CERN

Materials fabrication in SRF cavities: beyond niobium

Sergio Calatroni – CERN

With the contribution of: Cornell U., FNAL, ICMAB, INFN-LNL, JLAB, STFC, Temple U.

Outline

- Motivation (one of several): the FCC-ee study

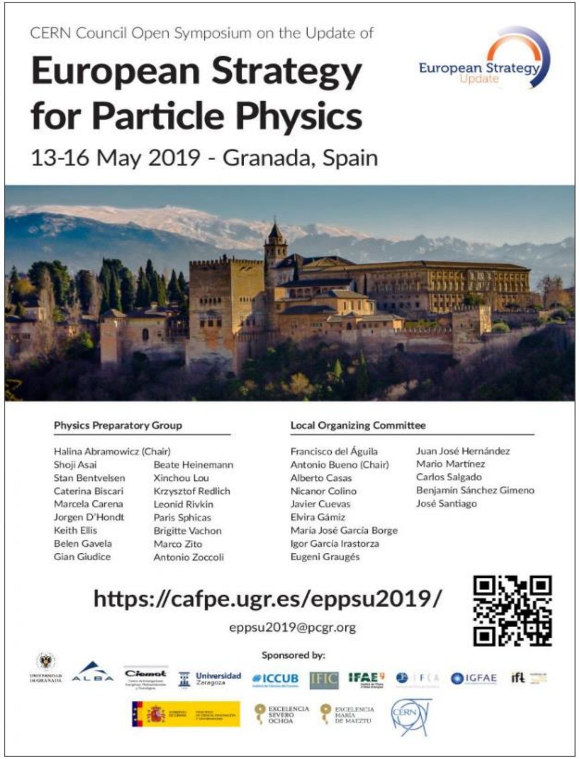
- State of the art of bulk Nb

- Techniques for Nb_3Sn SRF cavities:
  - Thermal diffusion of Sn vapours
  - Liquid Sn diffusion
  - Magnetron sputtering

- Techniques for NbN / NbTiN SRF cavities
  - Thermal diffusion of N
  - Magnetron sputtering

- Techniques for other materials
  - MgB_2
  - REBCO

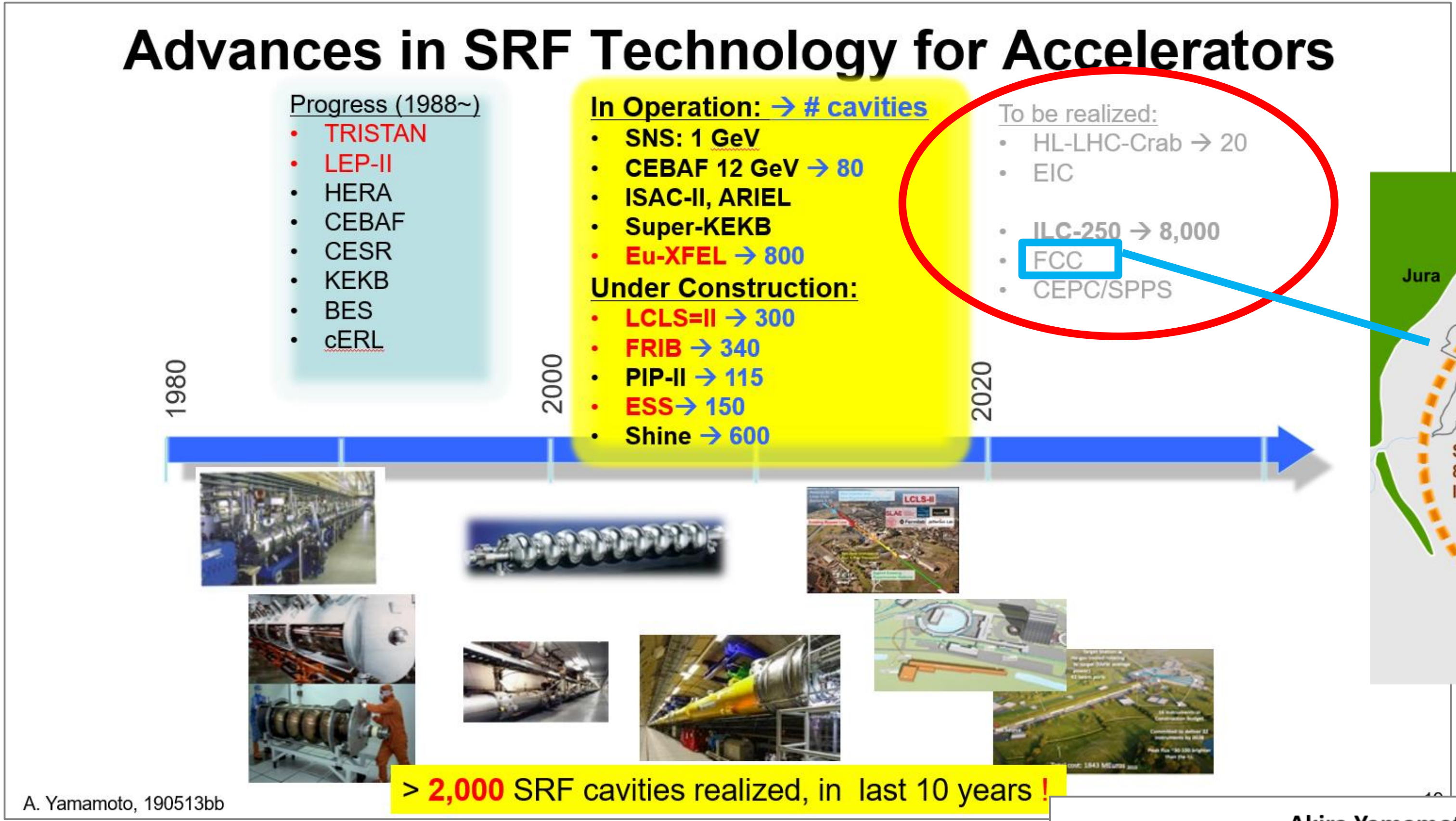
Preamble

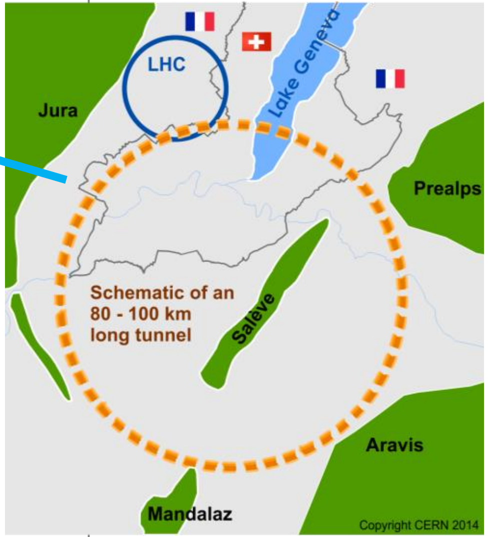


- The European Strategy for Particle Physics must provide a clear prioritisation of European ambitions for the long-term future of the field.
- Mandated by the CERN Council, it is formed through a broad consultation of the particle physics community, it actively solicits the opinions of physicists from around the world, and it is developed in close coordination with similar processes in the US and Japan in order to ensure coordination between regions and optimal use of resources globally.

  - Europe is engaged in R&D projects for post-LHC facilities under the CLIC and FCC umbrellas
  - Globally-coordinated neutrino programme with experiments to be carried out in the USA and Japan
  - The International Linear Collider remains on the table with a site having been identified in Japan
  - There are ambitious plans to build a large collider in China
  - At CERN, a study to investigate the potential for physics beyond colliders, maximising the potential for CERN's unique accelerator complex, was launched in 2016.

- The discussions are based on scientific evidence gleaned from the results coming in from the LHC, as well as from technological and resourcing considerations.
- Deliberations are underway. The Strategy is due to be updated by May 2020





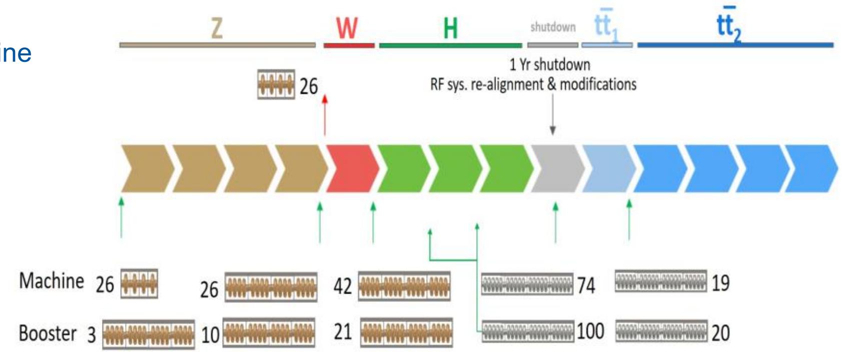
Akira Yamamoto

(KEK and CERN)

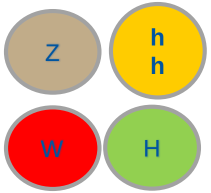
A Plenary Talk at CERN Council Open Symposium on the Update of European Strategy for Particle Physics (ESPP)
13-16 May, 2019 – Granada, Spain

The FCC-ee project: a 14 years program prior to the FCC_hh

"High current" machine

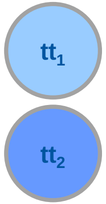


"High gradient" machine



high intensity (Z, FCC-hh): 400 MHz Nb/Cu 1-cell cavities

Higher energy (W, H): 400 MHz 4-cell Nb/Cu cavities (4/CM)



tt machine complement: 800 MHz 5-cell cavities (4/CM.), based on bulk Nb

~1 MW per cavity !!

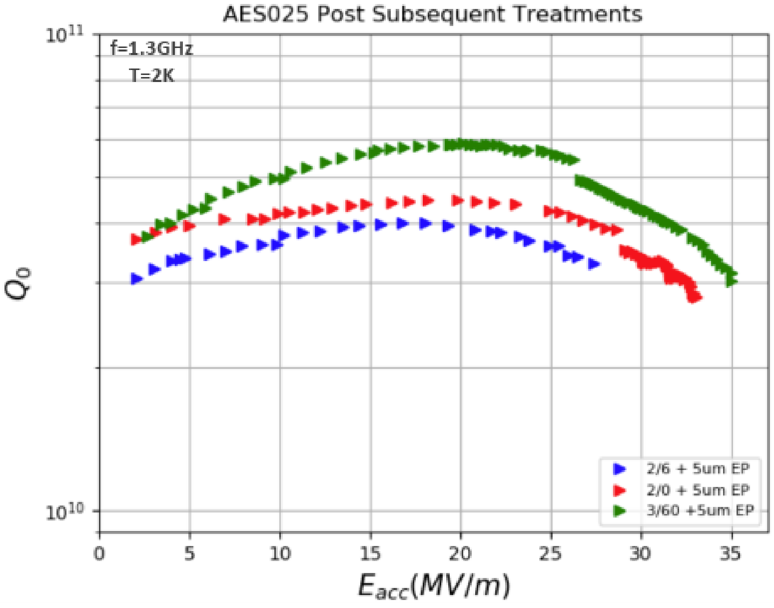
- Cavity design, beam interaction
- FPC & HOM couplers
- Innovative CC designs (WOW for FCC_hh)

> 20 MV/m

- Cavity fabrication (>850)
- CM design
- integration…

Courtesy O. Brunner - CERN

State of the art: bulk niobium + nitrogen doping



2/6 + 5um EP (baseline):

+40um EP reset

2/0 + 5um EP:

- Higher Q and **quench increases by +6MV/m**

+40um EP reset

3/60 + 5um EP:

- **Quench improves by additional +2MV/m, Q_0=6E10 @ 20MV/m!**

Grassellino - Progress in High Q/high G

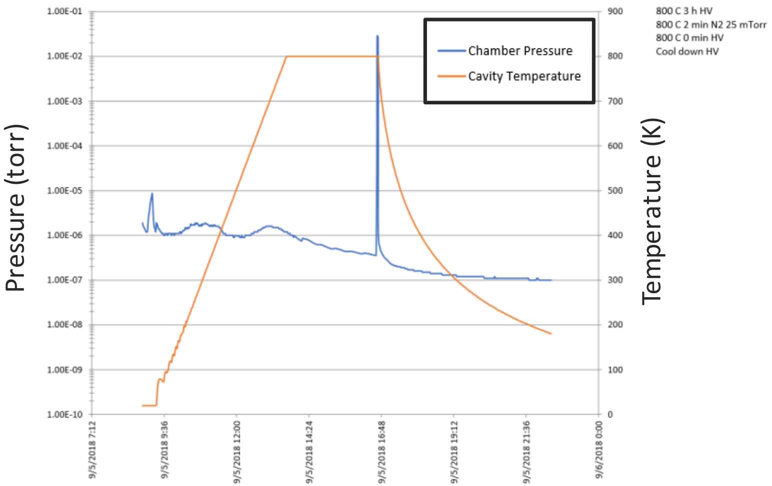
Courtesy A. Grassellino - FNAL

Fermilab

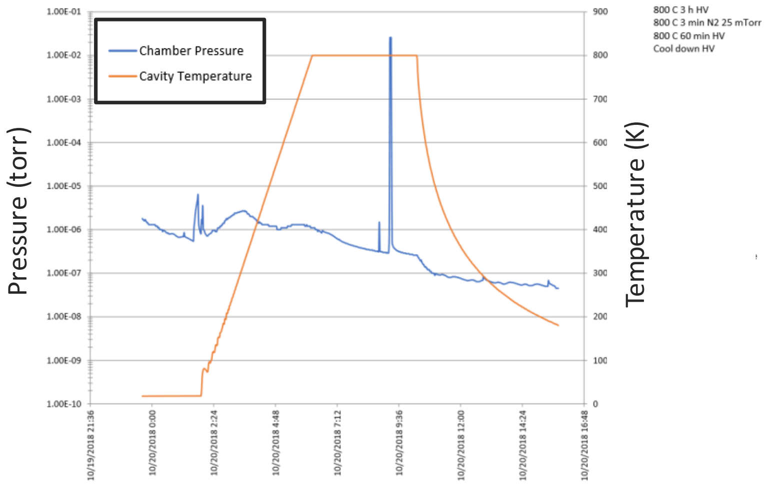
Doping?

- Using Nb 3 cavities, we test sequential treatments with a 40µm EP surface reset in between
- Working in the context of Fermilab R&D and LCLS-II HE, we studied the following recipes:

2/0 Doping - Fermilab

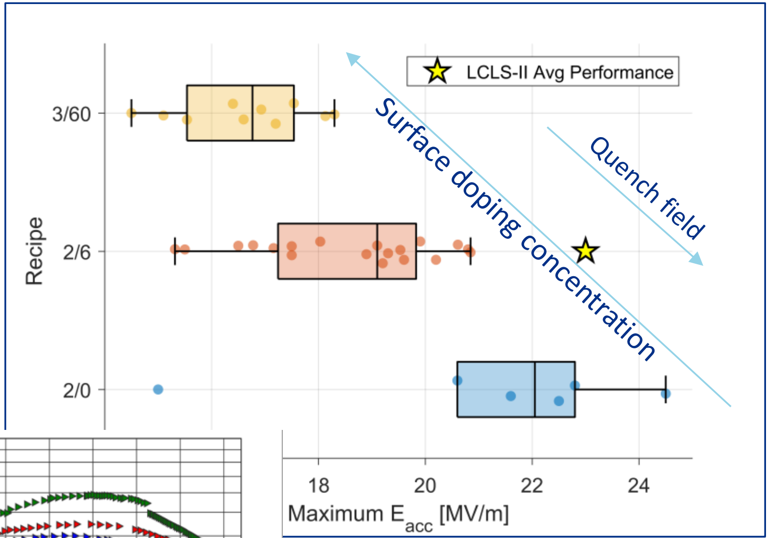


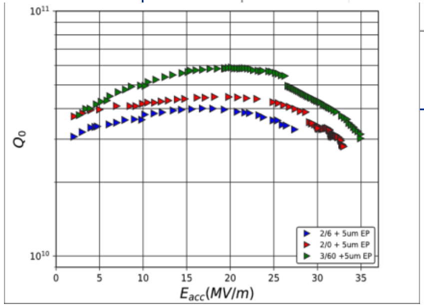
3/60 Doping - JLab



LCLS-II-HE
Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

Results





FNAL single-cell cavities (cold EP post-doping)

- Quench field scaling with surface nitrogen level (NbN) in 9-cell cavities suggest **etching instead of polishing** during EP (due to different reactivity of NbN compare to Nb)
- **Colder EP help achieve higher gradients in doped cavities** – independent of recipe – because **the etching phase of the EP is reduced**

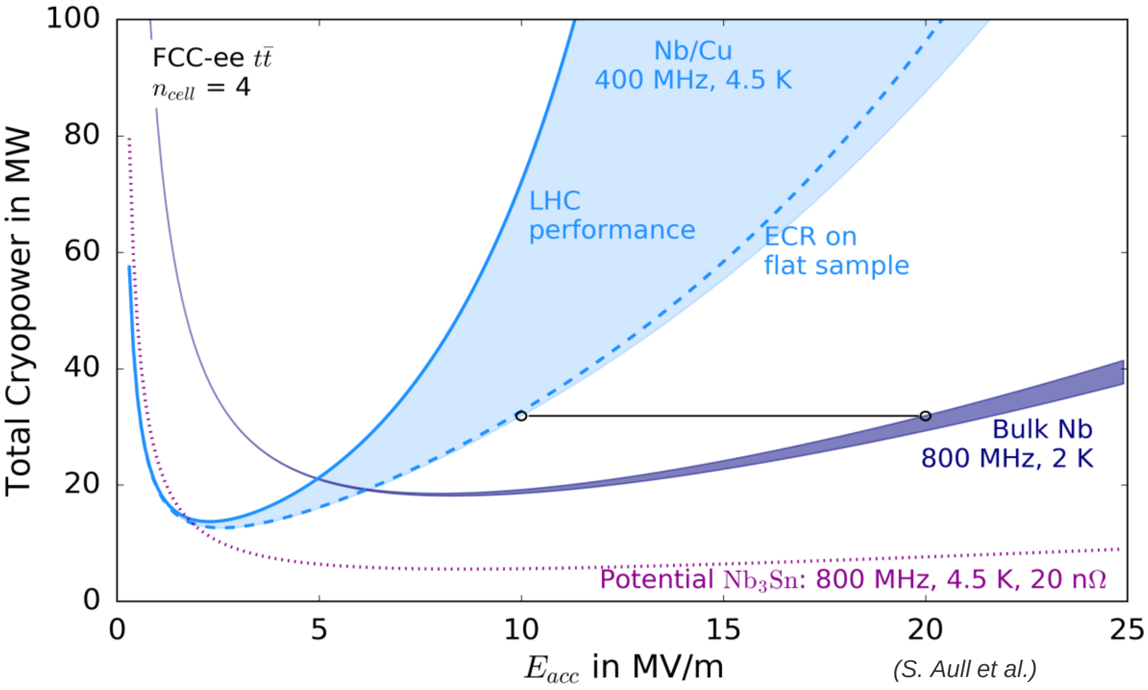
Fermilab

Power losses

$$E_{acc} \approx H_s$$

$$Q_0 = \frac{\Gamma}{R_s}$$

$$P = \frac{1}{2} R_s H_s^2$$



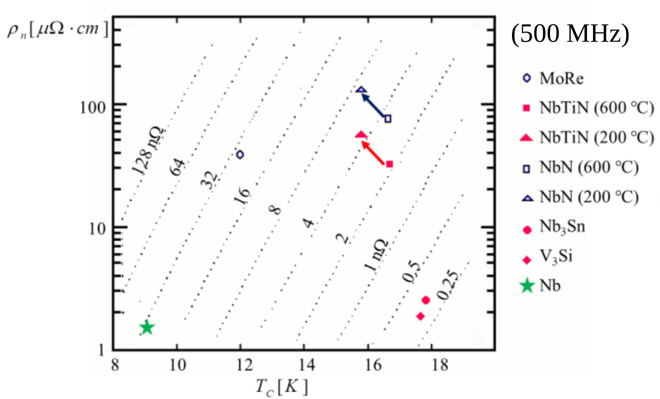
(S. Aull et al.)

