Thin film SRF perspectives in UK

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ASTeC/CI
On behalf of a TF SRF team at STFC Daresbury Laboratory

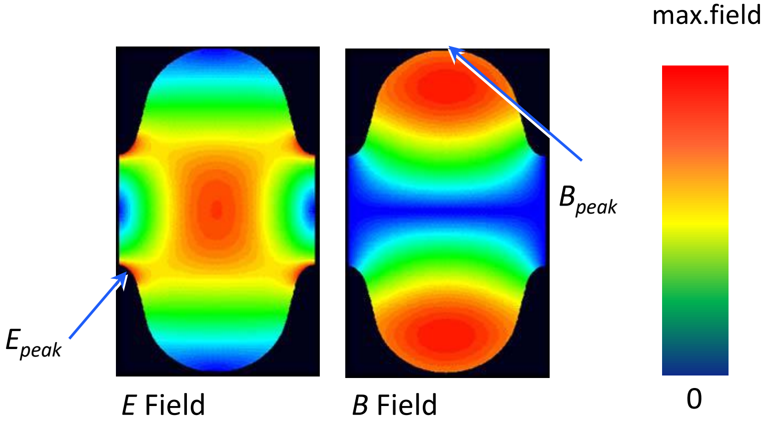
Science and Technology Facilities Council

Introduction

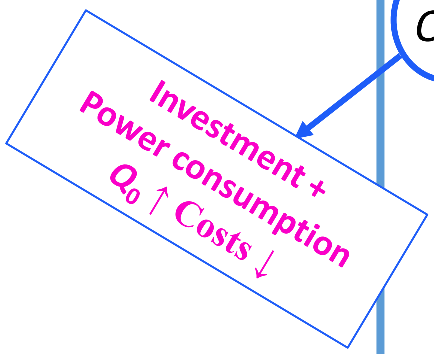
Present state

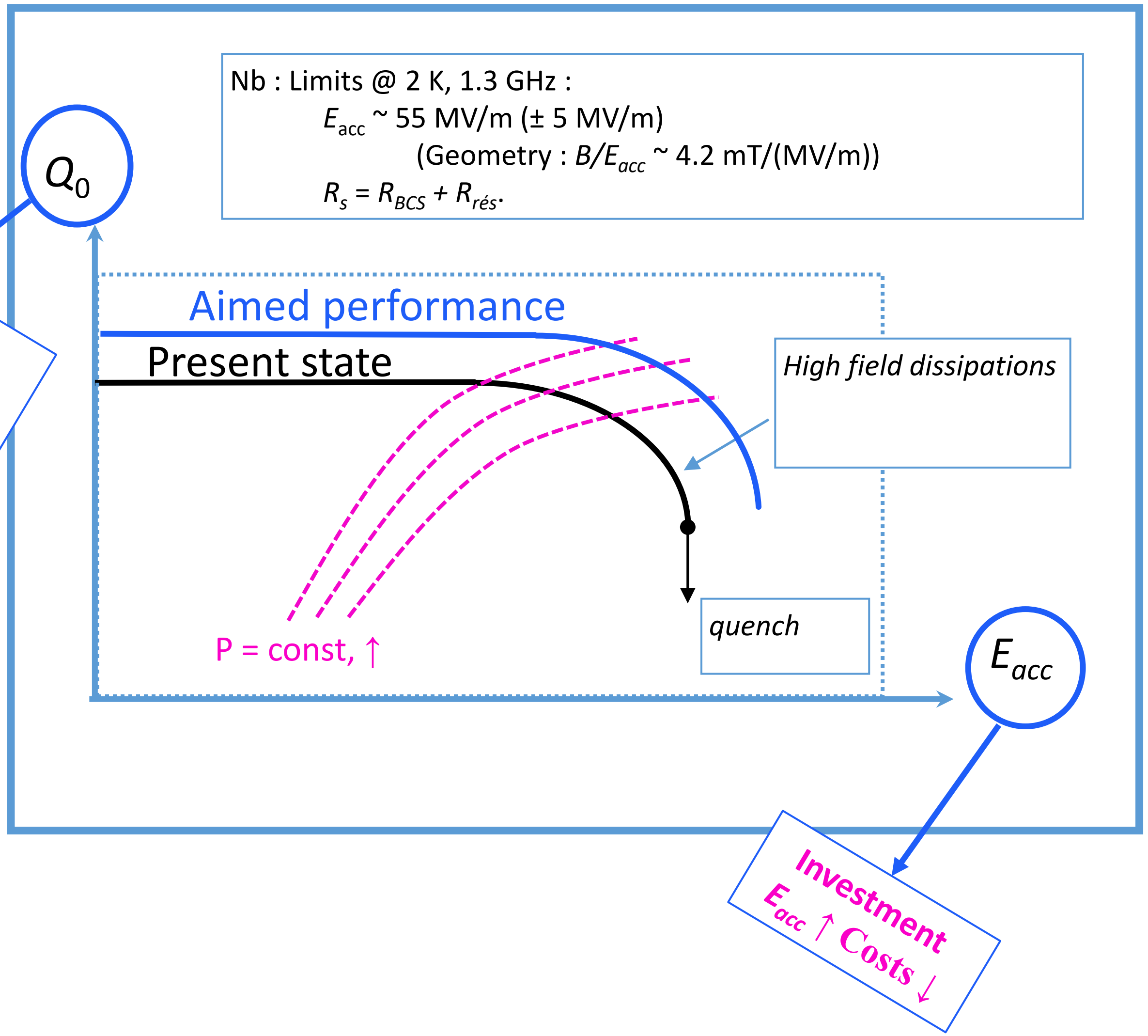
Bulk Nb: monopoly since > 50 years

- Nb/Cu applications at low accelerating field only until recently



- Figures of merit:
  - $E_{acc} \propto B_{RF} \leq B_{SH}$ *limitation = magnetic transition*
  - $Q_0 \propto 1/R_S$ *limitation = thermal transition*
  - Duty cycle (=> 100%): *limitation = cryogenic power*
  - $\beta = \frac{v}{c}$ (particle speed /light speed): *influences design*
- At $f < 3$ GHz: cavities are mainly limited by B_{RF}!!!





