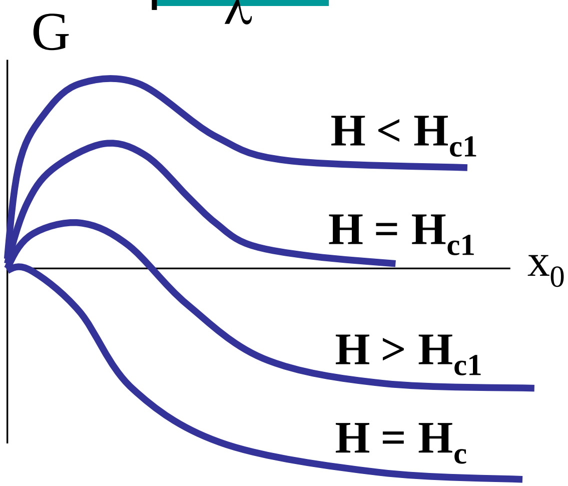
Two forces acting on the vortex at the surface:

- Meissner currents push the vortex in the bulk
- Attraction of the vortex to its antivortex image pushes the vortex outside

Thermodynamic potential $G(x_0)$ as a function of the position x_0:

$$G(b) = \phi_0[H_0 e^{-x_0/\lambda} - 0.5H_v(2x_0) + H_{c1} - H_0]$$

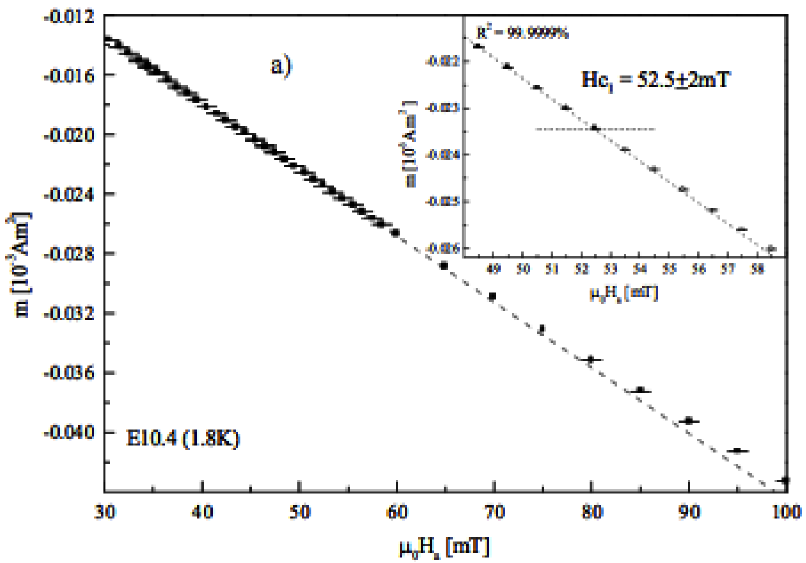
Meissner   Image

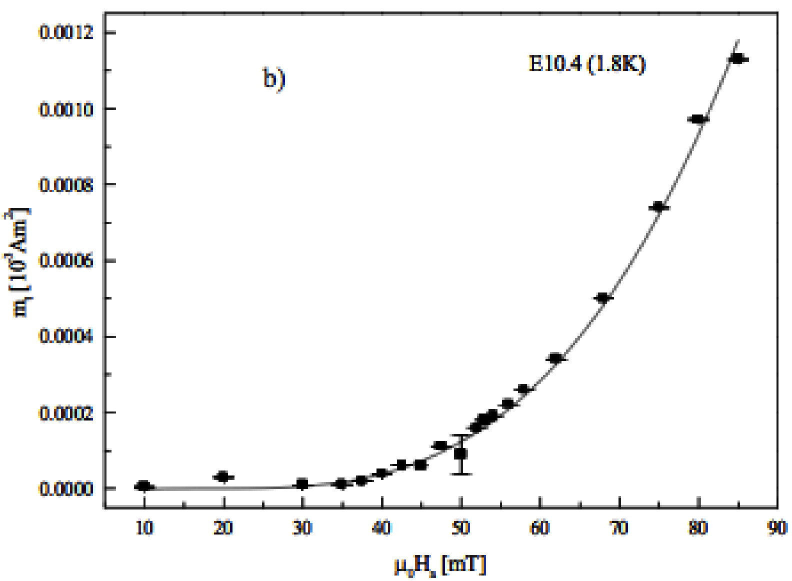


Vortices have to overcome the surface barrier even at $H > H_{c1}$ (Bean & Livingston, 1964)