A small accelerating field is favorable in circular accelerators, in terms of overall energy consumption

Example FCC-ee (tt^{-}): orders of magnitude

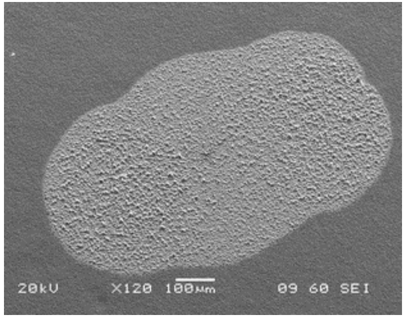
Surface resistance

$$R_{BCS}(T) = \frac{A\rho_n^{1/2}\omega^2}{T}\exp\left(-\alpha\frac{T_c}{T}\right)$$



R_{res}: defects, impurities, inhomogeneities, grain boundaries, hydrogen, welds, contamination, …

Surface resistance
$R_{BCS}(T) + R_{res}$



$R_{BCS}(T)$: "Intrinsic"

R_{res}: "Extrinsic"

R_{BCS} (4.5 K) of these A15 and B1 materials is comparable to R_{BCS} (1.9 K) of Nb

Provided R_{res} is also kept similar, operation at 4.5 K could allow great power savings

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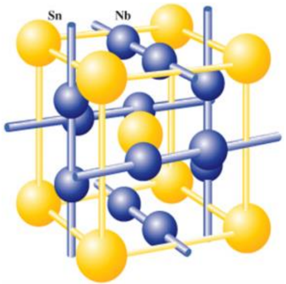
Nb_3Sn



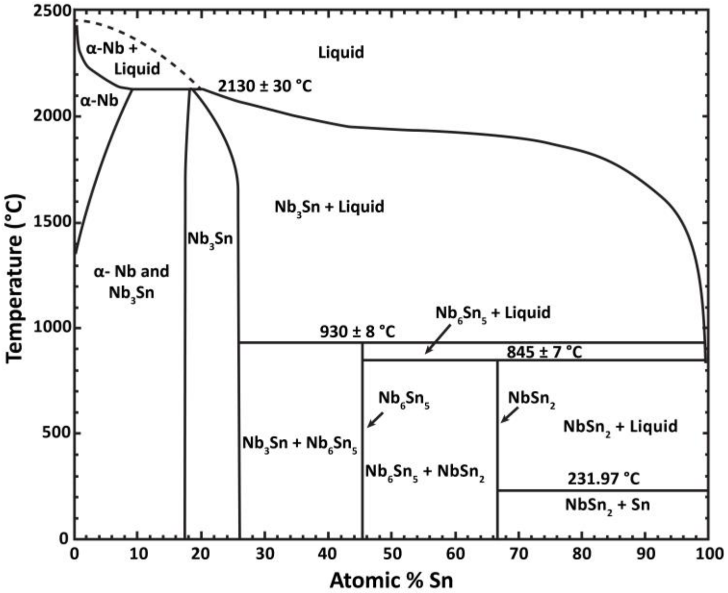


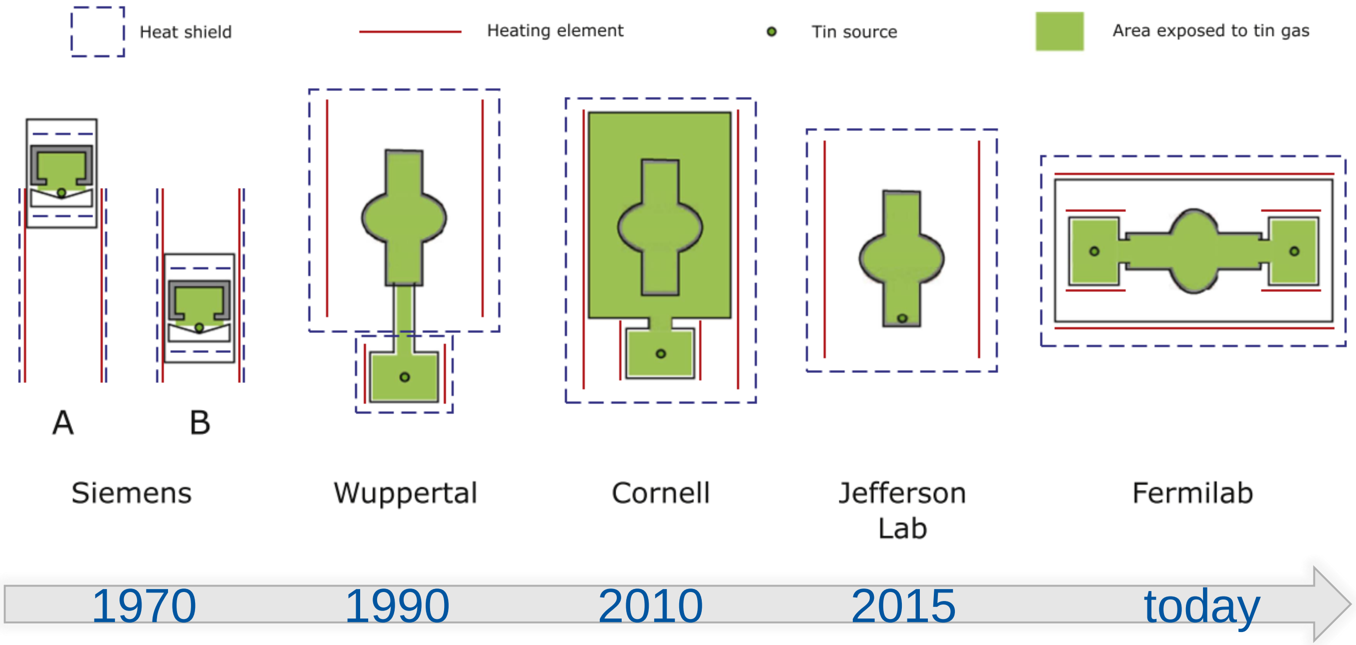
Image by Charlie Sanabria - CC BY 4.0

Two main routes:

Using a bulk Nb cavity, and forming Nb_3Sn on its surface , reacting either Sn vapours or Sn liquid

Using a Cu cavity, and sputter a thin Nb_3Sn film on its surface, either by co- or sequential sputtering or from an alloyed target

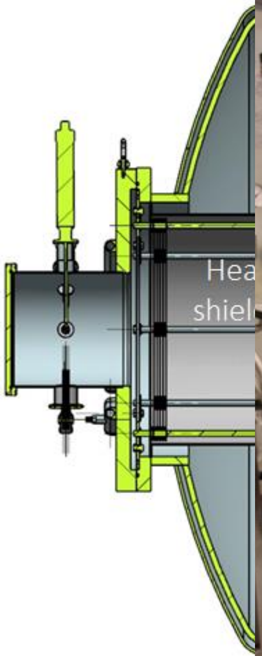
Furnace configurations

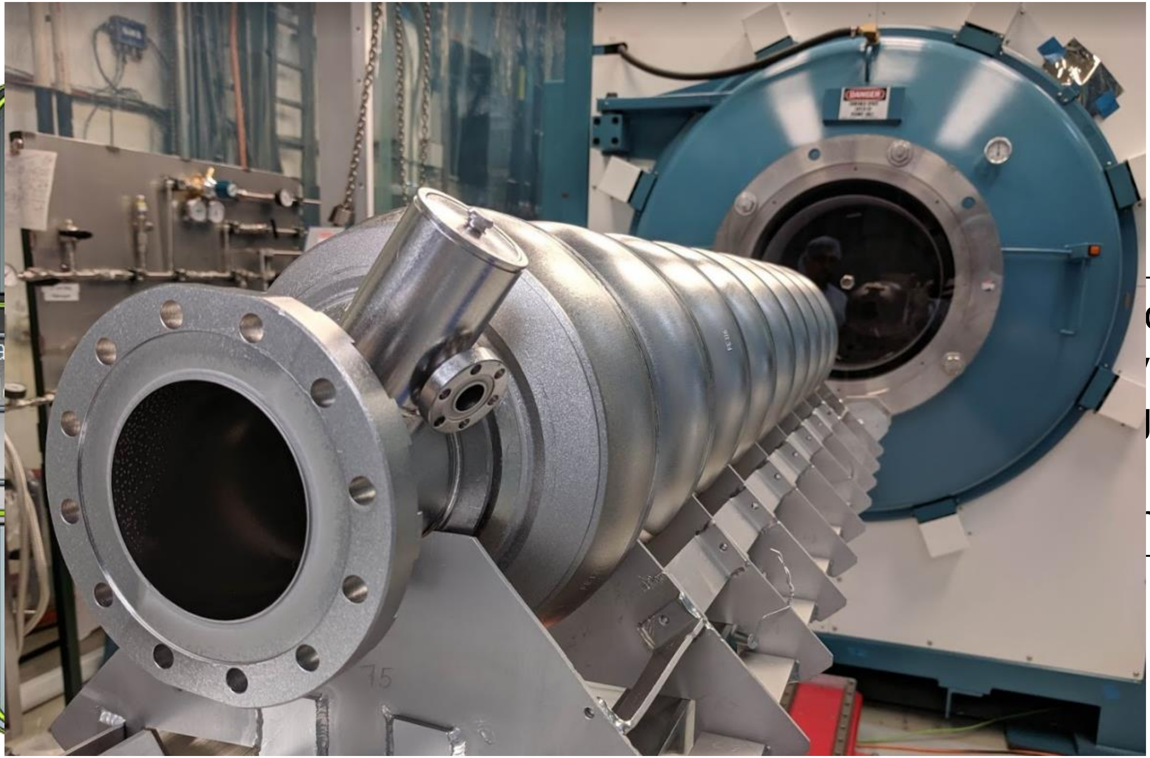


(Coordinated development work)

Image courtesy S. Posen, D. Hall - Supercond. Sci. Technol. 30 (2017) 033004

Nb_3Sn from vapours

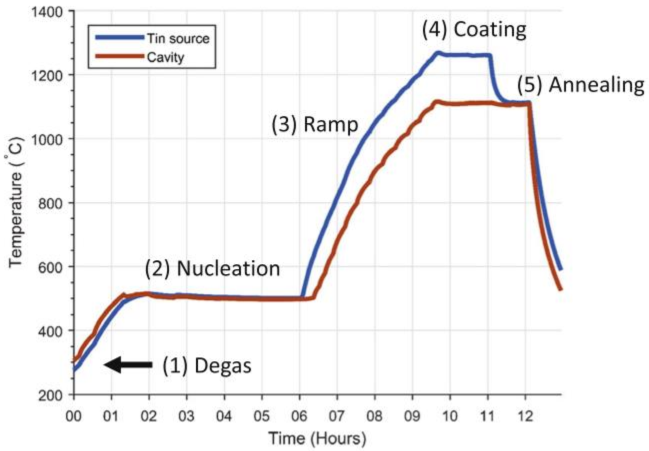


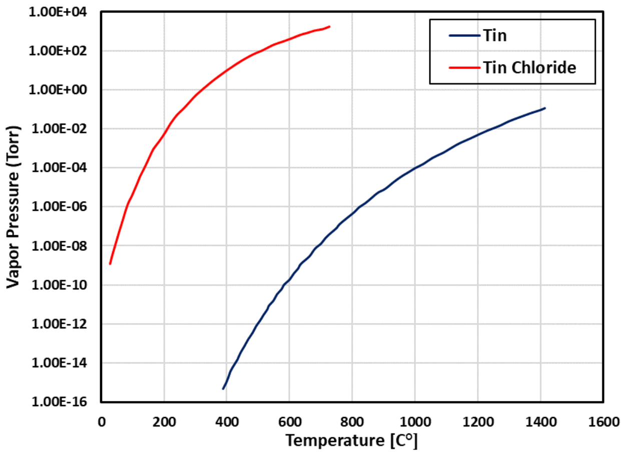


of a 9-cell ILC
in Fermilab
furnace (two
sources,
ndent heating)

Courtesy S. Posen – FNAL (SRF 2019 talk)

Thermal cycles, vapour pressures





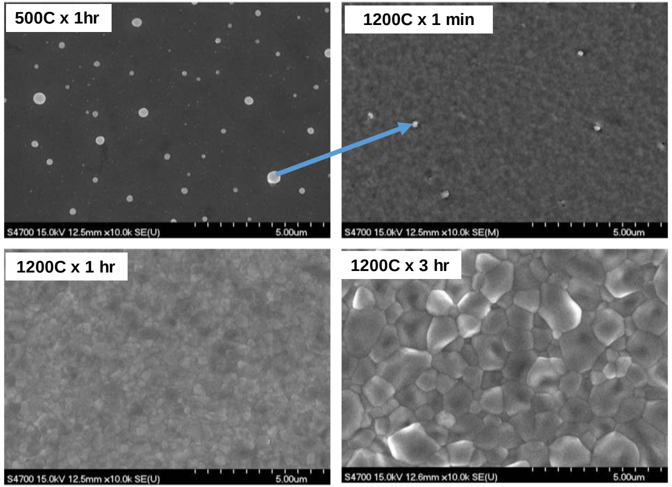
Excess of Sn to uniformly cover all the surface is needed, before Nb natural oxide is reduced.

- By means of controlled-temperature Sn source
- By means of added $SnCl_2$ source (larger Sn vapour pressure)
  - (still unclear the role of Cl, might promote nucleation sites)
- By means of thicker Nb oxide (anodization)
  - (thicker oxide detrimental to RRR, leading to quenches)

Plots courtesy S. Posen, D. Hall - Supercond. Sci. Technol. 30 (2017) 033004

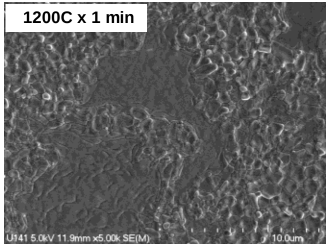
Layer evolution with and without $SnCl_2$

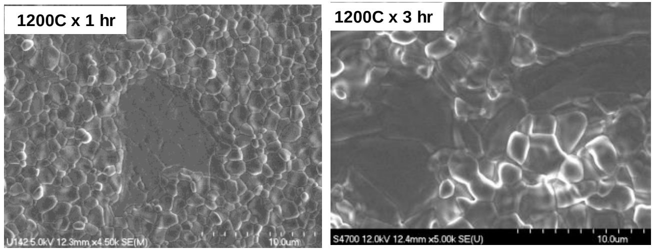
With $SnCl_2$



Little to no patches.

Without $SnCl_2$, the coating is susceptible to irregular coating with "patchy" regions.