Courtesy of C. Antoine (CEA, France)

Superconductors considered for SRF

Material	T_C (K)	B_{SH} (mT)@ 0 K
Pb	7.1	100
Nb	**9.2**	**219,0**
NbTi	9.2-10	
NbTiN	**10.6-11.8**	
V_3Si	**17.0**	
NbN	**17.3**	**214,0**
Nb_3Sn	**18.3**	**425,0**
Nb_3Al	18.5-19.1	
MgB_2	**39.0**	**170,0**
Pnictides: $Ba_{0.6}K_{0.4}Fe_2As_2$	**38.0**	**756,0**
Cuprates: YBaCuO	**93.0**	**1050,0**

High H_{SH} => High E_{acc}… in theory

High T_C => High Q_0

Courtesy of C. Antoine (CEA, France)

International collaborations

I.FAST WP9: Innovative superconducting cavities (01/05/2021-30/04/2025)

15 partners from 9 countries

The main emphasis is on applying the result of ARIES to RF cavity deposition with non-Nb STF and SRF testing

Surface preparation
- Cleaning, etching,
- Polishing, passivating

Thin film deposition
- **PVD**: DC, pulsed, HIPIMS…
- (PE)CVD, (PE)ALD
- **Nb, NbN, Nb_3Sn**, MgB_2, SIS, etc.
  - Nb film laser treatment

Film characterisation
- SEM, FIB, AFM,
- XPS, XRD, RBS, TEM…

Superconducting properties measurement

RRR, H_c, H_{fp}, H_{sh}, …
DC magnetic susceptibility,
Field penetration

Superconducting RF properties evaluation
- QPR at CERN
- QPR at HZF
- HW choked cavity at ASTeC

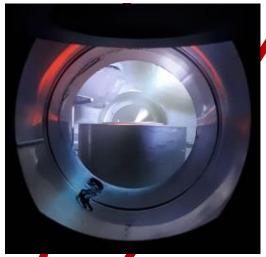
Real cavity measurement

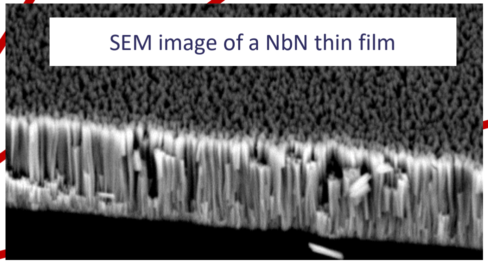
ARIES WP15: (01/05/2017-30/04/2021)

9 partners from 6 countries

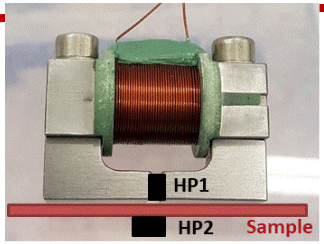
The main emphasis is on a systematic study of correlation between

Film deposition

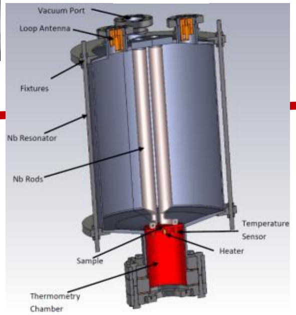




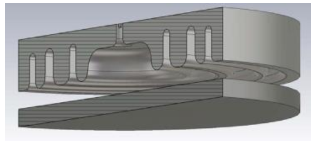
DC magnetisation



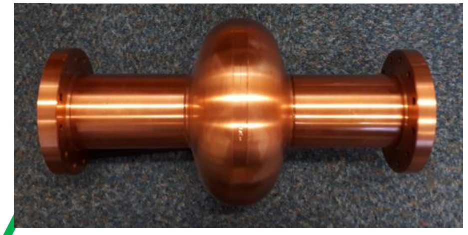
QPR



Choked cavity



1.3 GHz cavity for STF deposition



Superconducting Thin Film Coating for Radio Frequency Cavities (TF-SRF) at STFC/DL/CI

- **Main goal**:
  - To enable STFC for the superconducting thin film coated cavity production and testing
- **Main objectives**:
  1) Developing coating technology for **superconducting thin films** (STF)
     - Deposition of Nb, Nb_3Sn, NbTiN, V_3Si, Mg_2B, … and SIS structures
     - Thin film characterisation
     - AC/DC superconductivity evaluation
  2) Developing **cavity deposition** expertise
     - Copper cavity production (incl. EB welding)
     - Polishing and cleaning of copper cavities
     - Building deposition facilities
     - Developing deposition targets
     - Optimising deposition parameters
  3) **SRF testing** at DL
     - 1.3 GHz (and 6 GHz) single cell cavity testing as a 1^{st} step
     - Scaling up to a routine cavity coating and testing
     - Multicell cavities

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A path towards the goal

(1) Superconducting thin film development

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Copper surface preparation

- Mechanical polishing
- Fine mechanical polishing
  - diamond turning (for flat samples) at STFC
  - tumbling
- Chemical polishing:
  - SUBU5 solution
  - Electropolishing (EP)
- Laser polishing
  - not proved yet
- Combination of different techniques