Surface barrier disappears only at the overheating field $H = H_c > H_{c1}$ at which the surface J becomes of the order of the depairing current density

Measurements of H_{c1} on Nb films





Magnetic moment with squid magnetometer filed parallel to the sample

H_{C1} = 52.5 ± 2 mT

Same film, trapped magnetic moment with squid magnetometer
(fit with V.V. Moshchalkov et al., Physica C 175 (1991) 407)

H_{C1} = 31 ± 3 mT

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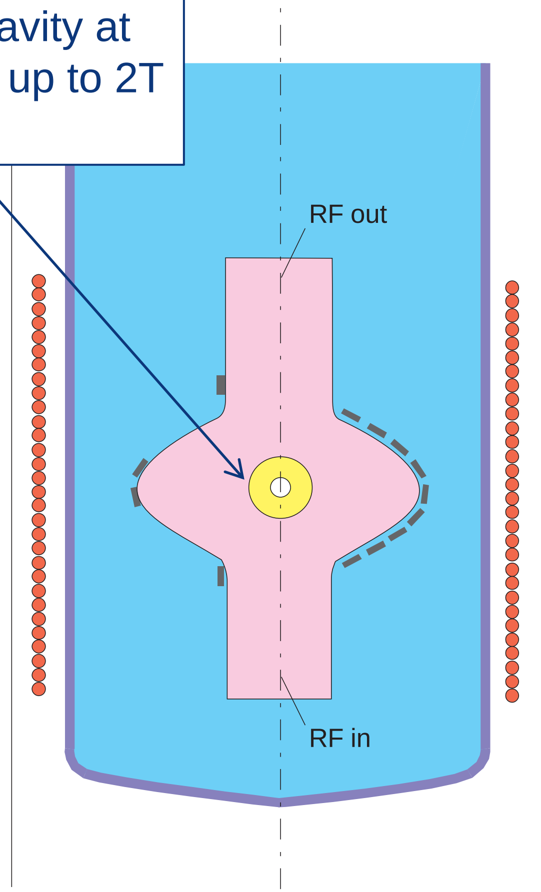
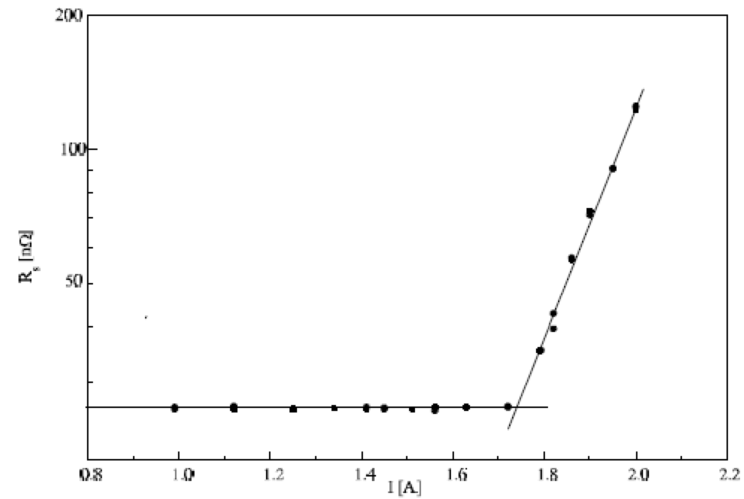
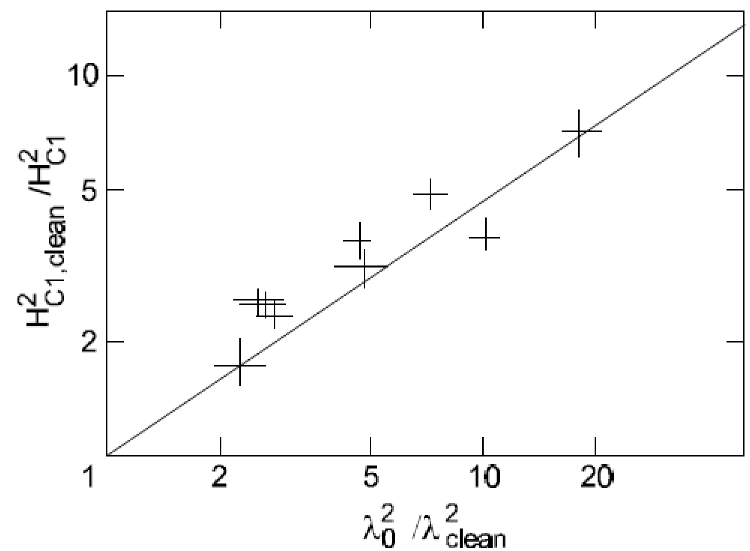
Measurement of H_{c1}