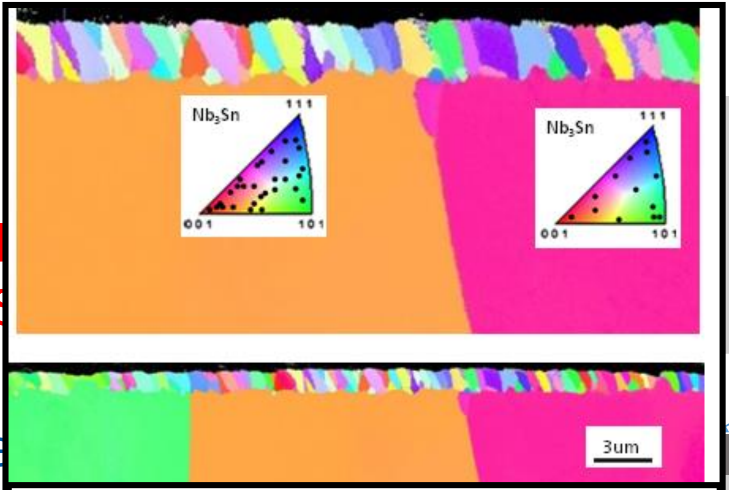
Jefferson Lab
Thomas Jefferson National Accelerator Facility

WILLIAM & MARY

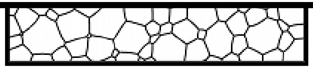
Slide courtesy of Uttar Pudasaini, Jefferson Lab - Thin Films 2018 Talk

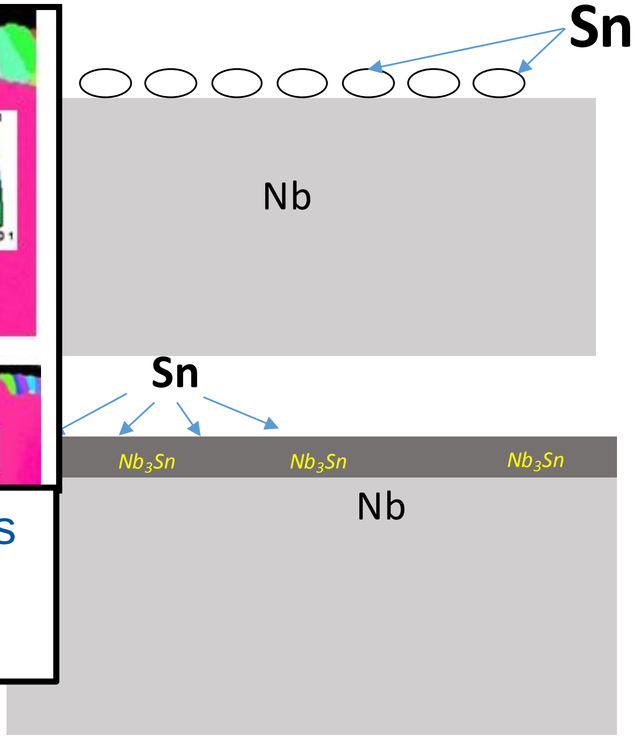
Growth process

1. Sn arrives at Nb
   Sn source
2. Sn reacts with N
   coverage of Nb_3
   obtained.
3. Nb_3Sn progresse
   diffusion through
   boundaries, reac
   reacting with the
   substrate.



Nb_3Sn film grain orientation is independent from Nb grain orientation

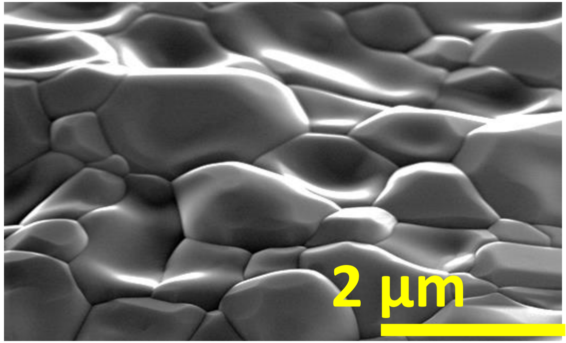


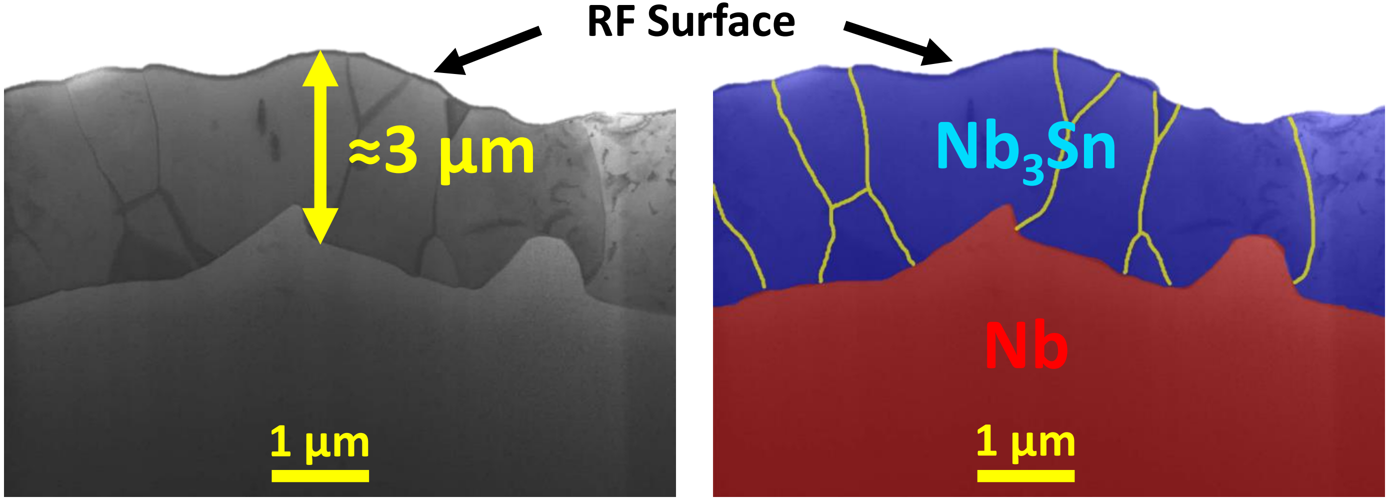


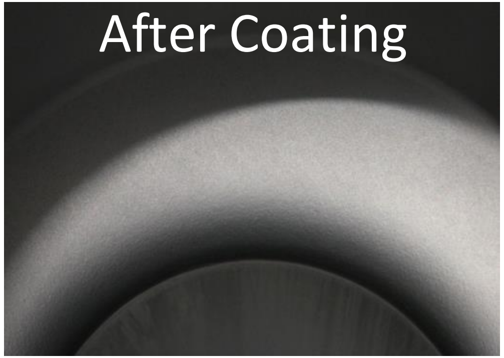
Images courtesy of Uttar Pudasaini, Jefferson Lab - Thin Films 2018 Talk

Nb_3Sn layer

Nb_3Sn forms a polycrystalline layer on the surface of the Nb

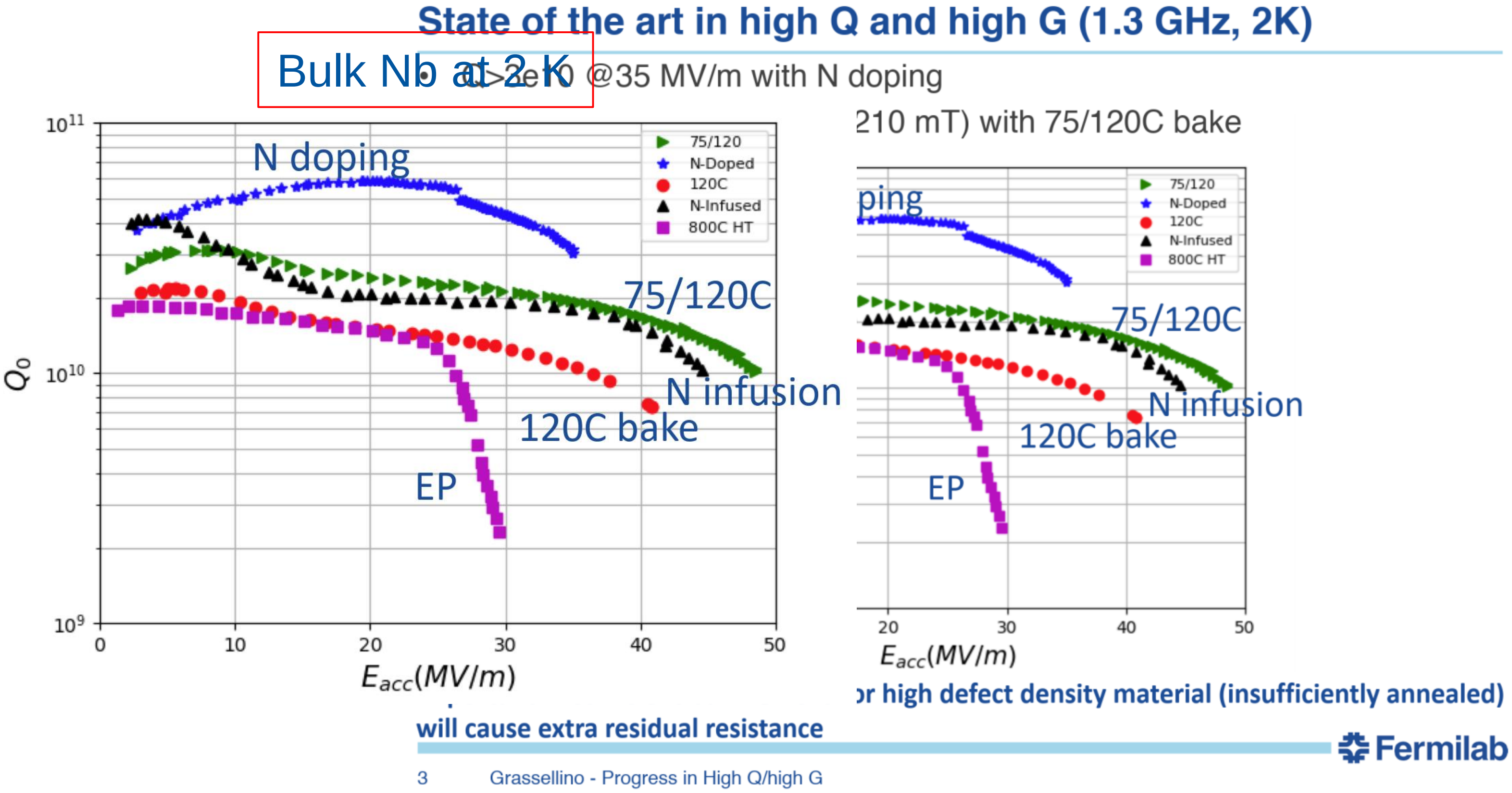




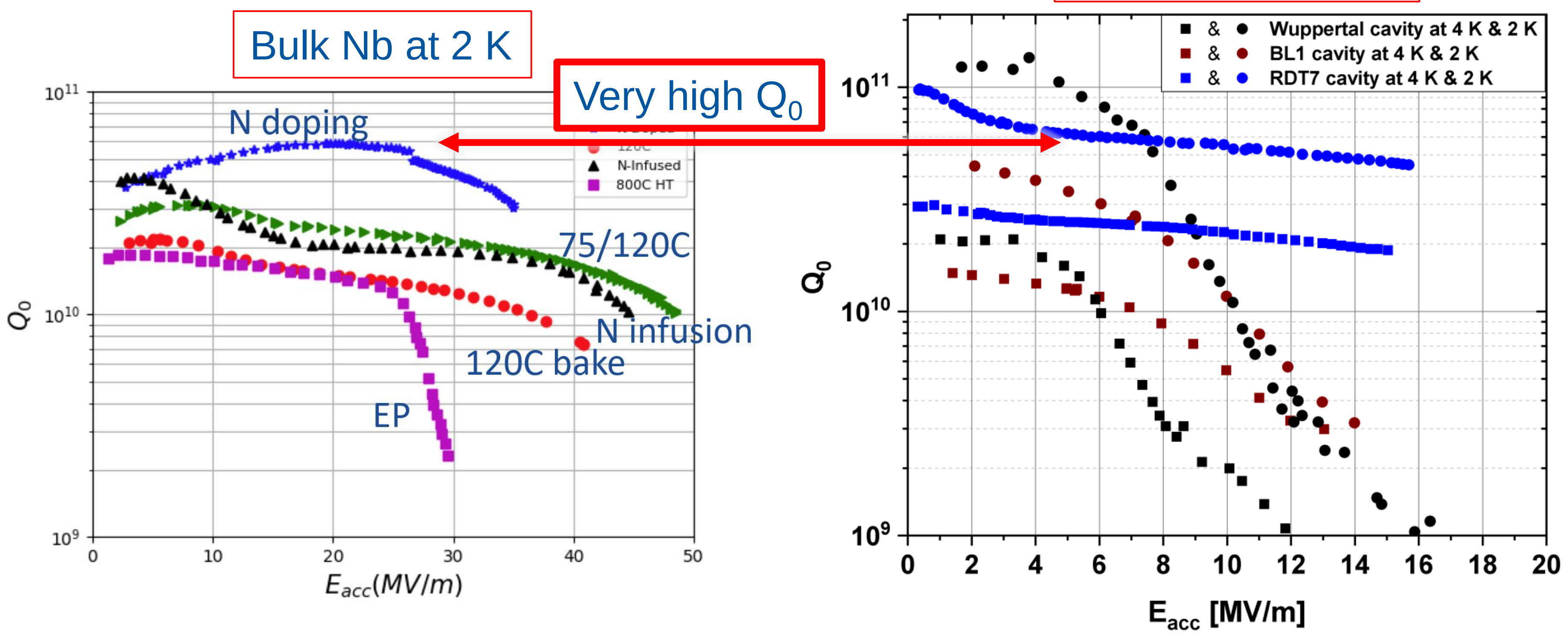


Slide courtesy of Ryan Porter, Cornell U.

RF results: Nb bulk reference



Nb_3Sn results (1.3 GHz cavities)



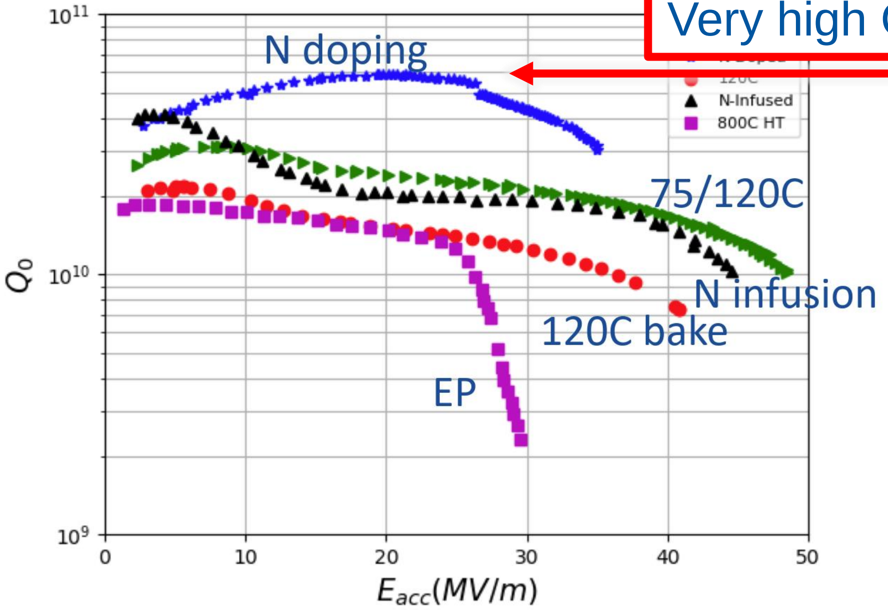
Plot courtesy of Uttar Pudasaini, Jefferson Lab - Thin Films 2018 Talk

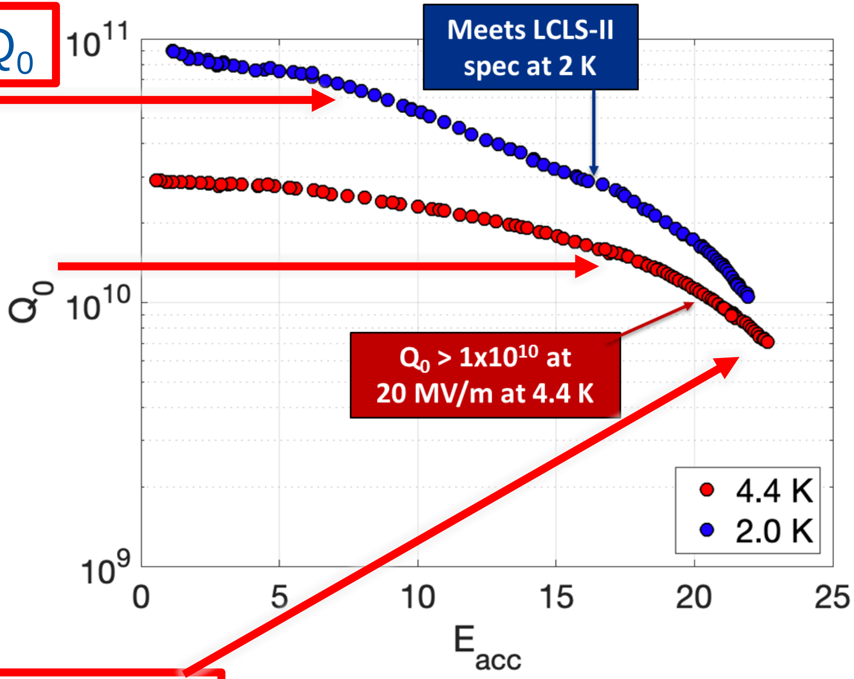
Nb_3Sn results (1.3 GHz cavities)