In present, relying on IFAST partners: INFN/LNL and IJCLab

Needs to be developed at STFC

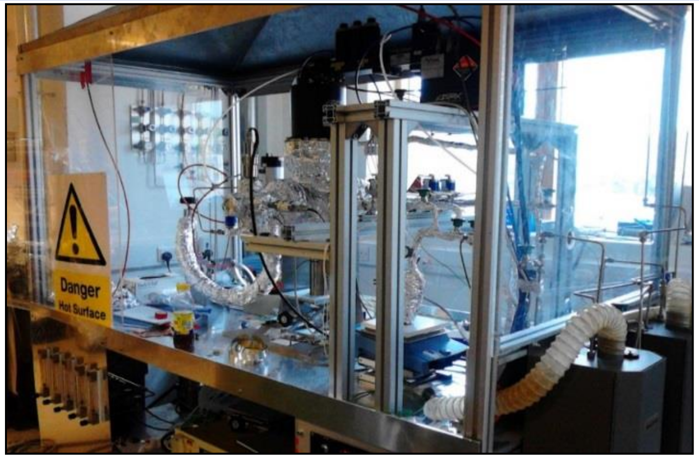
Thin Film Deposition in VISTA

Stablished and coordinated by R. Valizadeh (ASTeC)
CI collaborators: Prof J. Bradley and Dr V. Danak (Liverpool University)
Participants: : J. Conlon, C. Benjamin, S. Simon

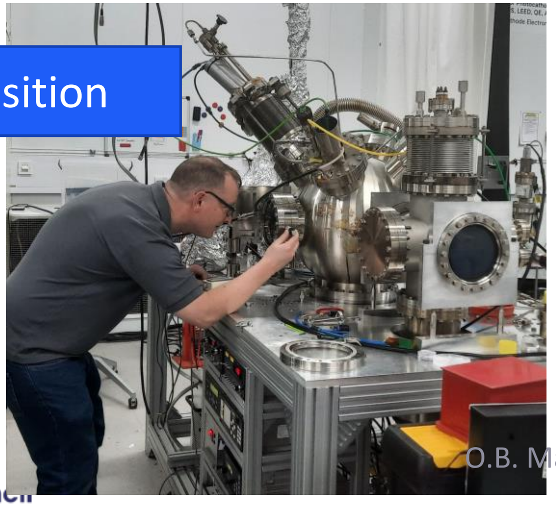
VISTA laboratory

Physical Vapour Deposition (PVD)

Chemical Vapour Deposition (CVD)

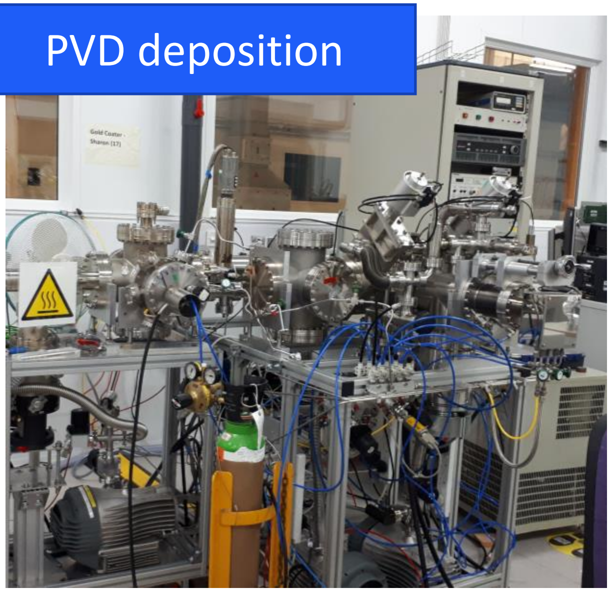


PVD deposition



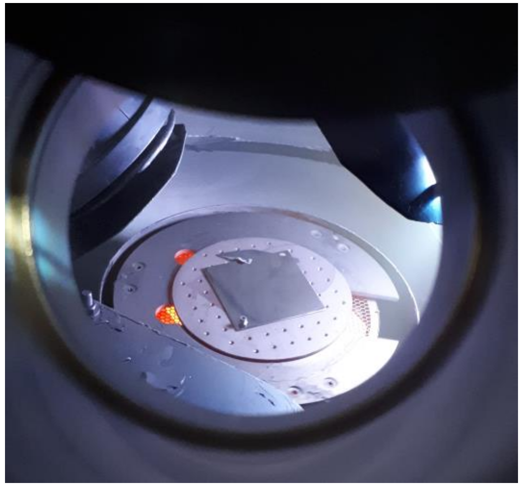
Hybrid Physical Chemical Vapour Deposition (HPCVD) Facility

PVD deposition

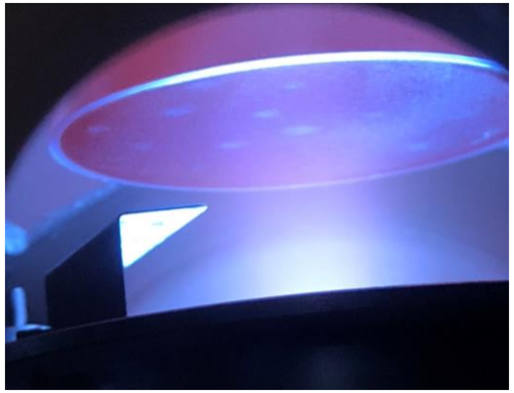


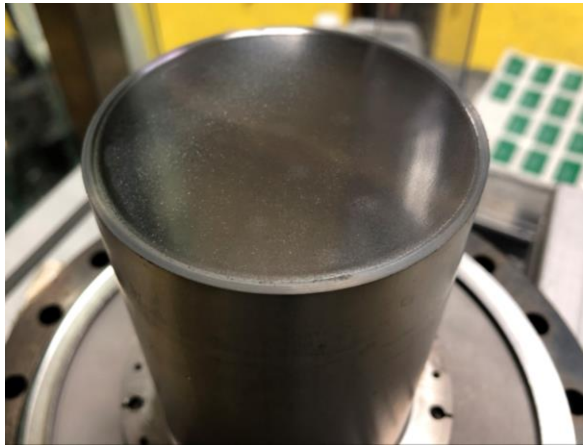
Thin film development

- **Techniques:**
  - **PVD**: DC, pulsed, HIPIMS…
  - (PE)CVD, (PE)ALD – under development
  - Combined: PCVD – under development
- **Materials:**
  - **Nb**
  - **Nb_3Sn**, **NbTiN, V_3Si**, NbN, MgB_2, etc.
  - SIS structures
- **Deposition facilities**
  - For planar samples
  - For QPR samples