SC coil at the outer wall of the cavity at equator H_{ext} up to 2T over 3 cm^2







$H_{penetration}$ films $\leq$ 0.6 $H_{penetration}$ bulk

Local magnetometry (1)

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

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

  Perpendicular field : field distribution can be determined analytically.

  - If r_{sample}> 4 r_{coil} : Sample ≡ infinite plate approximation
  - Applied field : perpendicular, induction (B) // surface (below B_{C1})

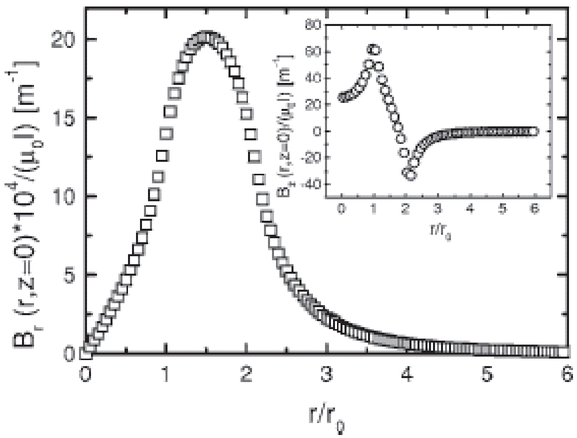
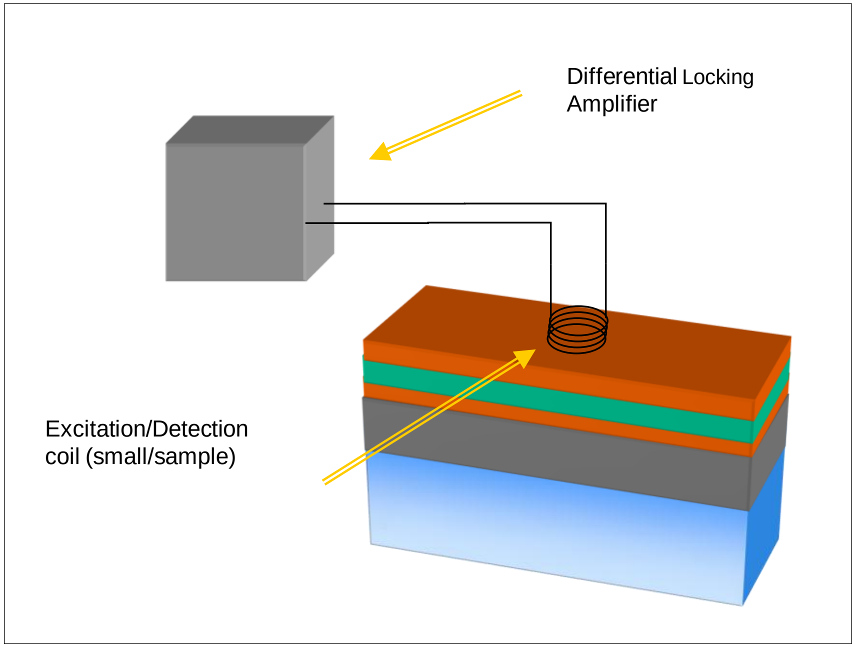
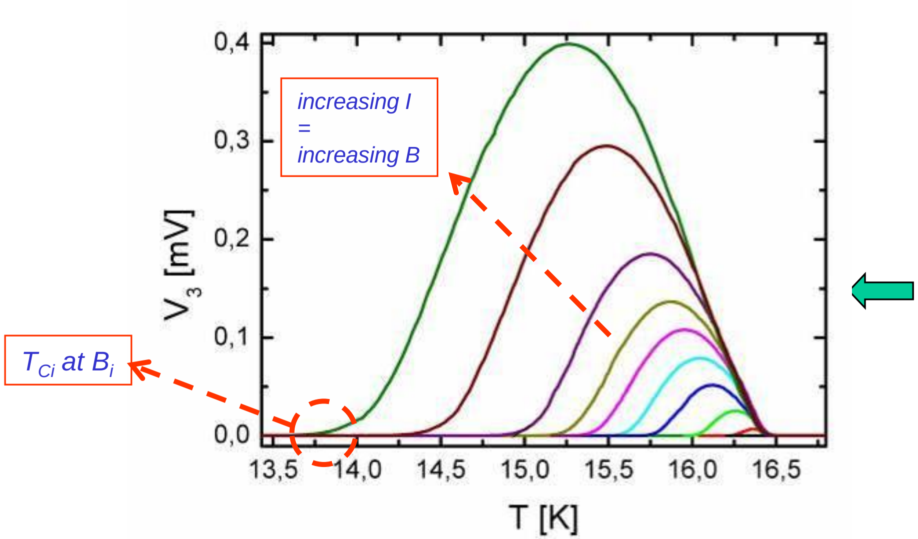