Nb_3Sn from FNAL

Bulk Nb at 2 K

Very high Q_0





Largest achieved E_{acc}

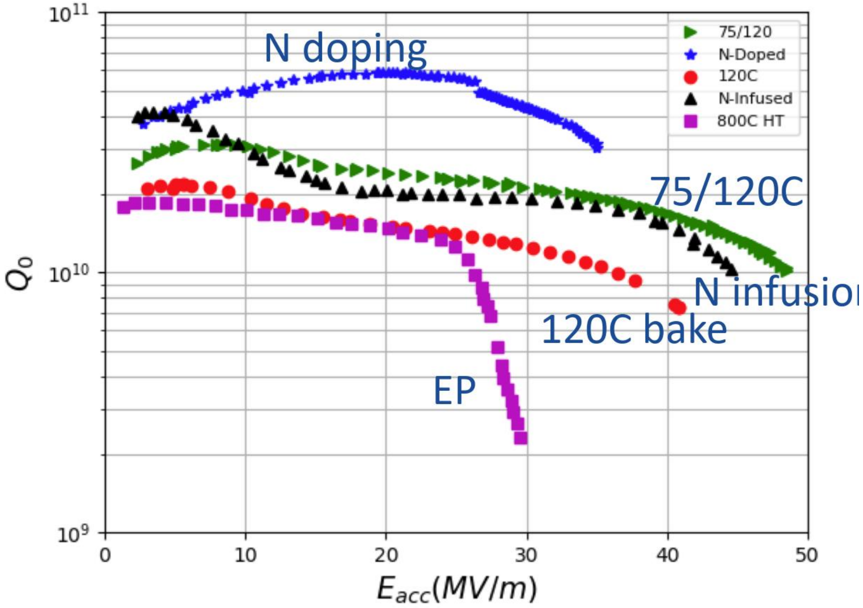
Plot Courtesy S. Posen – FNAL (TTC 2019 talk)

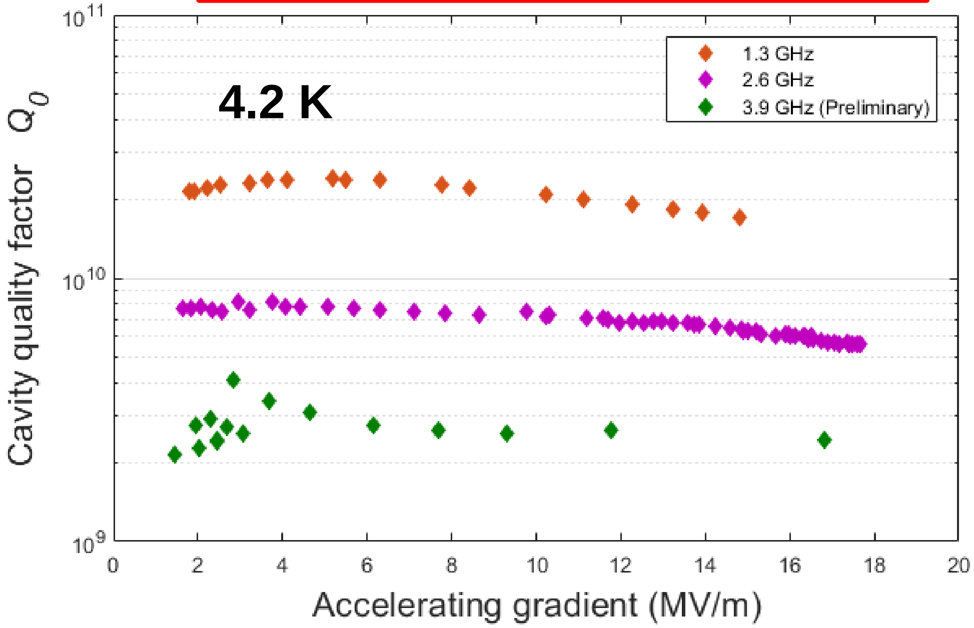
Nb_3Sn results (1.3 GHz cavities)

Nb_3Sn from Cornell U.

Bulk Nb at 2 K

Very good performance at 4.2 K

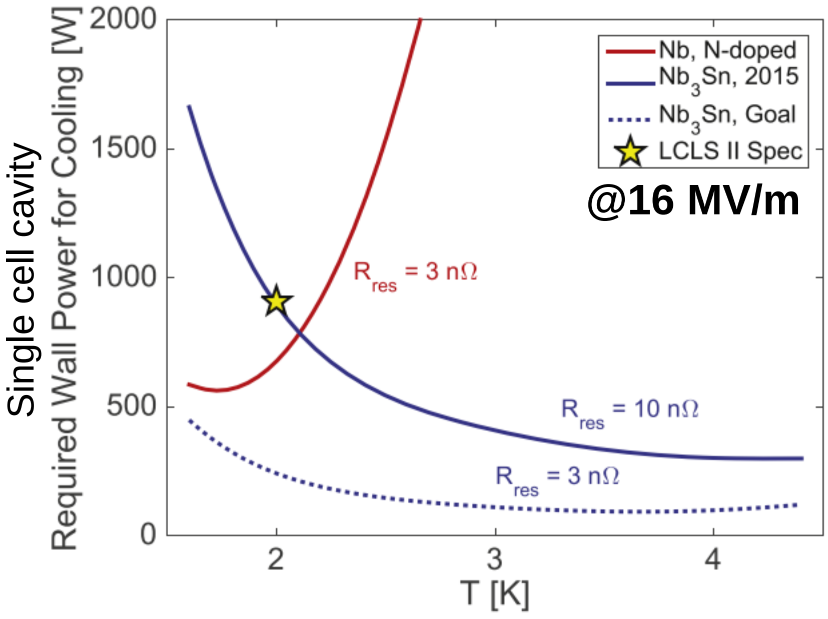




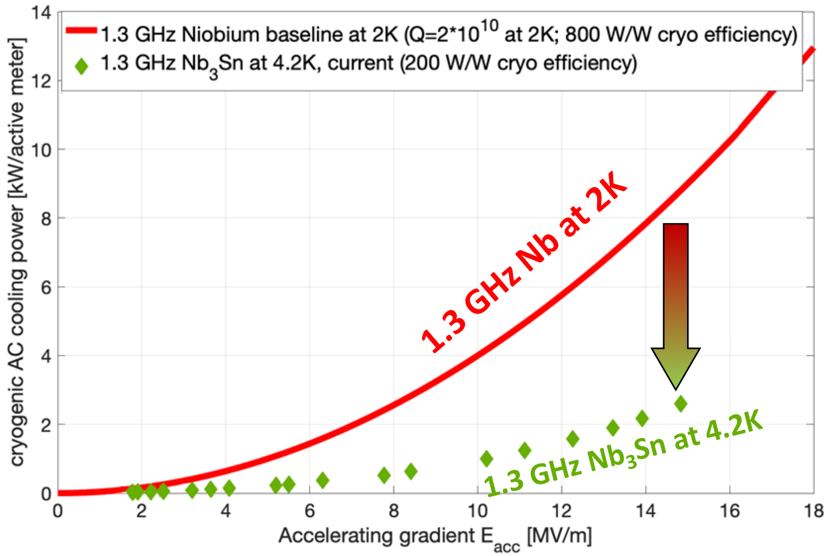
Plot Courtesy R. Porter – Cornell U.

Cryogenic efficiency: operation at 4.2 K

Potential for 1.3 GHz cavities, ILC / LCLS-II type



Plot from S. Posen, D. Hall - Supercond. Sci. Technol. 30 (2017) 033004

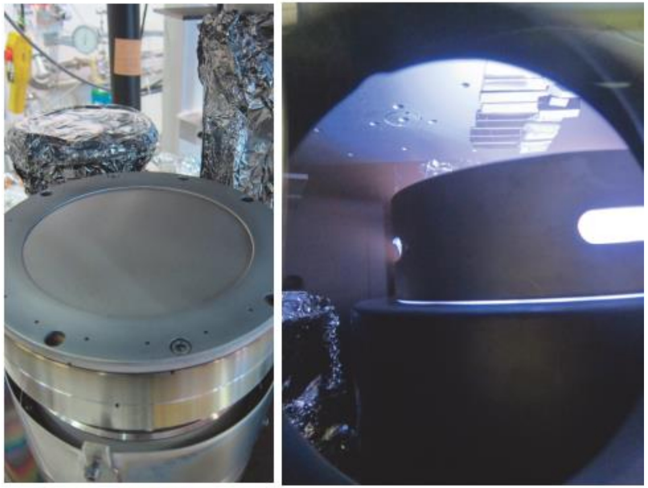


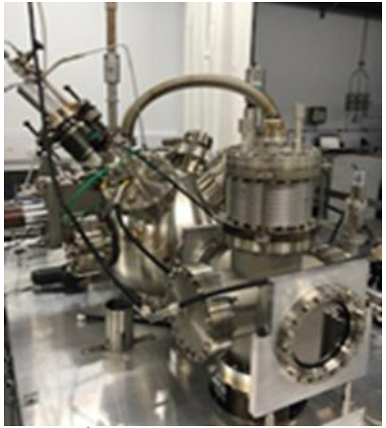
Plot Courtesy R. Porter – Cornell U.

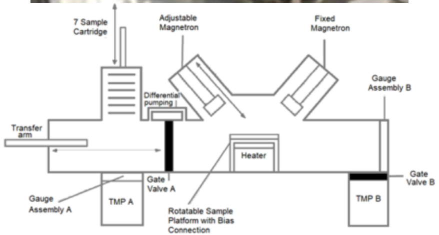
Nb_3Sn thin films on copper

JLAB, INFN-LNL:
multilayer sequential sputtering

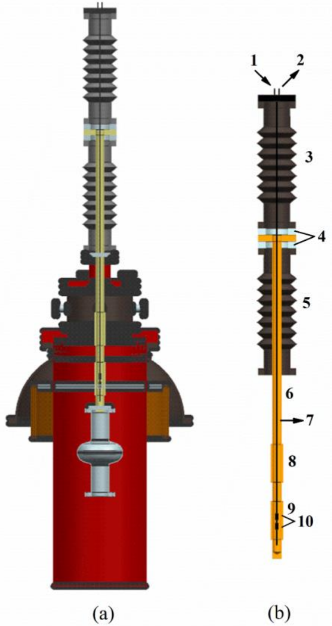
CERN: sputtering from alloyed target





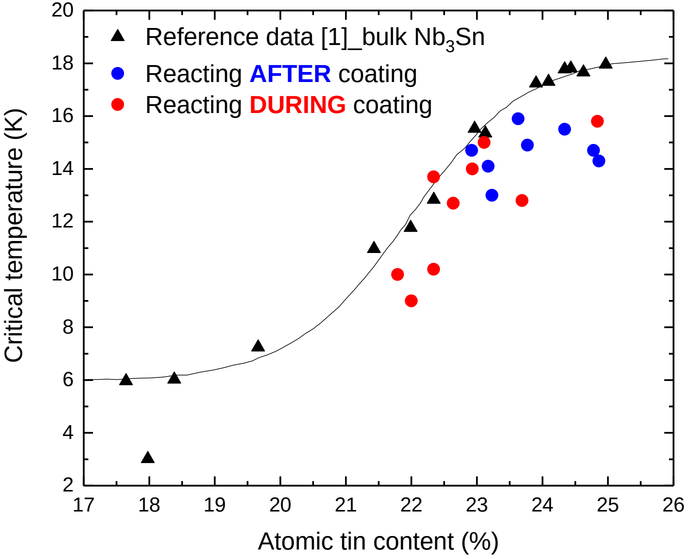


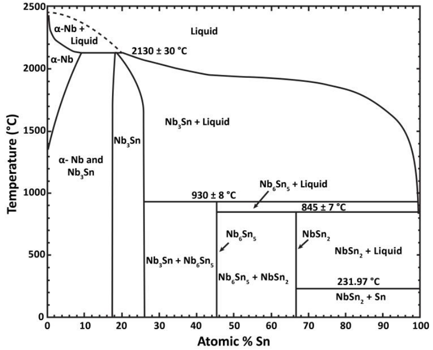
STFC: co-sputtering from
Nb and Sn targets

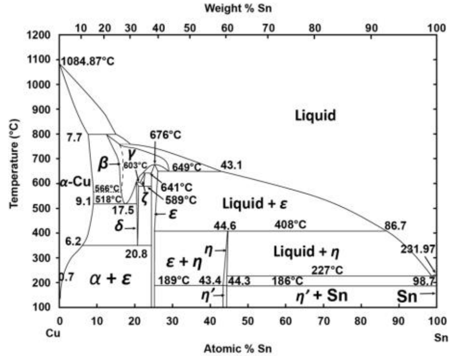


Images courtesy of G. Rosaz – CERN, R. Valizadeh – STFC, N. Sayeed - JLAB

Thermal treatment







Phase diagrams by C. Sanabria - CC BY 4.0

Annealing temperatures must be compatible with copper, brazed SS flanges

Cu-Sn diffusion problem

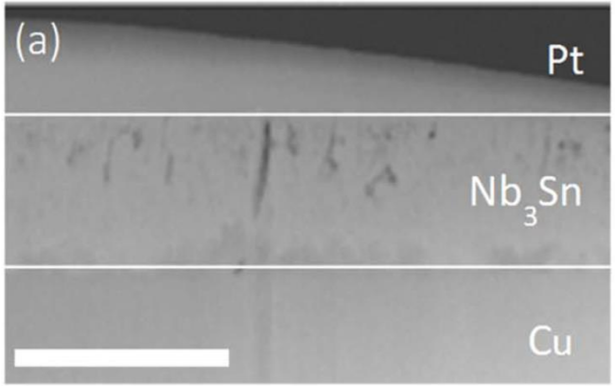
Annealing temperatures	600 - 800ºC
Annealing time	24 h… 72 h

Coating temperatures	600 - 735ºC
Additional Annealing	24 h… 72 h

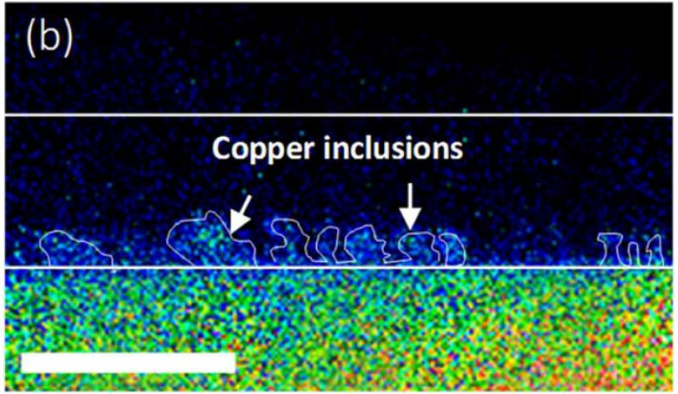
Images courtesy of G. Rosaz – CERN. [1] A. Godeke. Supercond. Sci. Technol., 19 (2006) R68-R80

Intermixing – Cu diffusion

SEM

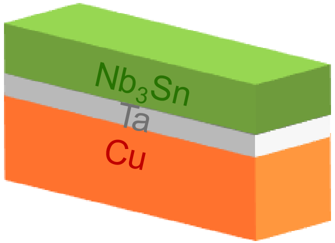


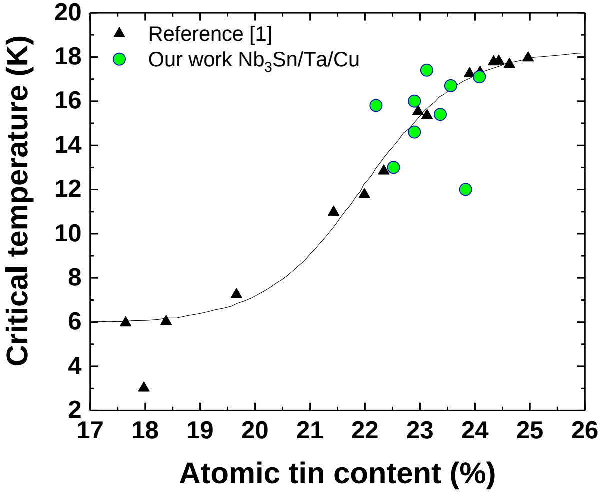
EDS

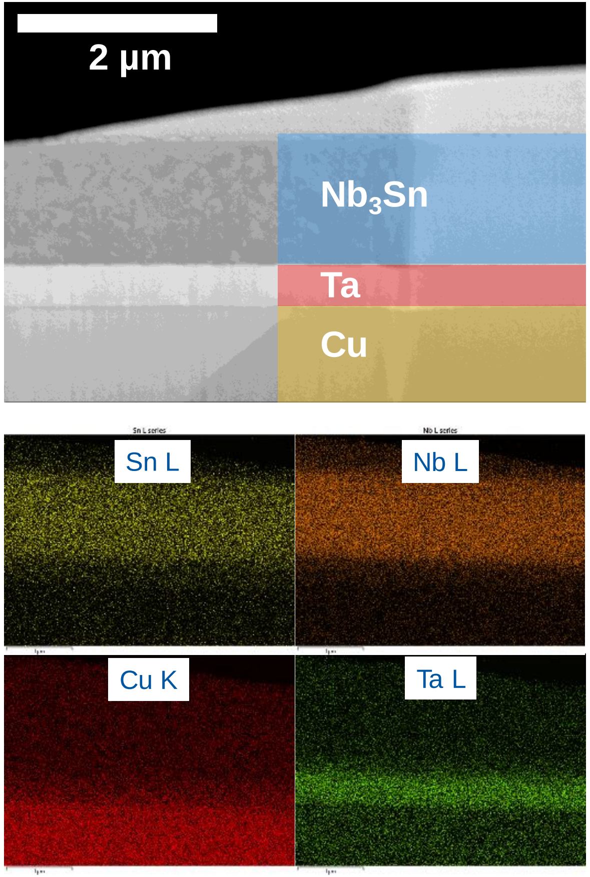


E. A. Ilynia, G. Rosaz, et al., Supercond. Sci. Technol. 32 (2019)

Barrier Layer of Ta



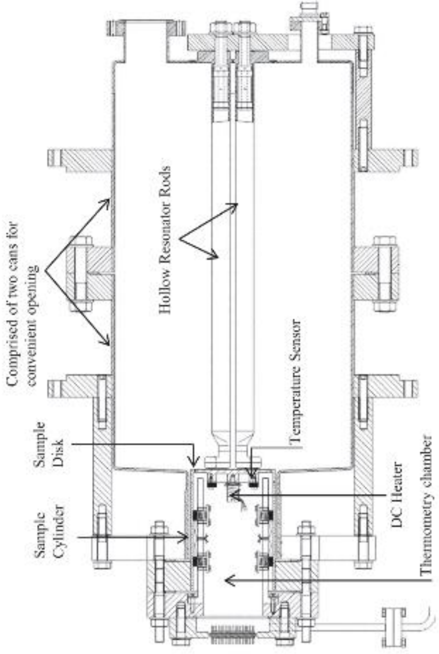




Courtesy of G. Rosaz – CERN. [1] A. Godeke. Supercond. Sci. Technol., 19 (2006) R68-R80

The Ta barrier layer is the solution in order to avoid any Cu diffusion into the Nb_3Sn layer.