A sample during the Nb deposition
Courtesy of R. Valizadeh (STFC)





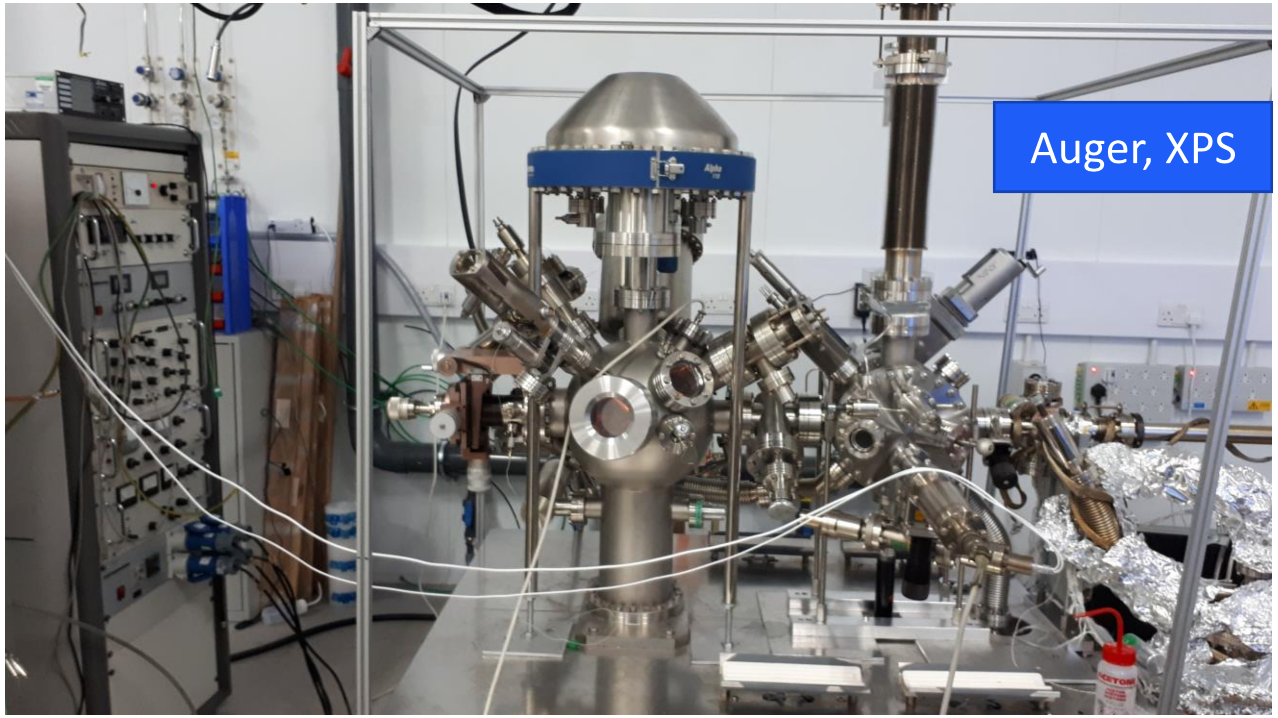
A QPR sample during and after the Nb TF deposition
Courtesy of R. Valizadeh (STFC)

Thin Film Characterisation in VISTA

Stablished and coordinated by R. Valizadeh (ASTeC)
CI collaborators: Prof J. Bradley and Dr V. Danak (Liverpool University)
Participants: J. Conlon, C. Benjamin, S. Simon, A. Hannah, G. Stenning