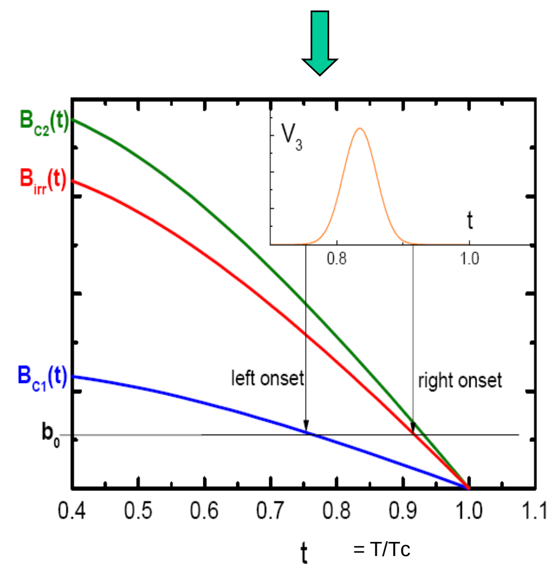
FIG. 4. Radial component of the total induction field (open squares) for a multiturn coil. In the inset the result for the normal component (open circles) is shown. Both components have been calculated at the sample surface as a function of r/r_0.



Local magnetometry (2)

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



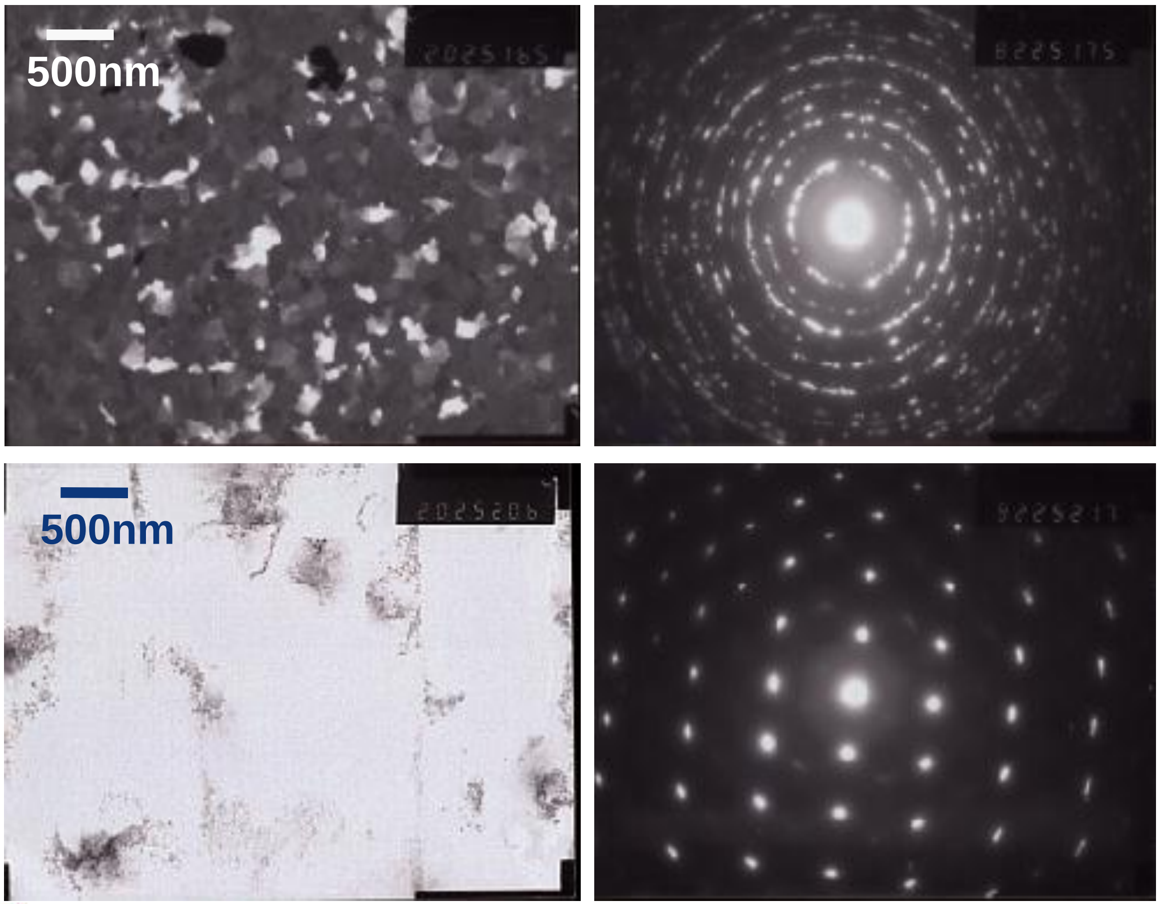


Sample SL : third harmonic signal for various b0

TEM micrographs in plan view

Standard

Oxide-free

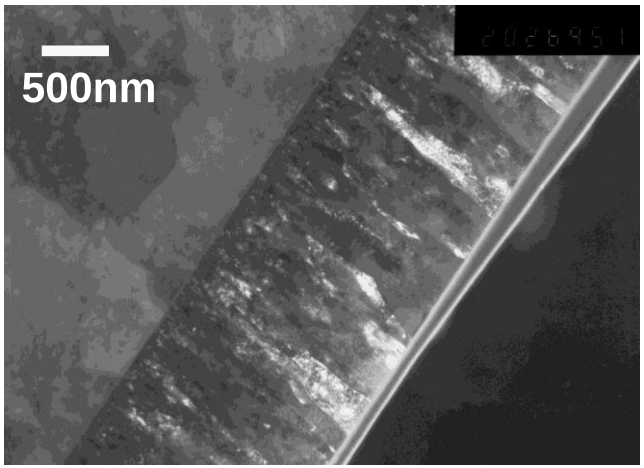


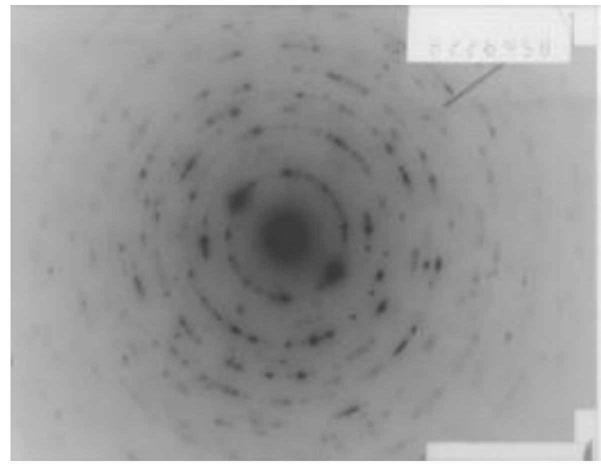
Grain size ~ 100 nm
Fibre texture
Diffraction pattern:
powder diagram