RF characterization with quadrupole resonator



Calorimetric technique

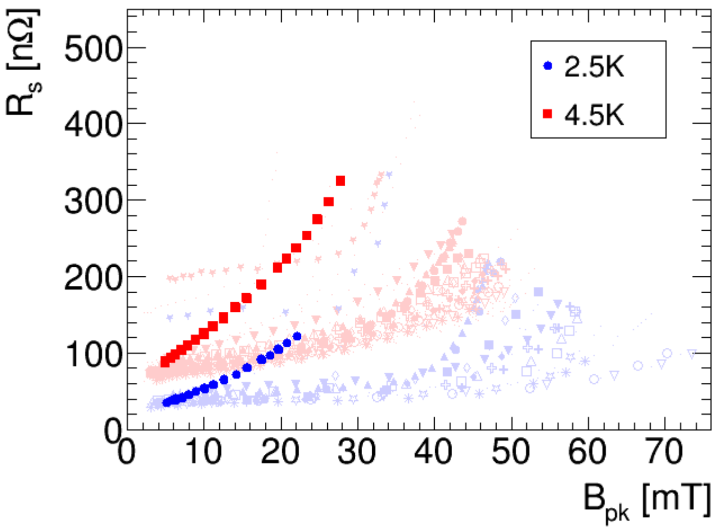
$$R_s = \frac{2\mu_0^2 (P_{DC1} - P_{DC2})}{\int_{sample} |\vec{B}|^2 dS}$$

Courtesy of M. Arzeo – CERN

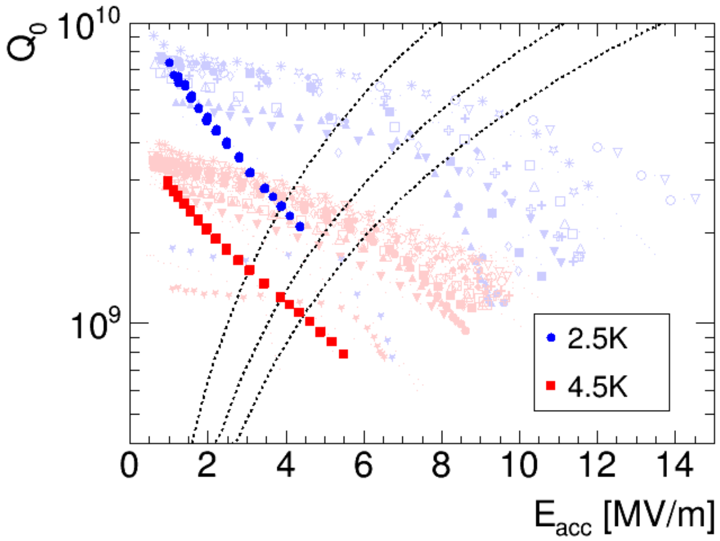
Nb_3Sn by sputtering: QPR results

Comparing to Nb/Cu LHC cavities

Best cool down



Predicted Q vs E assuming uniform coating

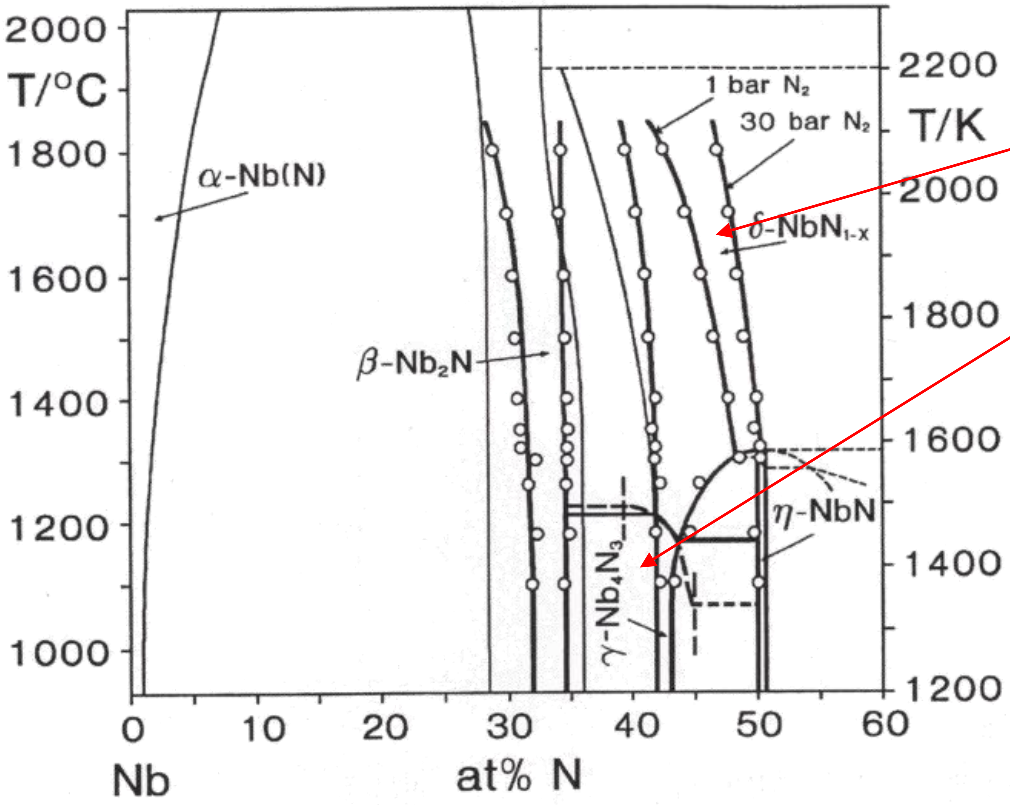


Courtesy M. Arzeo, A. Miyazaki, W. Venturini-Delsolaro – CERN

Outline

- Motivation (one of several): the FCC-ee study
- State of the art of bulk Nb
- Techniques for Nb_3Sn SRF cavities:
  - Thermal diffusion of Sn vapours
  - Liquid Sn diffusion
  - Magnetron sputtering
- Techniques for NbN / NbTiN SRF cavities
  - Thermal diffusion of N
  - Magnetron sputtering
- Techniques for other materials
  - MgB_2
  - REBCO

The NbN phase diagram

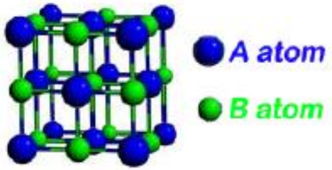


SC fcc phase

T_C = 17.3 K

SC tetragonal phase

T_C = 12÷15 K



Courtesy R. Musenich – Genova U.

NbN Thermal diffusion

5944 J. Appl. Phys. 66 (12), 15 December 1989

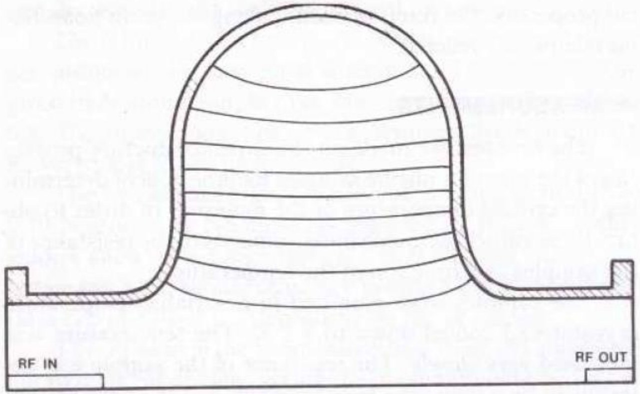
Study of niobium nitrides for superconducting rf cavities

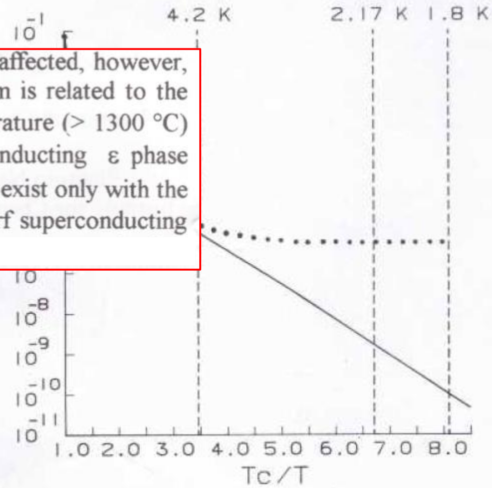
P. Fabbricatore, P. Fernandes,[a] G. C. Gualco, F. Merlo,[b] R. Musenich, and R. Parodi
I.N.F.N. Sezione di Genova, via Dodecaneso, 33 16146 Genova, Italy

(Received 16 May 1989; accepted for publication 17 August 1989)

This paper deals with the first results of a study on Nb-N system having as the main goal the performance of niobium nitride rf cavities. The nitrides were obtained by diffusion of nitrogen in bulk niobium at high temperature. Metallurgical and resistive measurements have been done to determine the phases and the cri… study the rf behavior of the materi… tested. The rf measurements showe… the computed values (1.15 $\mu\Omega$ at 4… obtained for niobium at the same t… residual resistance became prevale…

Devices obtained by direct nitridation of pure Nb are affected, however, by an unexpected high value of the residual rf resistance [1,2]. This problem is related to the behaviour of the δ phase (NbN_{1-x}, fcc structure), which forms at high temperature (> 1300 °C) and decomposes in the γ phase ($Nb_4N_{3\pm x}$, tetragonal) and the non-superconducting ε phase (NbN, hexagonal) during cooling [4]. Niobium-titanium mononitride seems to exist only with the fcc structure (δ phase) and, therefore, could be a more suitable material for rf superconducting cavities.





Reaction at 1700 K for 3 hours in 130 mbar N_2

The NbTiN phase diagram at 1200 °C

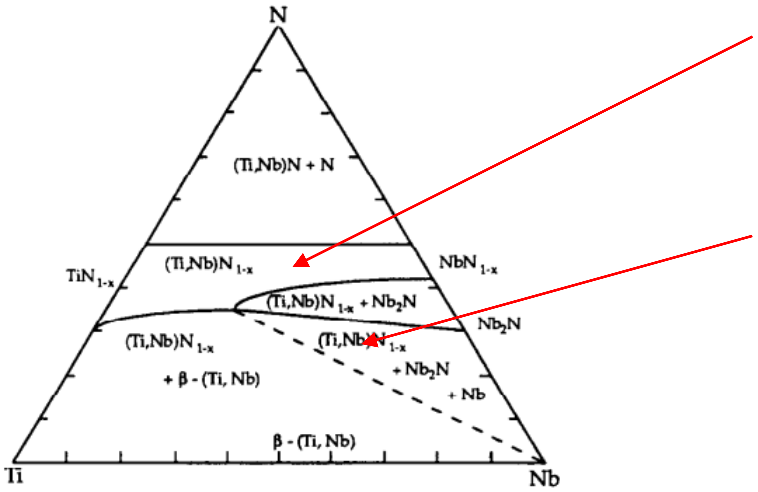


Fig. 1. Phase diagram for the Nb–Ti–N system at 1200°C and 1 bar N_2 pressure [14].

H. Hollek, Binäre und Ternäre Carbid- und Nitrid-Systeme der Übergangsmetalle (Gebrüder Borntraeger, Berlin, 1984)

Equilibrium nitride phase for any Nb,Ti ratio

Segregation of other phases for non optimal composition range

Stabilization of δ-phase at low temperature, associated with equilibrium segregation of TiN (from Musenich)

NbTiN by thermal diffusion

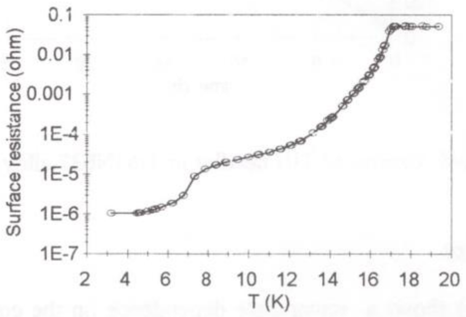


Fig. 10. Surface resistance of a Ti63Nb37 cavity after 24 h nitridation at 1300 °C.

Conclusions

Nitridation of four different Ti-Nb alloys (10, 37, 54 and 90 at.% Nb) was carried out at 1300, 1450 and 1600 °C and at nitrogen pressure of 0.3 and 30 bar. The phases present in Nb-Ti-N diffusion couples are isostructural with those present in the Nb-N, Ti-N and Nb-Ti binary systems; formation of individual ternary compounds was not detected. A layer of the δ-(Ti,Nb)N phase (fcc structure) was present at the surface for all compositions. This phase does not decompose during cooling down, in contrast to δ-NbN_{1-x}, which transforms into γ-$Nb_4N_{3\pm x}$ and ε-NbN. $T_c \geq 16.5$ K were measured for the three niobium-richer diffusion couples. As a consequence, the nitridation route can be successfully used to prepare superconducting rf devices with high T_c (17.5 K) starting from a Ti-Nb alloy. The residual rf surface resistance of a 4.7 GHz superconducting cavity at 4.2 K (≈ 1 μΩ) was three times lower than that of niobium at the same temperature, but still too high for practical applications.

(NbTi cavities were tested as well, but NbTi is not a good candidate material)

From R. Musenich – Genova U.

Surface Performance of Titanium
Edited by J.K. Gregory, H.J. Rack, and D. Eylon
The Minerals, Metals & Materials Society, 1997

$Nb_{1-x}Ti_xN$ by sputtering

$$R_s^{BCS} = \frac{A\rho_n^{1/2}\omega^2}{T}\exp\left(-\alpha\frac{T_c}{T}\right)$$

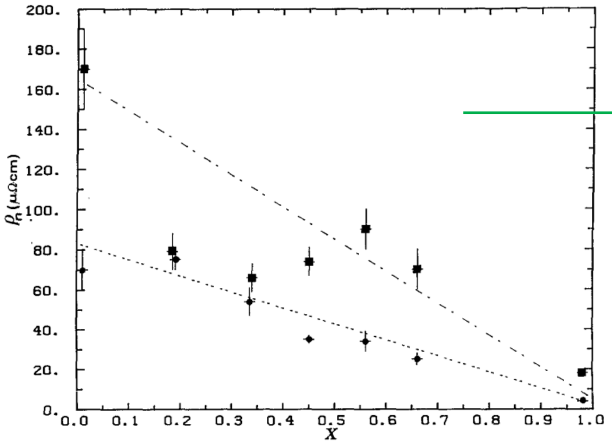


Fig. 2. Low-temperature normal state resistivity ρ_n as a function of the titanium composition (x) for the $(Nb_{1-x}Ti_x)N$ films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares).

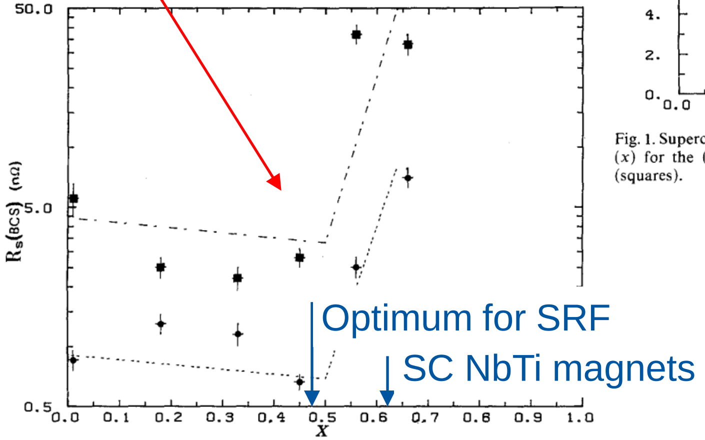


Fig. 3. Calculated BCS surface impedance $R_s(BCS)$ as a function of the titanium composition (x) for the $(Nb_{1-x}Ti_x)N$ films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares). The continuous lines correspond to the values of the lines through the data in Figs. 1 and 2.