FEI inspect S50 SEM

Auger



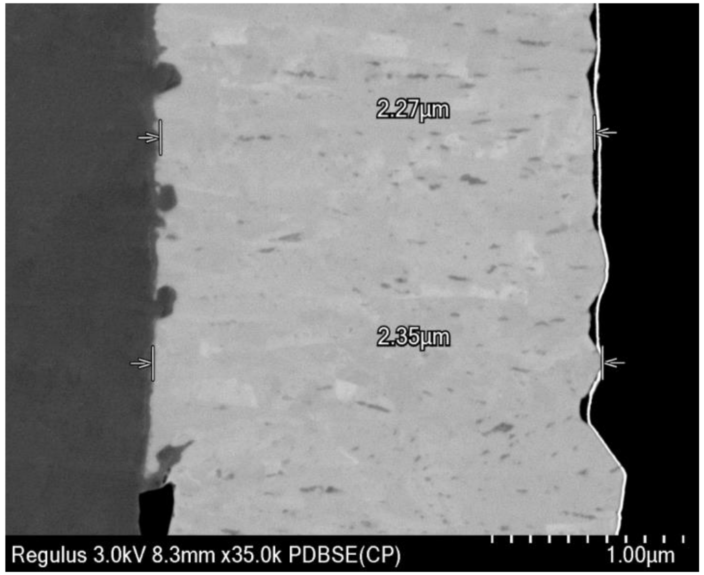
Auger, XPS

More characterisation facilities are available through collaborations with

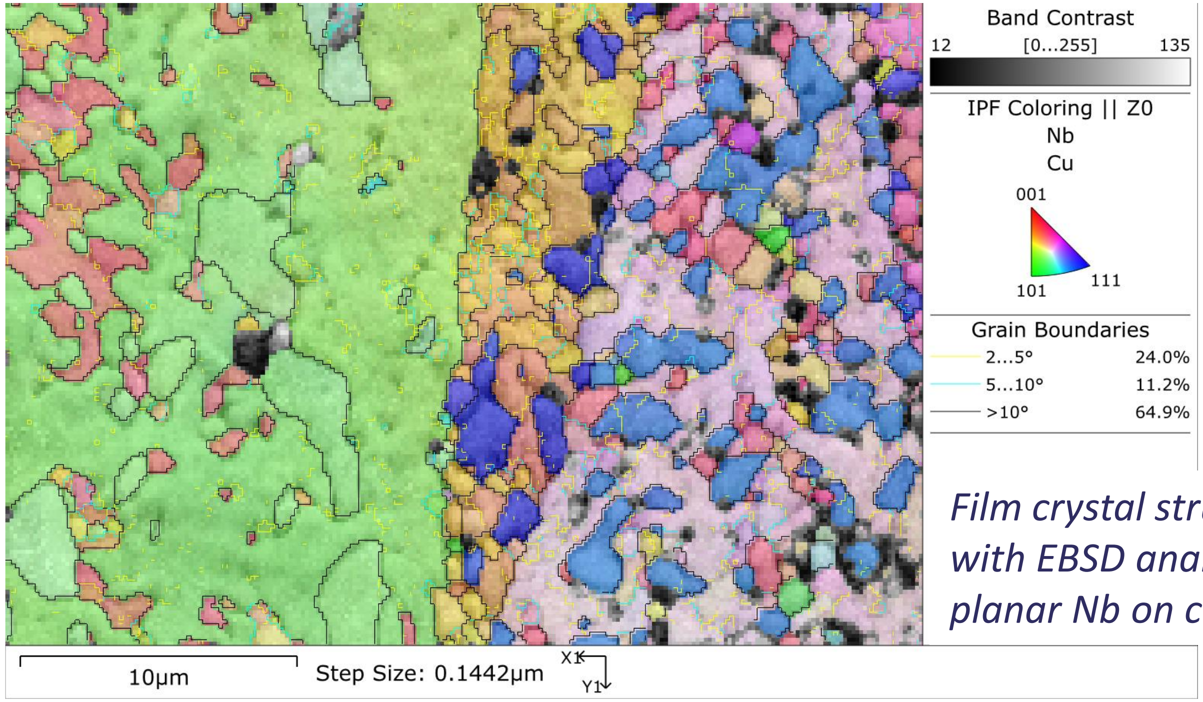
- The Materials Characterisation Laboratory at ISIS (RAL)
- CI universities
- Other UK universities
- International collaborations