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

TEM micrographs in cross section

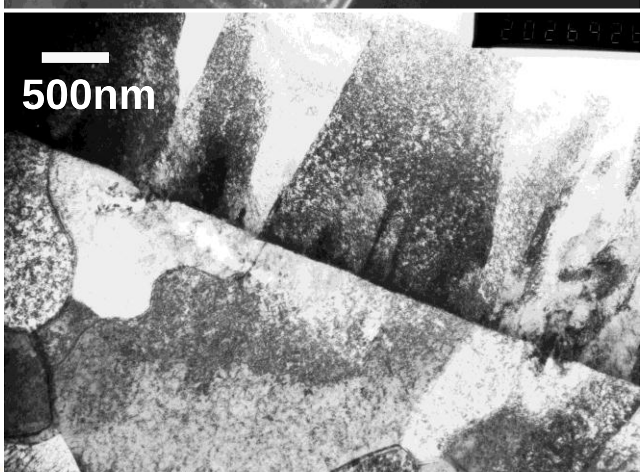
Standard

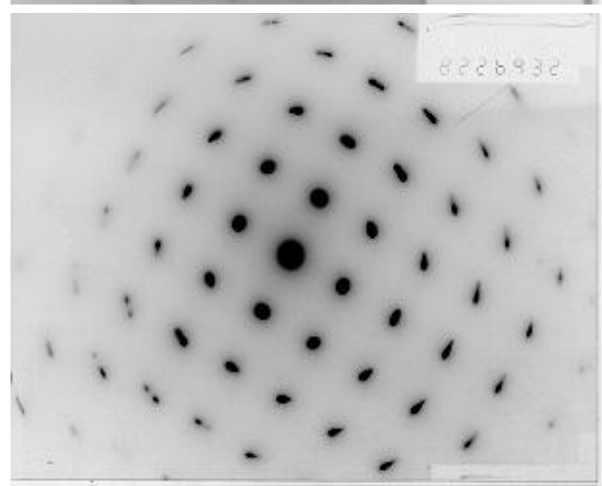




(110) fibre texture
⊥ substrate plane

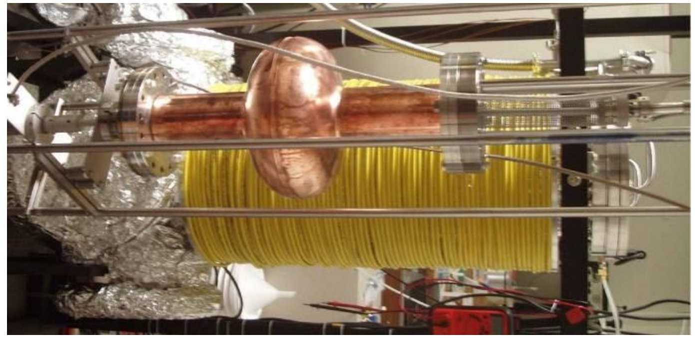
Oxide-free

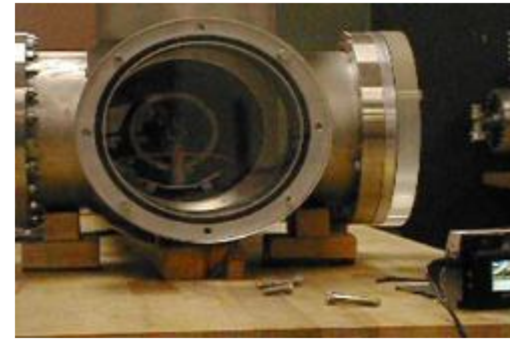




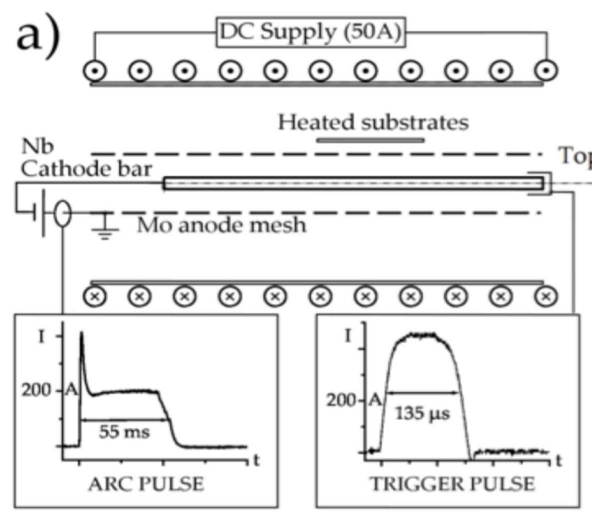
Heteroepitaxy