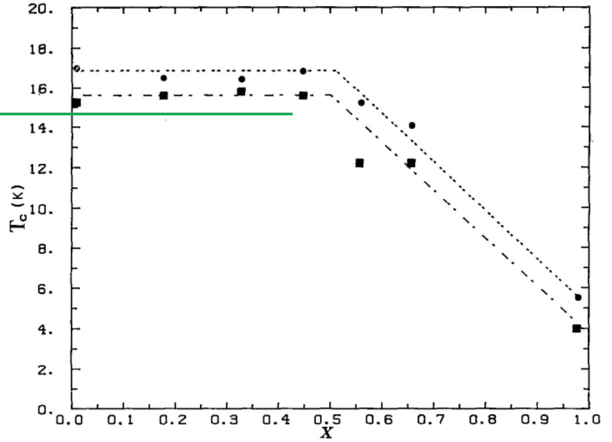
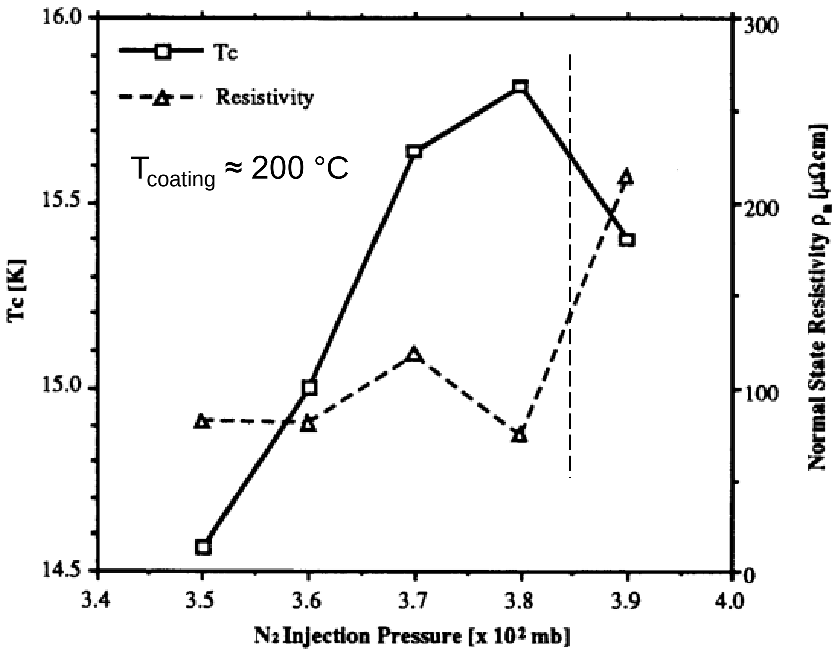


Fig. 1. Superconducting critical temperature T_c as a function of the titanium composition (x) for the $(Nb_{1-x}Ti_x)N$ films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares).

R. Di Leo, A. Nigro, G. Nobile, and R. Vaglio

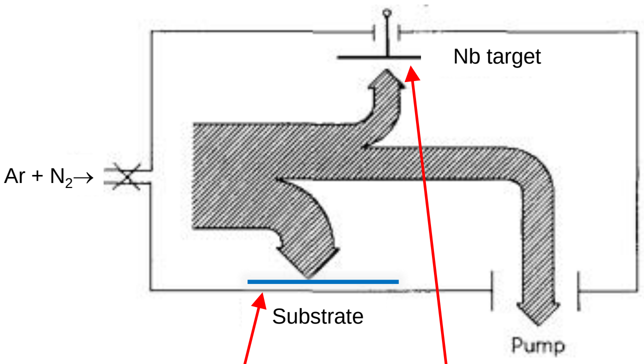
Journal of Low Temperature Physics, Vol. 78, Nos. 1/2, 1990

Sputtering of 500 MHz at CERN



Benvenuti C., Calatroni S., Hauer M., Minestrini M.*, Orlandi G.**, Weingarten W.

Proc. SRF 1991



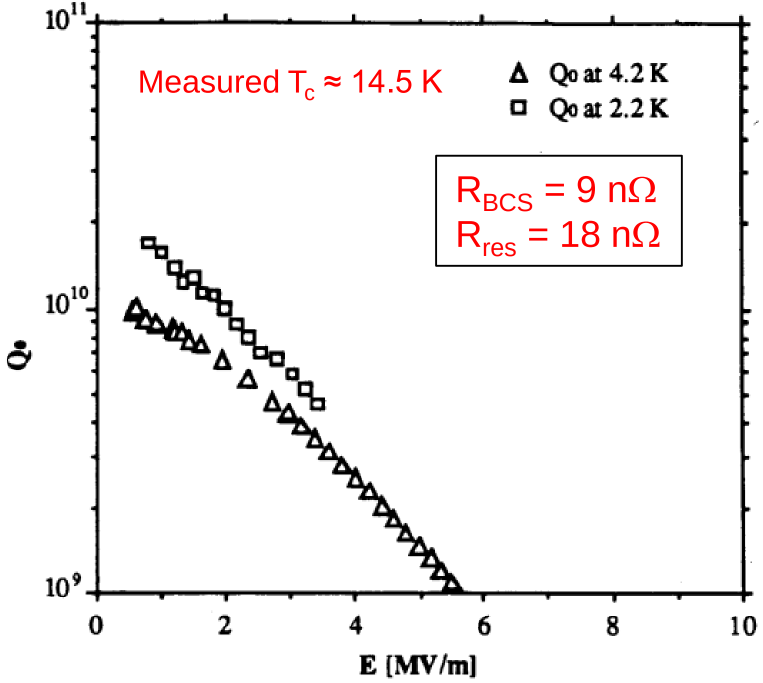
Formation of nitrides

Sputtering yield: $Y_{Nb} > Y_{NbN}$

S. Berg, T. Larsson, C. Nender, and H-O. Blom

J. Appl. Phys. 63 (3), 1 February 1988

Sputtering of 500 MHz at CERN



Benvenuti C., Calatroni S., Hauer M., Minestrini M.*, Orlandi G.**, Weingarten W.

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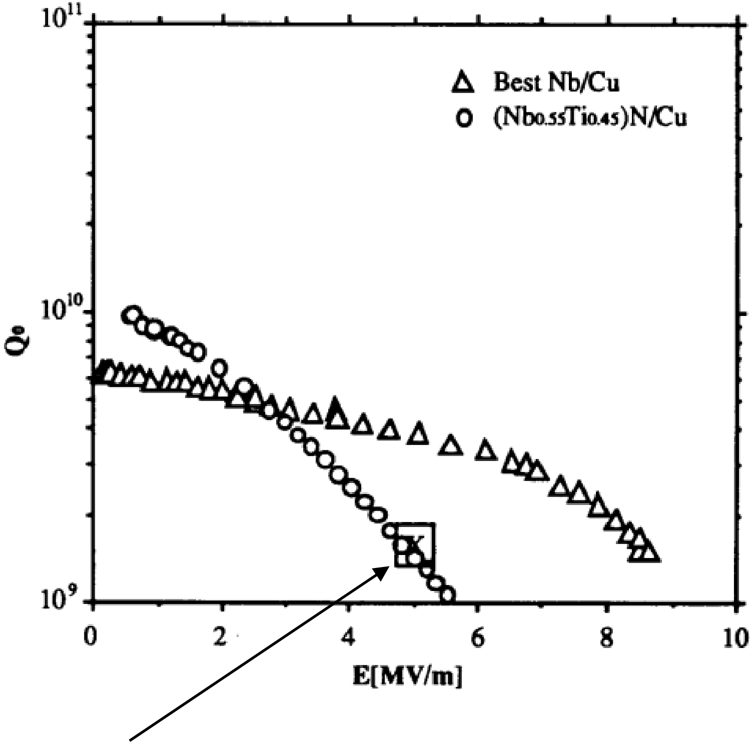
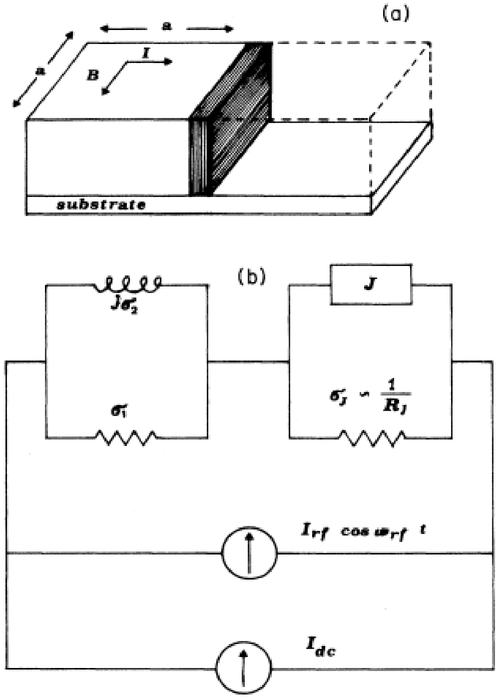


Scaled LEP specs for bulk Nb @ 4.5 K

Grain-boundary model



$$R_{sj} = \frac{1}{2\lambda_{\text{eff}}} \frac{\sigma_1 + \sigma_r}{\sigma_2^2}$$

$$\sigma_r / \sigma_n = \left(\frac{\lambda_j}{\lambda} \right)^2 \frac{\pi \Delta}{2 e I_c R_j} F^{-2}$$

$$\lambda_{eff} = \left(\lambda^2 + \frac{\hbar}{2eaJ_c\mu_0 F} \right)^{1/2}$$

$$F = \sqrt{1 - (I_{rf}/I_c)^2} \, .$$

$$\rho = \rho_i + \rho_{G.B.} = \rho_i + \frac{I_c R_j}{J_c a}$$

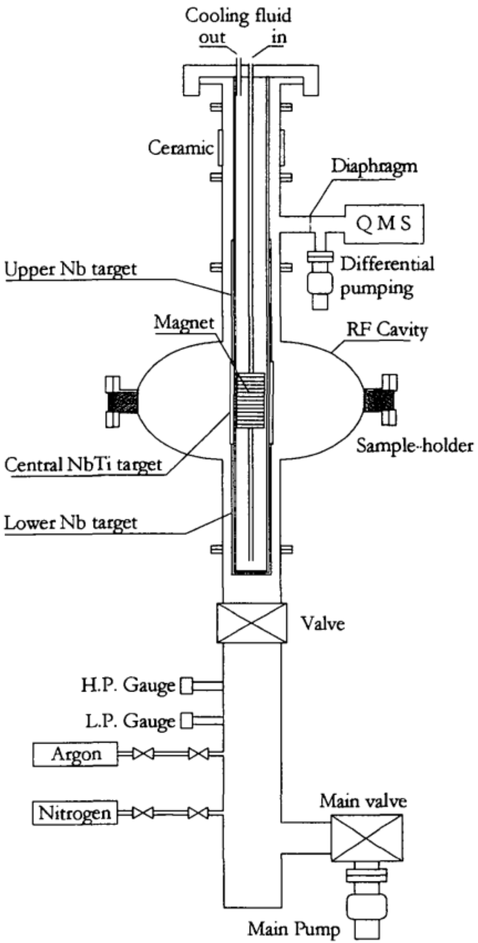
$$I_c R_j = J_c G = \frac{\pi \Delta}{2e} ,$$

Carmine Attanasio, Luigi Maritato, and Ruggero Vaglio
Phys.Rev.B 43 (1991) 6128

A. Andreone, A. DiChiara, G. Peluso, and M. Santoro
C. Attanasio, L. Maritato, and R. Vaglio
J. Appl. Phys., Vol. 73, No. 9, 1 May 1993

Known limitations

- Limit of pumping speed
- Cathode temperature and surface ratio
- Sputtering profile of cathode, differential adsorption
- Atomic composition distribution on cavity Ti/Nb



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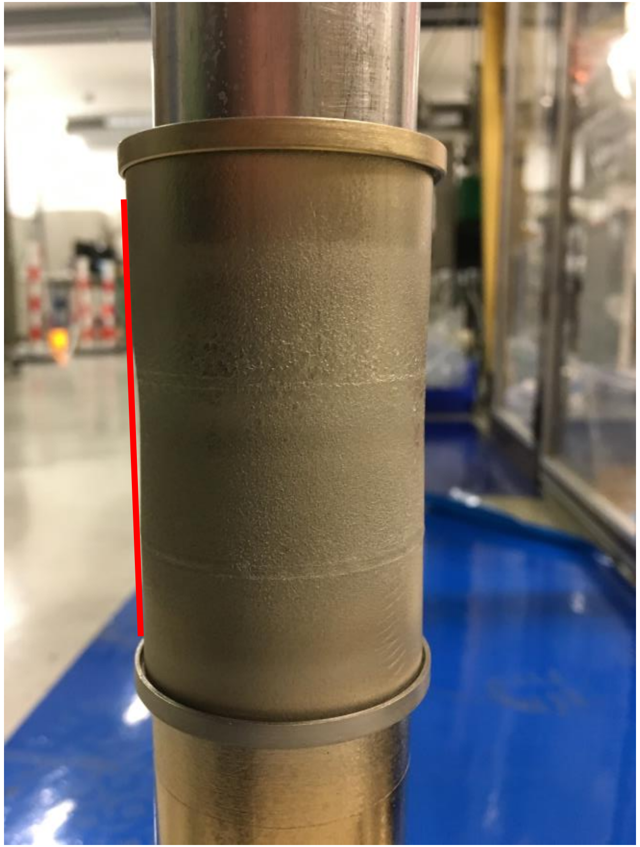


N_2 to NbTi ratio depends on position, can be problematic close to sputtering threshold.

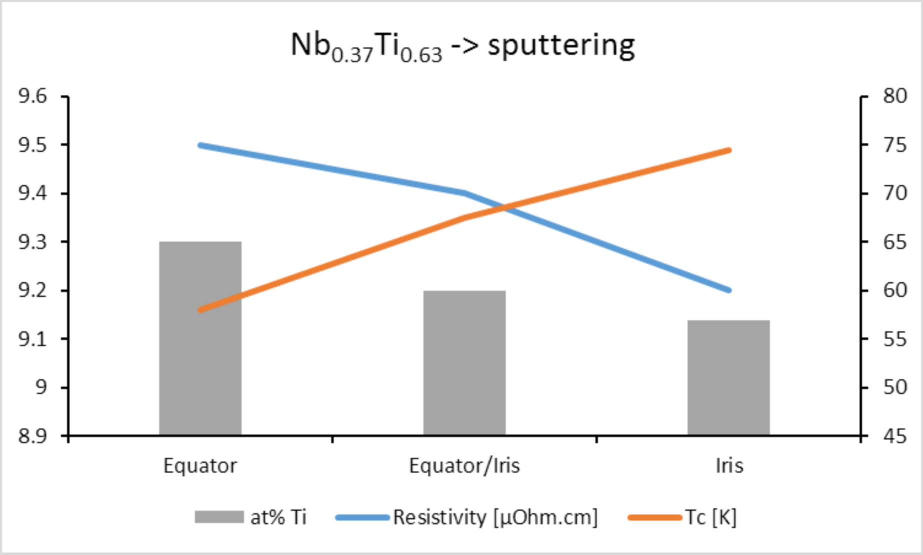
- Better designs are possible

Known limitations

- Limit of pumping speed
- Cathode temperature and surface ratio
- Sputtering profile of cathode, differential adsorption
- Atomic composition distribution on cavity Ti/Nb

Non homogenous composition along cavity meridian

- (Can be troublesome for Nb_3Sn)
- Better cathode design



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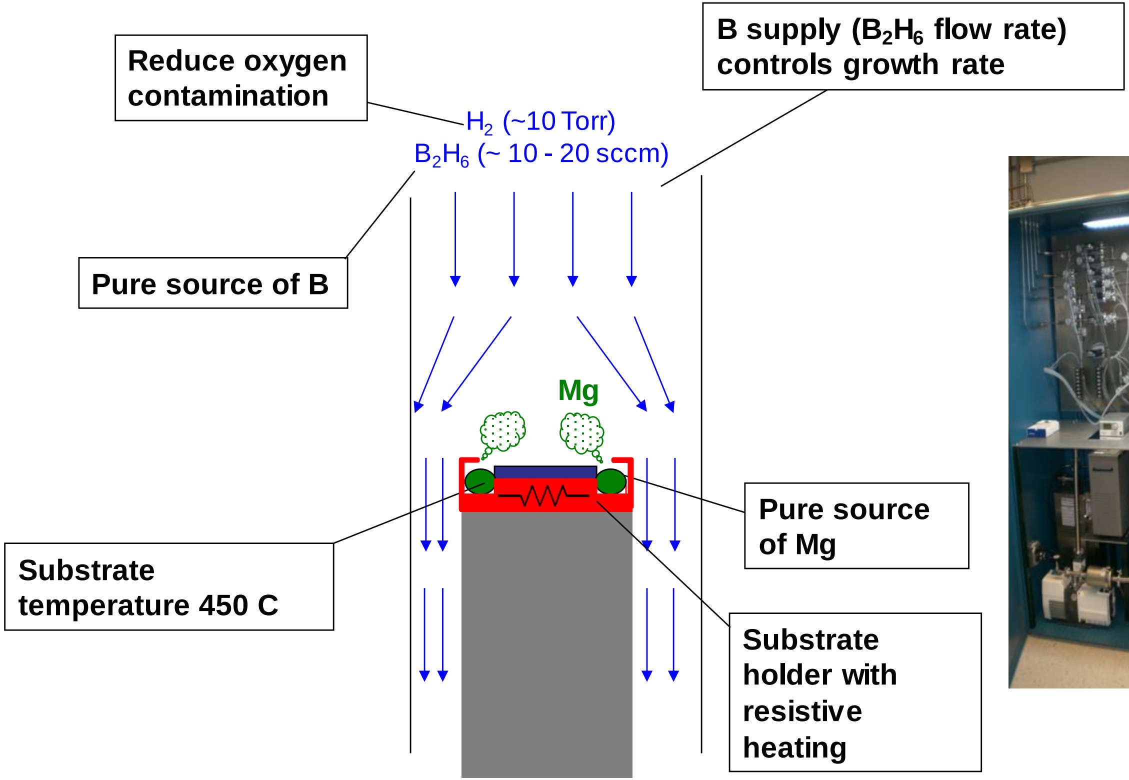
  - Magnetron sputtering
- Techniques for other materials
  - MgB_2
  - REBCO

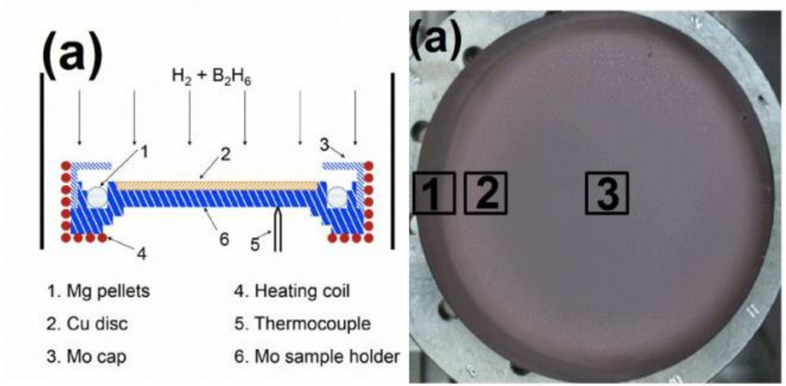
MgB_2 by HPCVD at Temple University

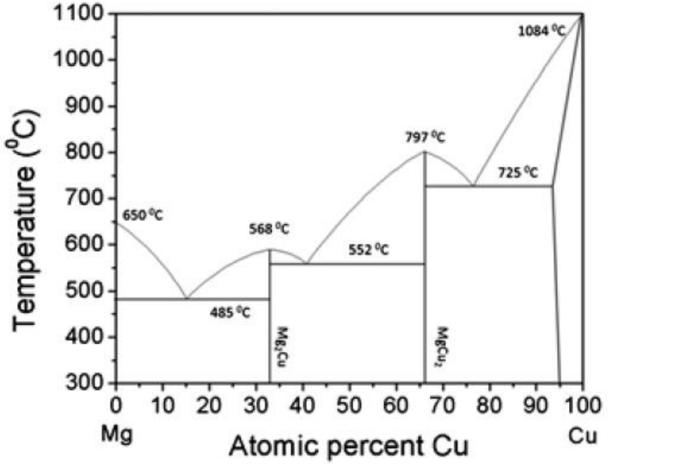


Courtesy Xiaoxing Xi – Temple U.