Courtesy of R. Valizadeh

Thin film characterisation - 1

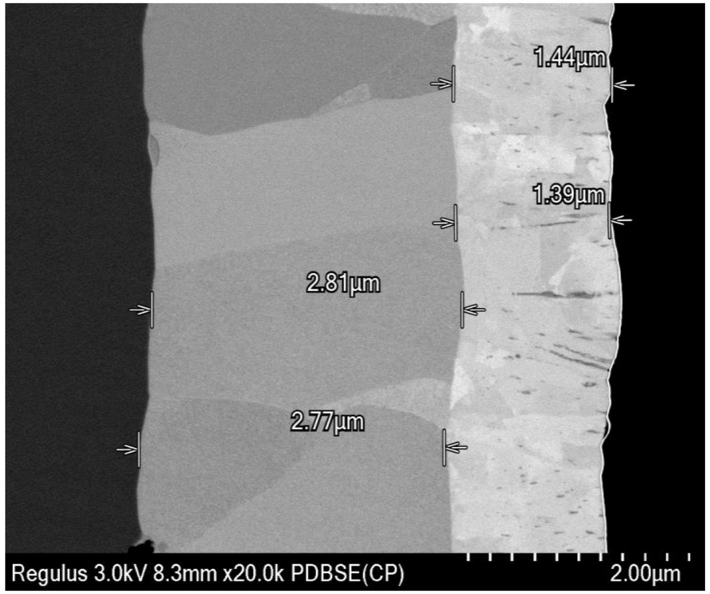


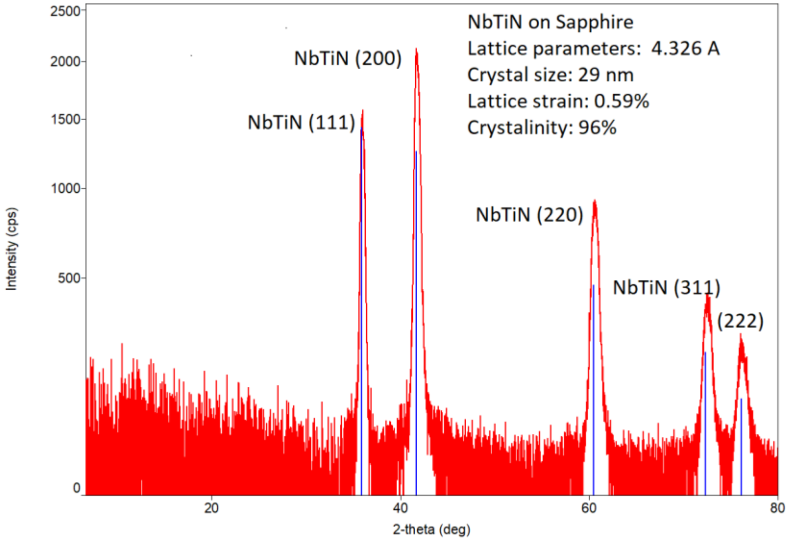
X-section SEM of Nb_3Sn deposited on Cu



Film crystal structure with EBSD analysis of planar Nb on copper

X-section SEM of Nb_3Sn with a Nb underlayer as double structure on Cu

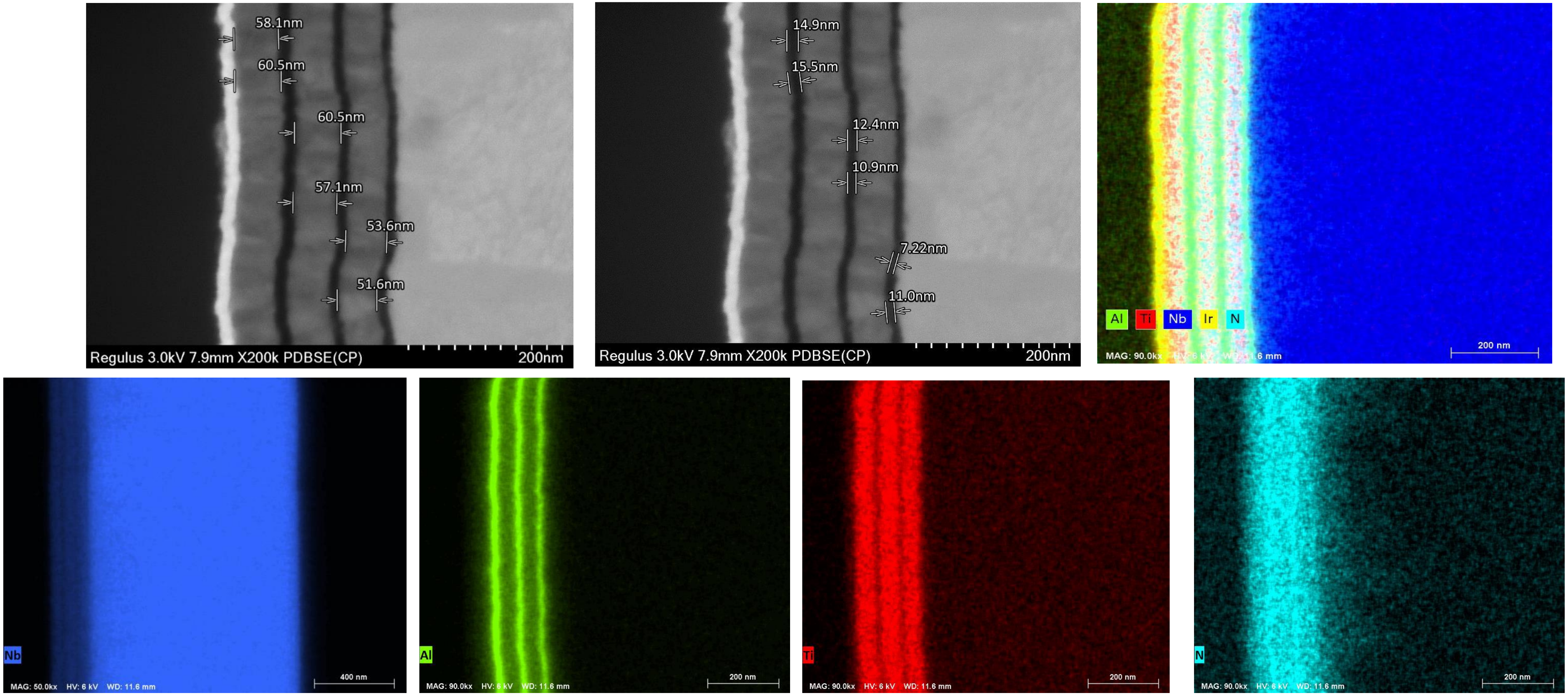




XRD analysis of NbTiN deposited on copper

Courtesy of R. Valizadeh (STFC)

Thin film characterisation - 2

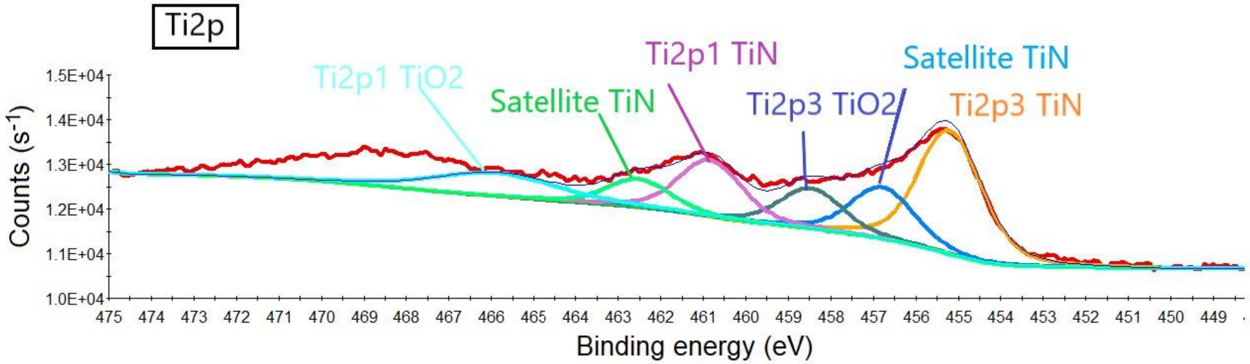


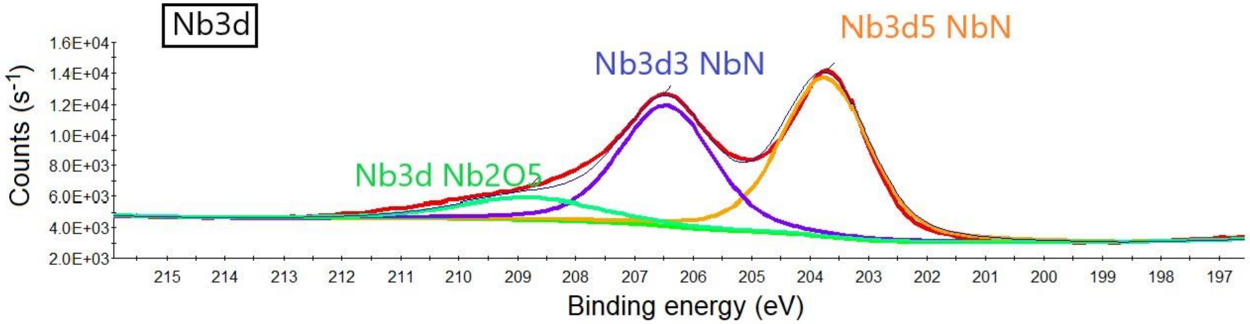
(a)High resolution SEM of ion milled X-section of SIS multilayer structure (Nb/AlN/Nb_3Sn) deposited on Ta.
(b) EDX chemical mapping of the X-section.