Nb (110) // Cu(010)
Nb (110) // Cu(111)
Nb (100) // Cu(110)

Coaxial Energetic Deposition (CED)





Coaxial Energetic Deposition (CED^{TM})

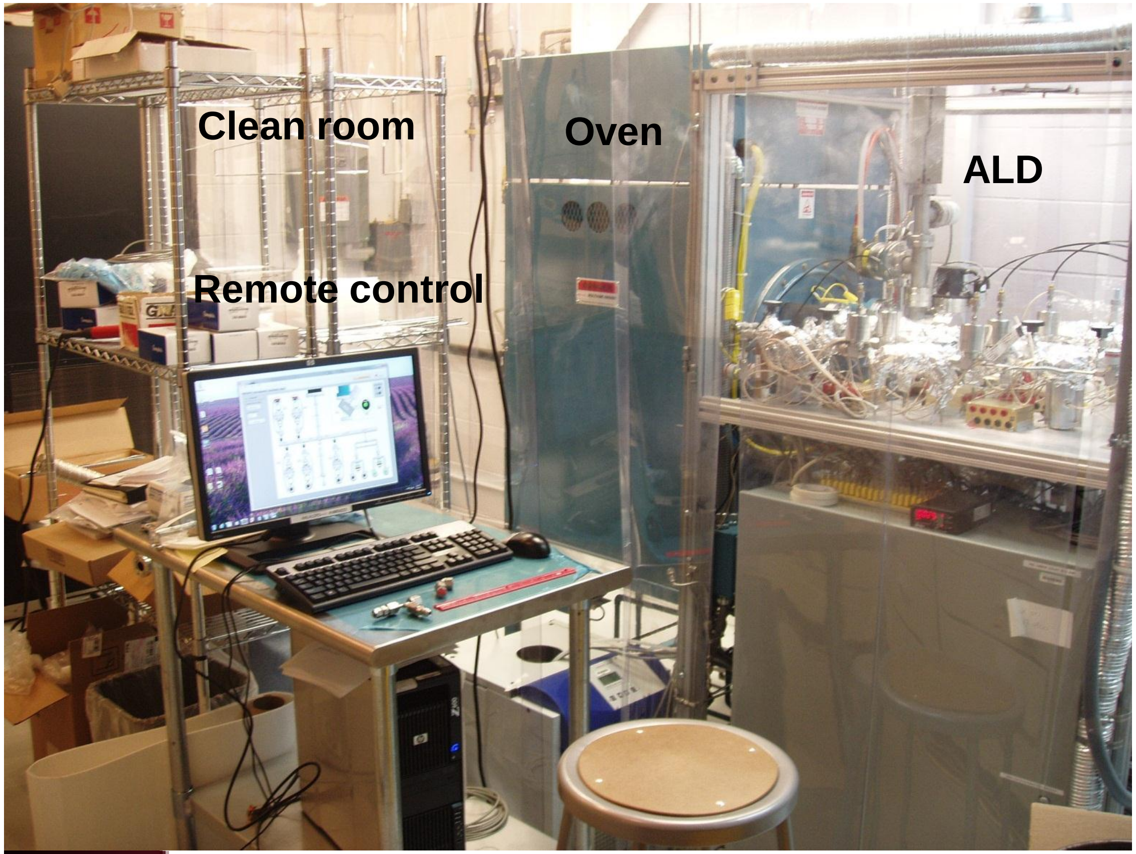


- CED coater uses “welding torch” technology
- Arc source is scalable to high throughputs for large scale cavity coatings
  - Present version deposits ~1 monolayer/pulse ~1 ms
- UHV and clean walls important