Film deposition--HPCVD

Challenge for coating on Cu --Mg-Cu reaction





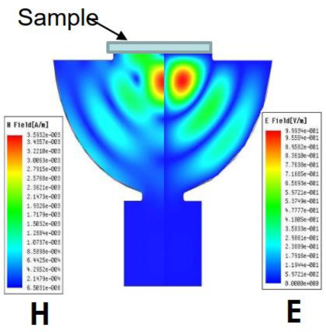
Au et al., J. Mater. Chem. A1, 9983 (2013)

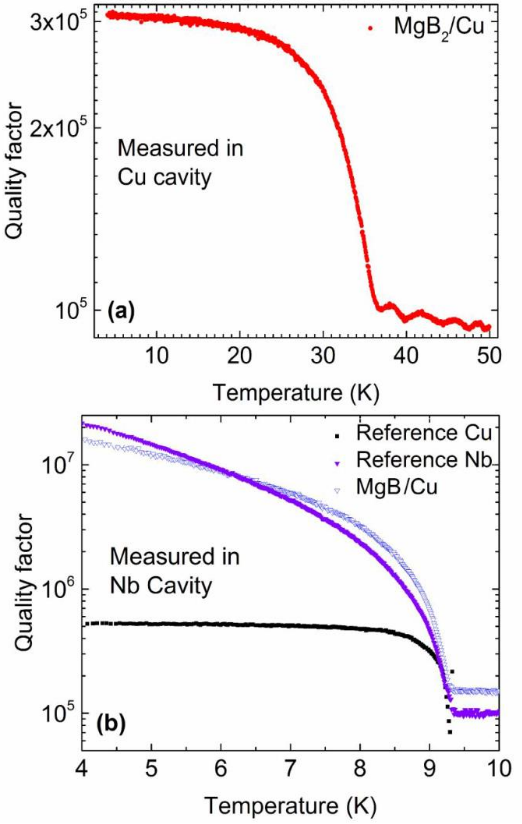
- To reduce Mg-Cu alloy formation the deposition temperature was lowered to ~ 470° C.

- Mg_2Cu alloy acts as a source of Mg for the growth of MgB_2.

W K Withanage et al, SUST. 30 (2017) 045001

RF results on samples



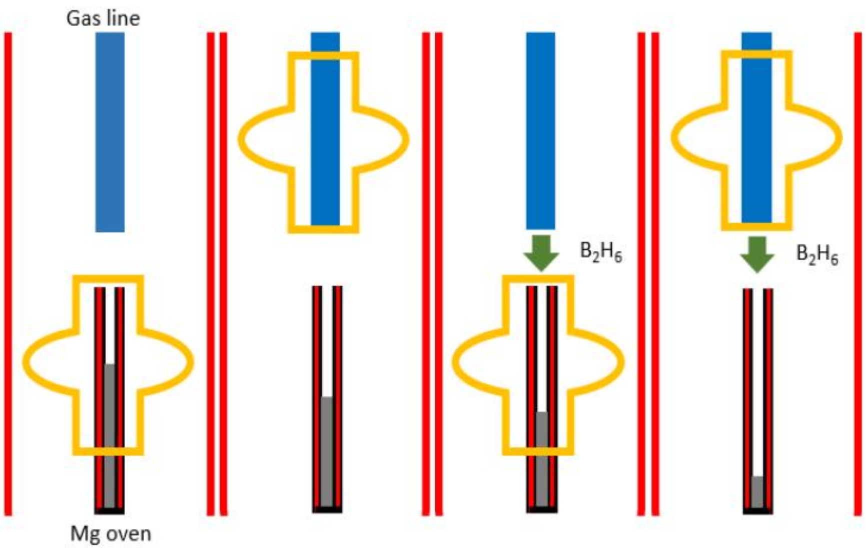


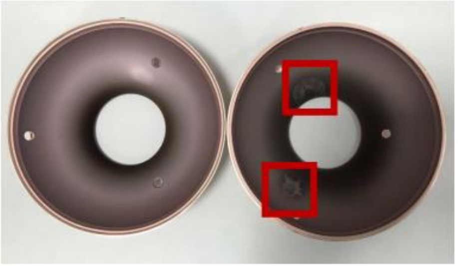
- The MgB_2 coatings were also characterized at 11.4 GHz at SLAC using a cryogenic RF system.
- The samples showed a Q factor comparable to a Nb reference sample and higher than the Cu reference sample.
- The films showed a T_c of 37 K.

- Mg-Cu eutectic liquid promote growth aty low temperature process, <500°C.
- $MgCu_2$ alloy layer grows on top of Cu substrate

Courtesy Xiaoxing Xi – Temple U.

Film deposition on 3.9 GHz mock cavity

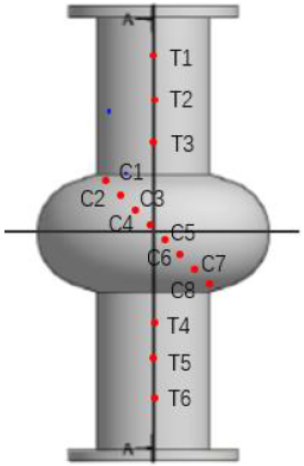


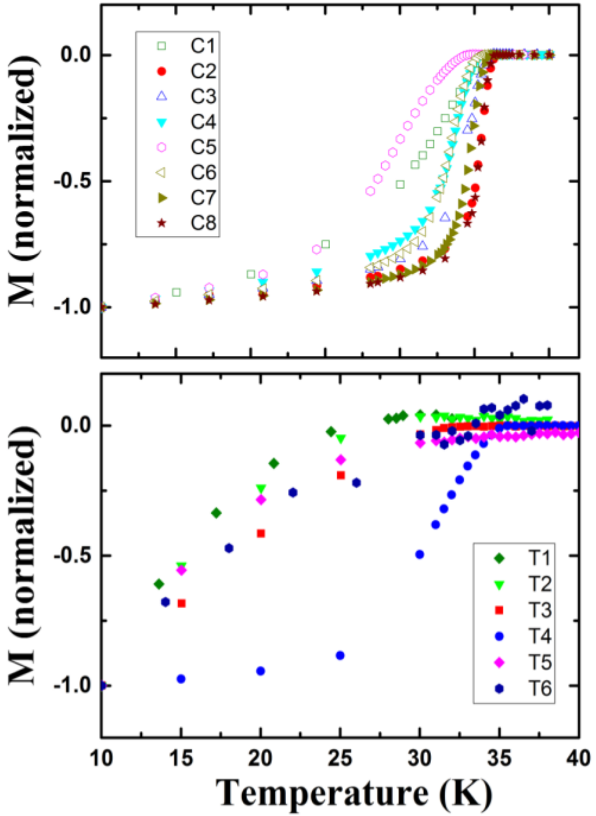


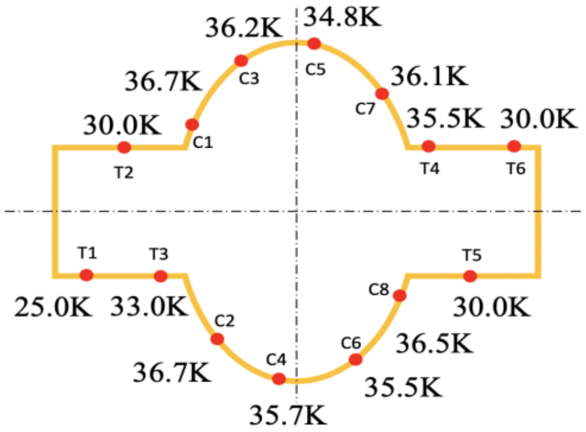
Mg-Cu alloy coated before MgB_2 deposition

Courtesy Xiaoxing Xi – Temple U.

Superconducting property



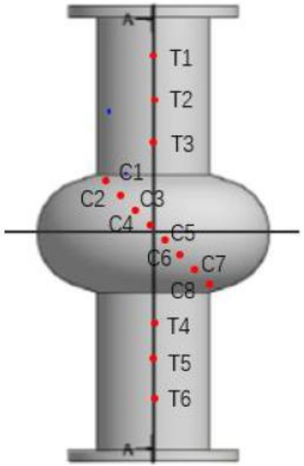


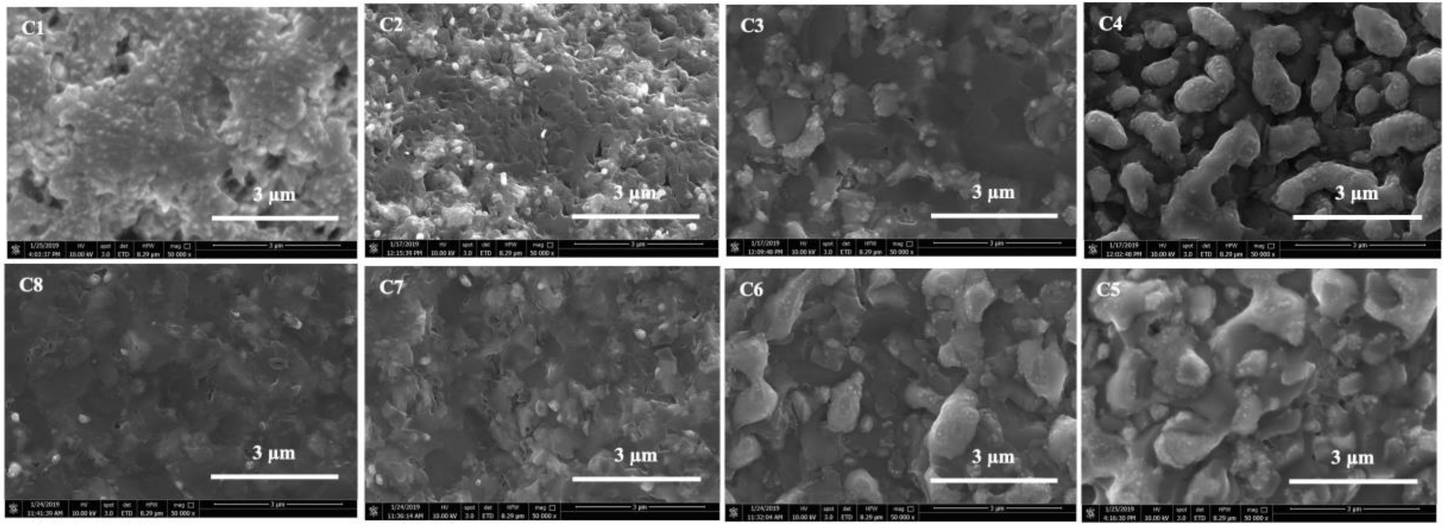


- All the samples show superconducting transition
- The transition temperature for MgB_2 films on cavity cell: around 34.8-36.7 K

Courtesy Xiaoxing Xi – Temple U.

Surface Characteristics

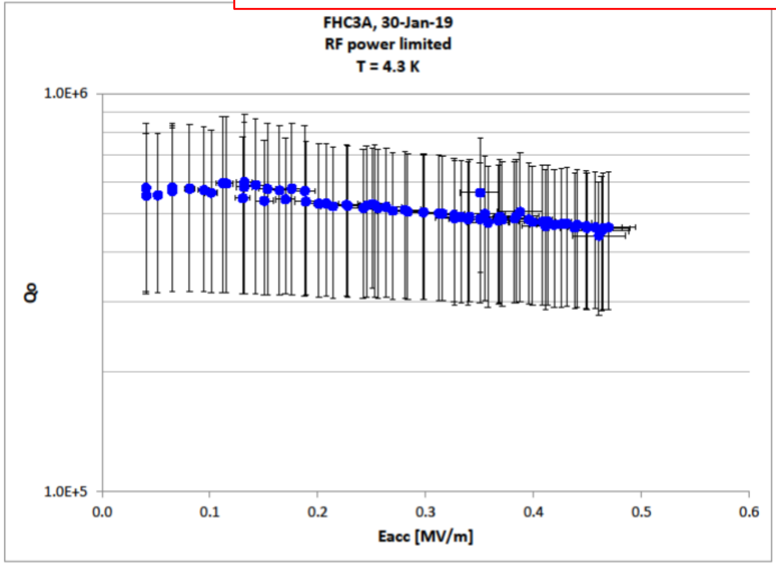


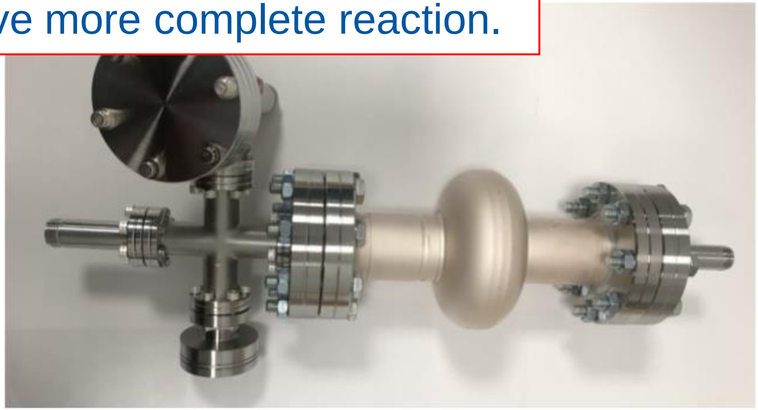


Courtesy Xiaoxing Xi – Temple U.

RF Test

Poor RF properties due to poor connectivity of MgB_2 coating caused by incomplete reaction of B with Mg-Cu alloy.
Longer time deposition can achieve more complete reaction.





- RF test performed at JLab
- The 3.9 GHz MgB_2 thin film cavity show transition at around 36K.
- Q value is low.

Courtesy Xiaoxing Xi – Temple U.

REBCO: old idea, new materials and technologies

- Collaboration within CERN FCC-hh study to apply HTS for beam impedance reduction
  - Operation at 50 K, 16 T, needed J_c of 25 kA/cm^2

- S. Calatroni, E. Bellingeri, C. Ferdeghini, M. Putti, R. Vaglio, T. Baumgartner and M. Eisterer, *"Thallium-based high-temperature superconductors for beam impedance mitigation in the Future Circular Collider"*, Supercond. Sci. Technol. 30 (2017) 075002
- T. Puig, P. Krkotić, A. Romanov, J. O'Callaghan, D. A. Zanin, H. Neupert, P. C. Pinto, P. Demolon, A. Granadeiro Costa, M. Taborelli, F. Perez, M. Pont, J. Gutierrez and S. Calatroni, *"Coated conductor technology for the beamscreen chamber of future high energy circular colliders"*, Supercond. Sci. Technol. 32 (2019) 094006

- Important results on RF behavior of HTS in presence of strong magnetic field
  - Potential use for muon collider capture cavities, SRF cavities for axion detection,
  - Potential operation at 77 K

REBCO: how to make cavities?