Courtesy of R. Valizadeh (STFC)

Thin film characterisation – 3

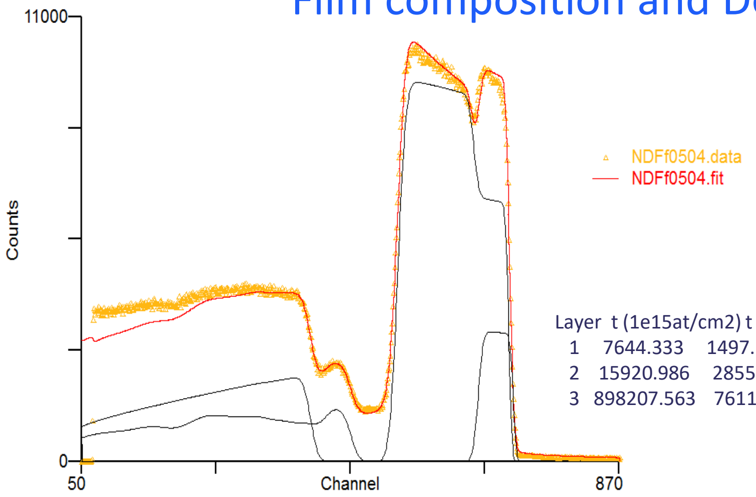
XPS: Composition and chemical analysis





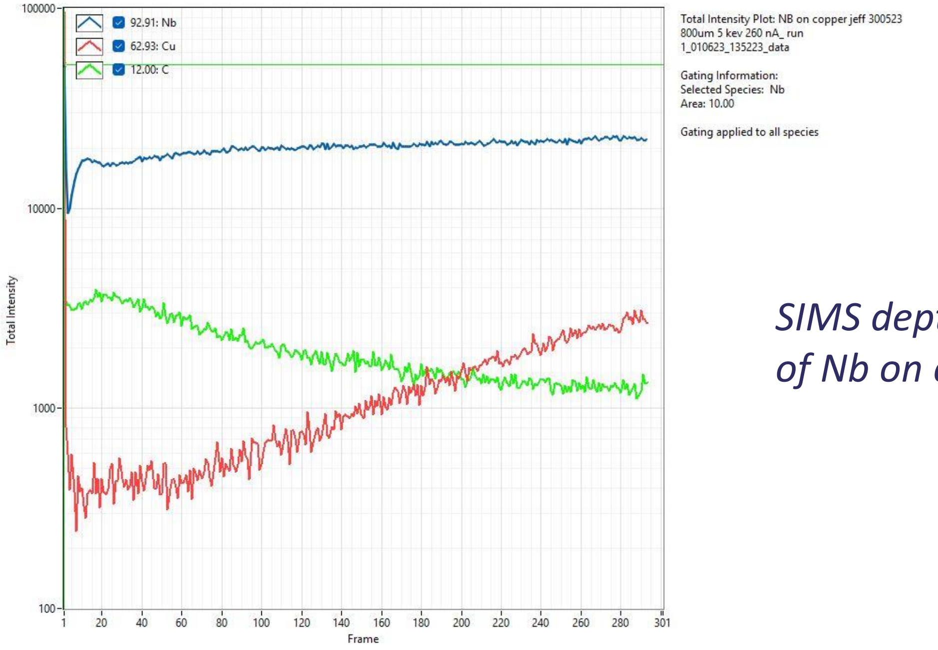
XPS analysis of NbTiN representing Nb and Ti chemical state)

Film composition and Depth profile



RBS analysis of Nb_3Sn on sapphire

Layer	t (1e15at/cm2)	t (nm)	r(1e22at/cm3)	Nb	Sn	O	Al
1	7644.333	1497.201	5.106	75.0000	25.0000	0.0000	0.0000
2	15920.986	2855.270	5.576	100.0000	0.0000	0.0000	0.0000
3	898207.563	76119.281	11.800	0.0000	0.0000	60.0000	40.0000