Atomic layer deposition – USA only

Atomic Layer Deposition Cavity System at ANL

Argonne NATIONAL LABORATORY



- Clean room class 100
- UHV Oven: 650C-10^{-7} T
- Fully automatized ALD
- Long deposition overnight
- Growth of films: 12.5 K T_c (for now)
- Uniform on cavity scale

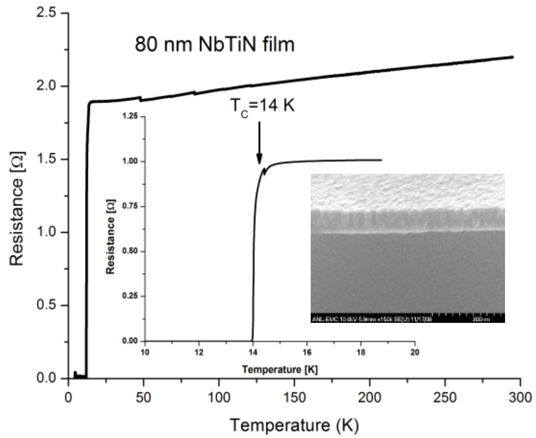
Thomas Proslier

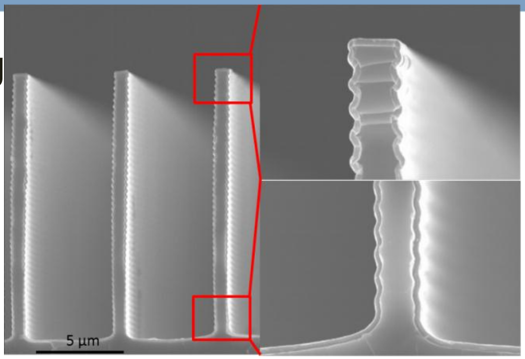
ALD

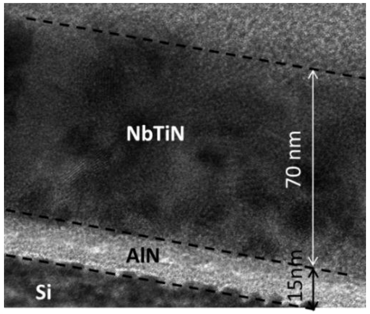
Atomic layer deposition of superconductors

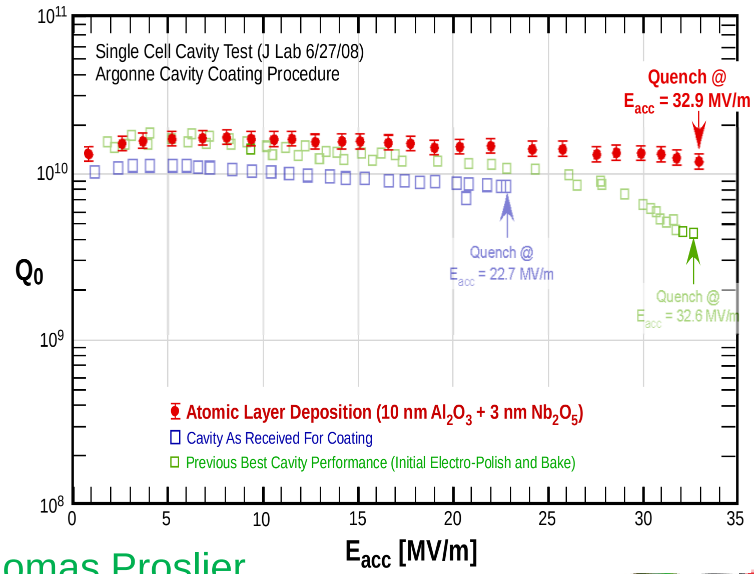
Argonne NATIONAL LABORATORY

- Self limiting surface reactions -> conformal coating
- Vapor phase precursors -> high aspect ratio









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Jefferson Lab