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009

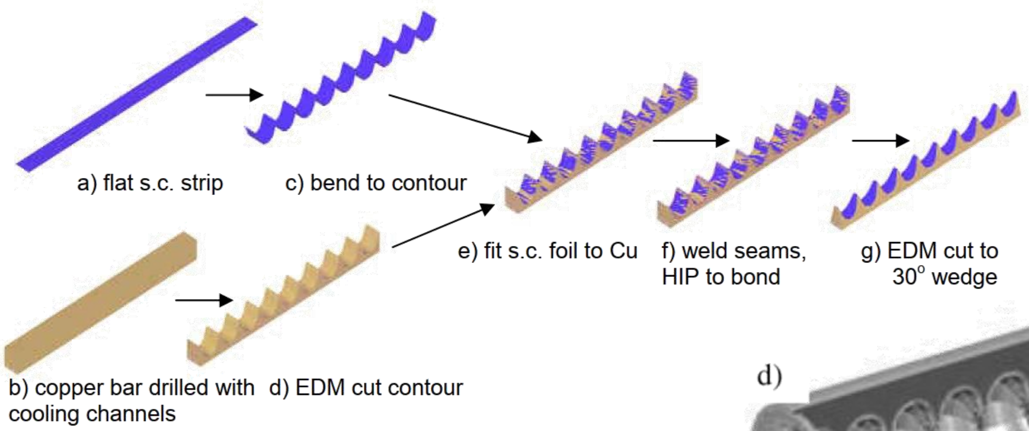
Polyhedral Superconducting Cavity for Particle Accelerators

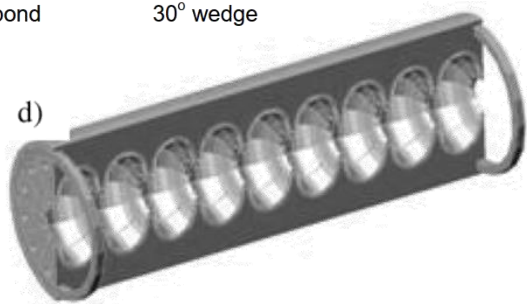
Peter McIntyre, Nathaniel Pogue, and Akhdiyor Sattarov

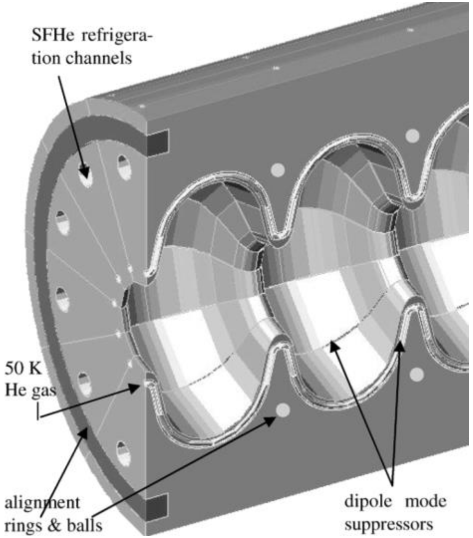
Proceedings of PAC07, Albuquerque, New Mexico, USA WEPMS002

POLYHEDRAL CAVITY STRUCTURE FOR LINAC COLLIDERS*

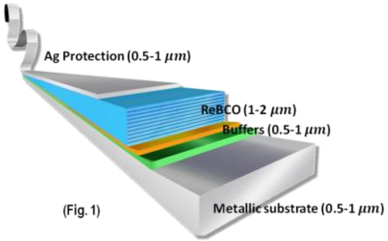
N. Pogue, P. McIntyre, and A. Sattarov, Texas A&M University, College Station, TX 77843 U.S.A.

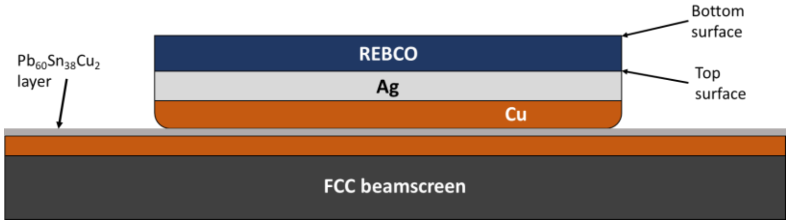


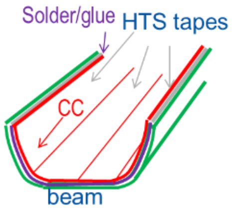




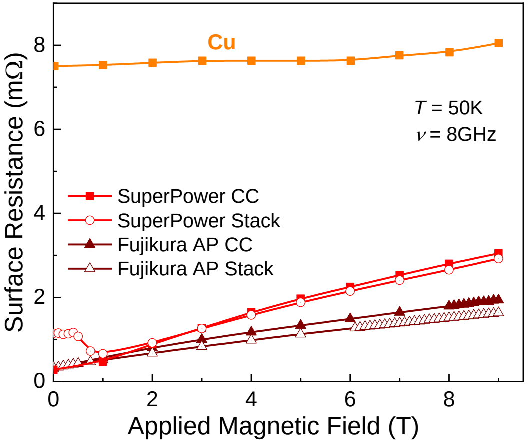
Technique and results







Bonding technology under active development (first results very encouraging)



3x improvement at 8 GHz at 50 K compared to copper
expected 20x improvement at 1 GHz ($f^{3/2}$)
no degradation from stacking

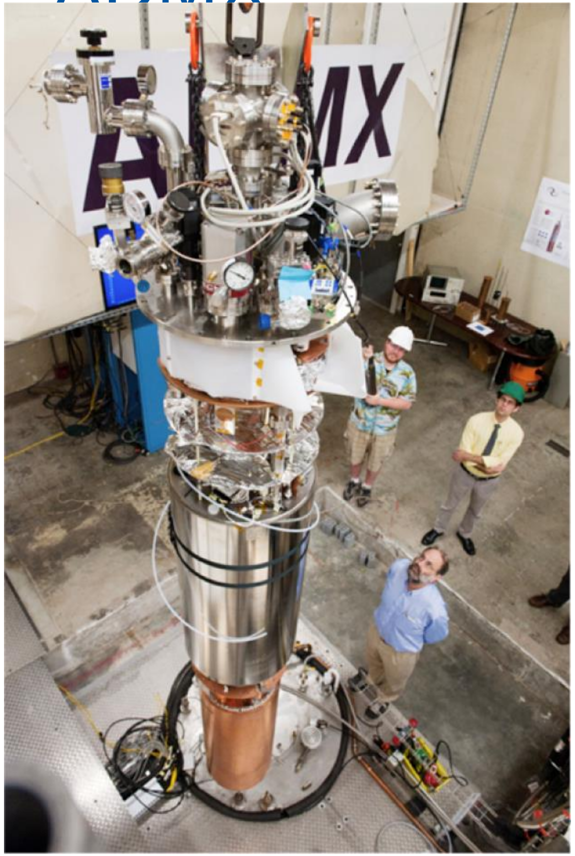
Courtesy J. Gutierrez - ICMAB

Spin-off: axion detection

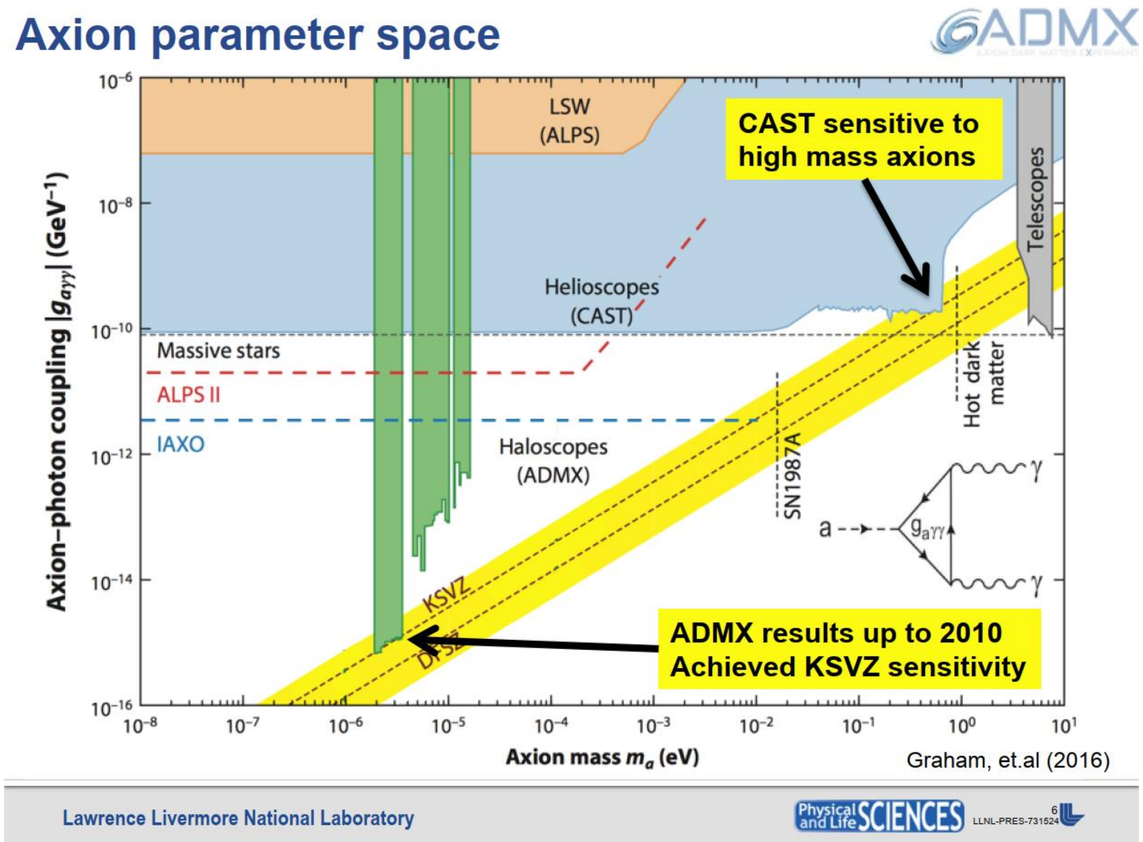
- Axions as solution for strong-CP problem
- Axions as dark matter candidates:
  - Dark matter axions (low mass) converting to photons in B-Field
  - By means of microwave cavities in solenoid magnet
  - Sensitivity goes as $B^2 V Q_{cav}$ where B is the applied field, V the total volume, Q is the quality factor of the cavity

- ADMX type experiment: using tunable cavities in the ~1 GHz range

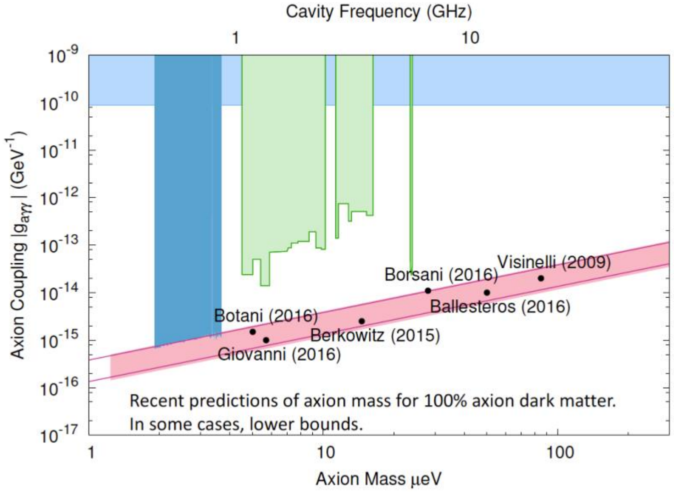
ADMX



From Gianpaolo Carosi LLNL

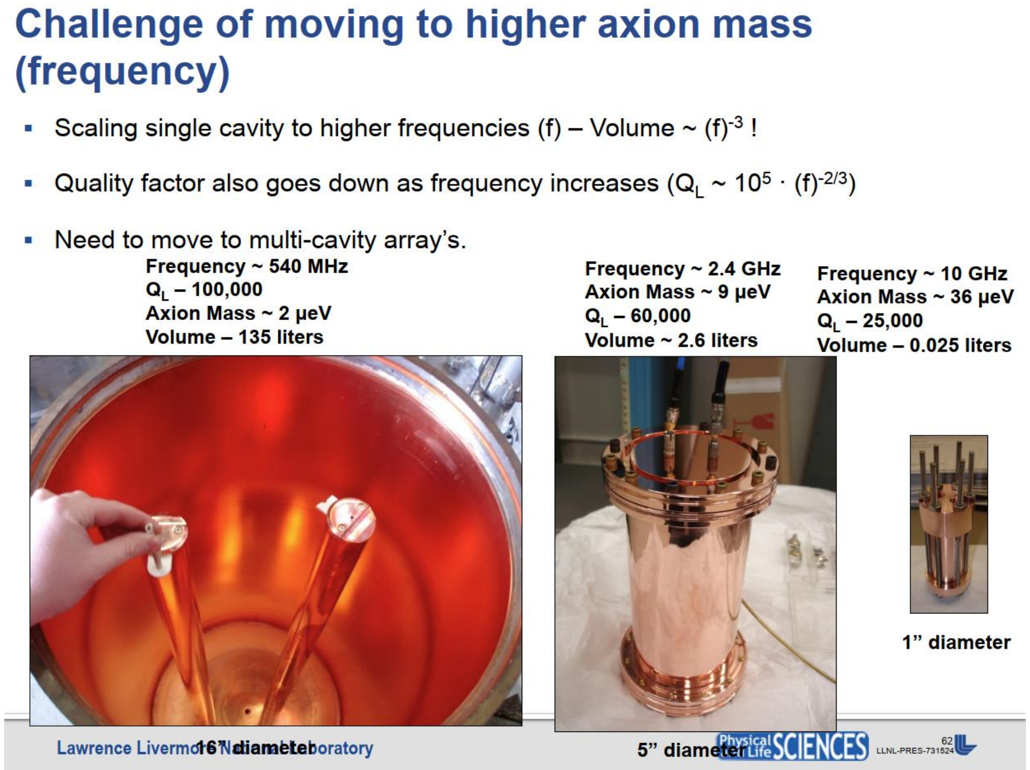


Checking other frequencies



Theoretical predictions (plot from Gray Rybka 2017)

- HTS can have much better Q at lower frequencies
- There is a crossover with copper at high frequencies: to be verified with our data



Pictures from CAPP

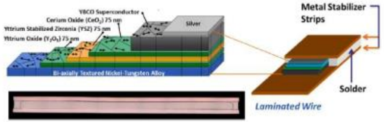


Figure 1 The architecture of the YBCO tape [18]

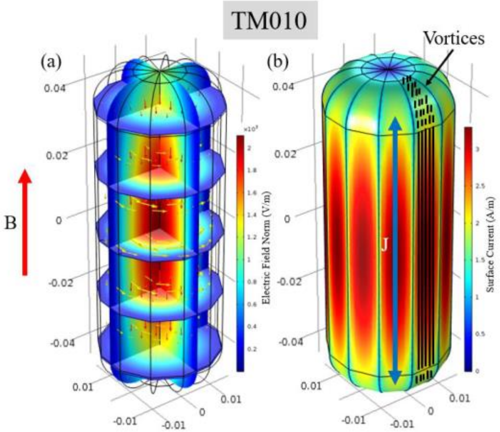
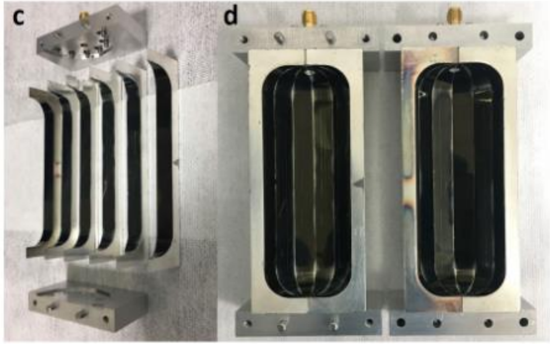


Figure 2 Simulation result for the TM_{010} mode in the polygon cavity. B is the direction of the applied magnetic field in the axion cavity experiment. (a) The electric field (Red Arrows, Colored 3D Plot) and magnetic field (Yellow Arrows) of the TM_{010} mode, (b) Surface current distribution of the TM_{010} mode. Current flows in the direction of J. The black lines represent vortices in the YBCO film. Since the motion of the vortices is governed by $\mathbf{f} = \mathbf{J} \times \boldsymbol{\Phi}_0/c$ ($\boldsymbol{\Phi}_0$: Magnetic Field Quanta for a Vortex in z-direction), the vortices vibrate at the curved films, but not vibrate at the side wall.



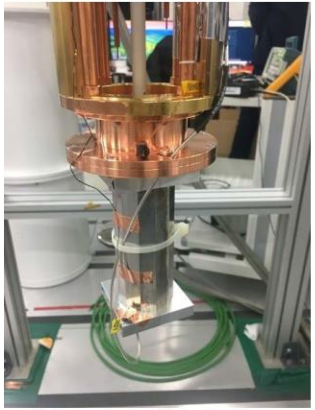
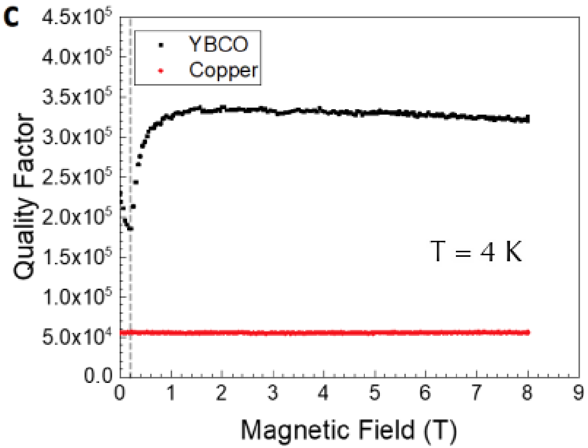


Figure 4 The polygon cavity installation in the cryocooler. The two RF lines connect to the cavity and two temperature sensor attached on the top and bottom parts of the cavity.

D. Ahn et al, ArXiV:2002.08769v1



Twelve sectors, with glued HTS tapes

Conclusions

- Promising candidate new materials for SRF: A15 (Nb_3Sn, V_3Si, …) and B1 (NbN, NbTiN, …)
- Very successful results for Nb_3Sn from Sn vapour diffusion
  - Technological evolution over >30 years, great leap in the past 10 years
- Fast-pace evolution for Nb_3Sn films on Cu
  - Mastering Sn-Cu diffusion is the key for success… as in magnets!
- NbN being pursued in several places
  - Probably intrinsically limited by metastable δ-phase
- NbTiN remains the best B1 candidate
  - Composition accuracy and grain size need to be solved
- Other innovative materials will require further developments
  - MgB2 being pursued only at Temple University
  - REBCO might be a viable alternative, for some niche applications. New-generation coated-conductors have very peculiar performance

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