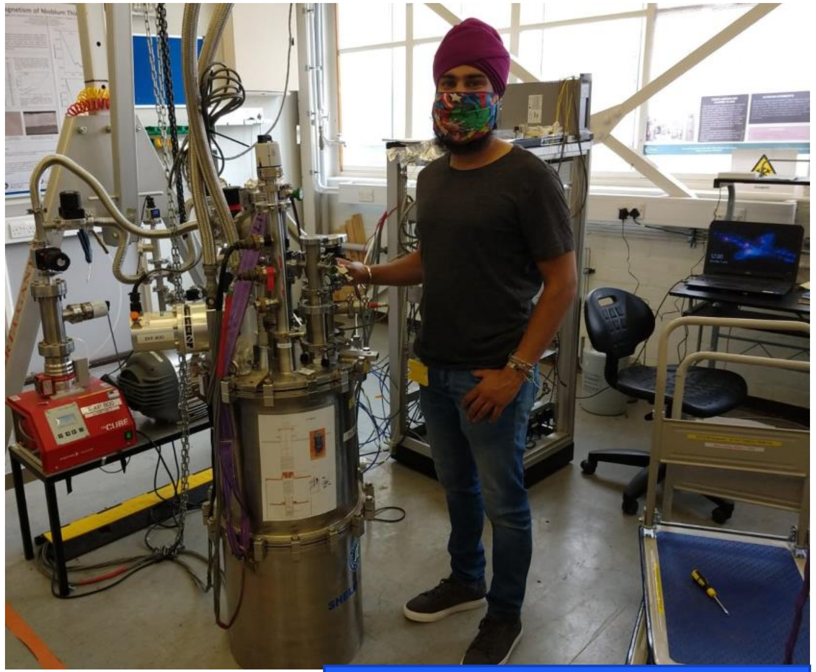


SIMS depth profile of Nb on copper

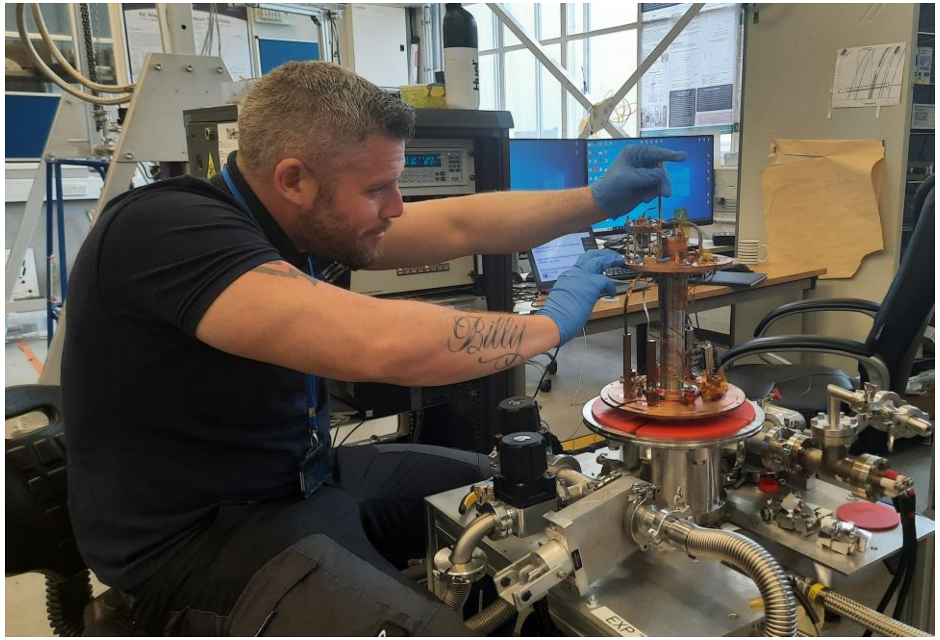
Superconducting Properties Evaluation

Coordinated by O.B. Malyshev (ASTeC)
CI collaborators: Prof G. Burt (Liverpool University)
Participants: D. Seal, L. Smith, T. Sian, D. Turner, N. Leicester, K. Marks, J. Conlon, S. Pattalwar, A. May, K. Dumbel, J. Wilson, G. Stenning

CryoLab



RRR/T_c
+ 3 other experiments



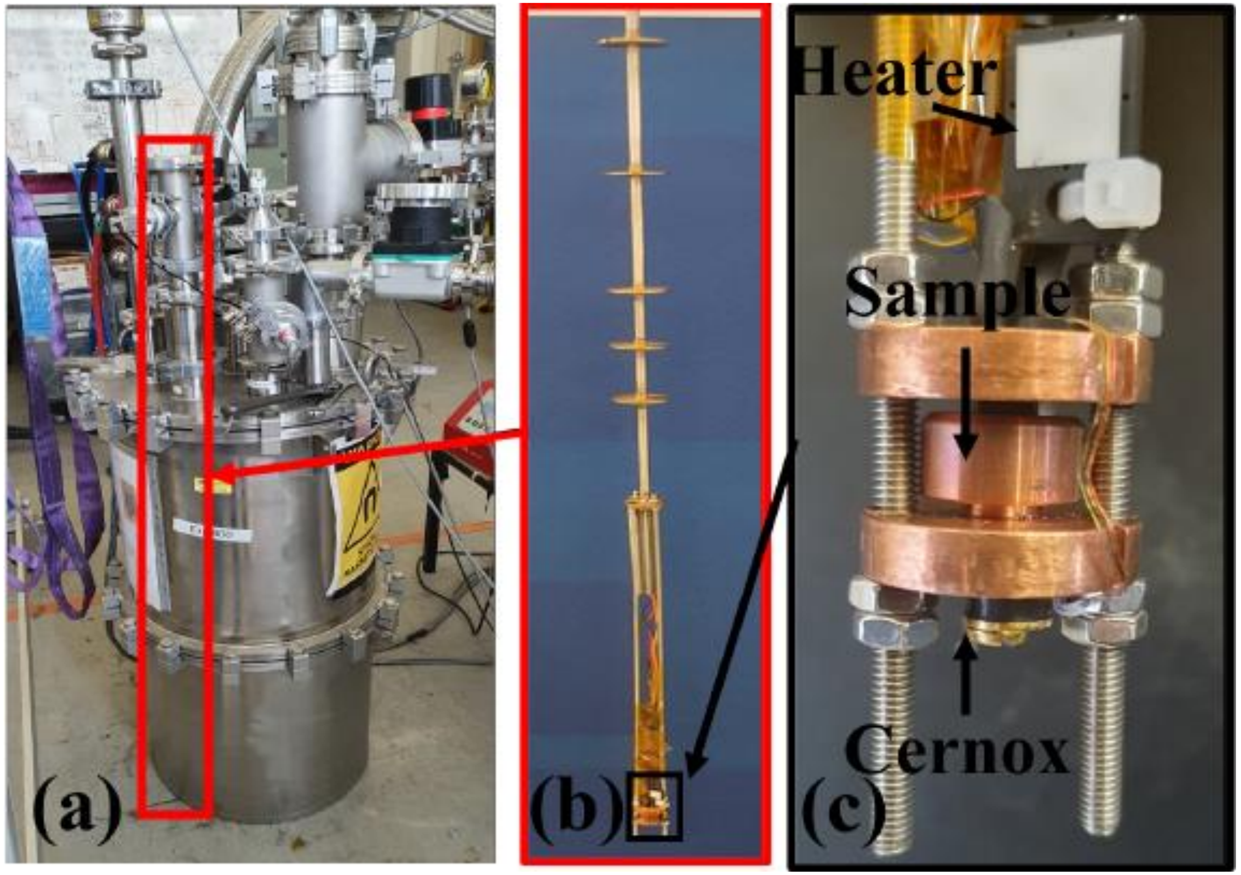
Magnetic field penetration facility

CrabLab

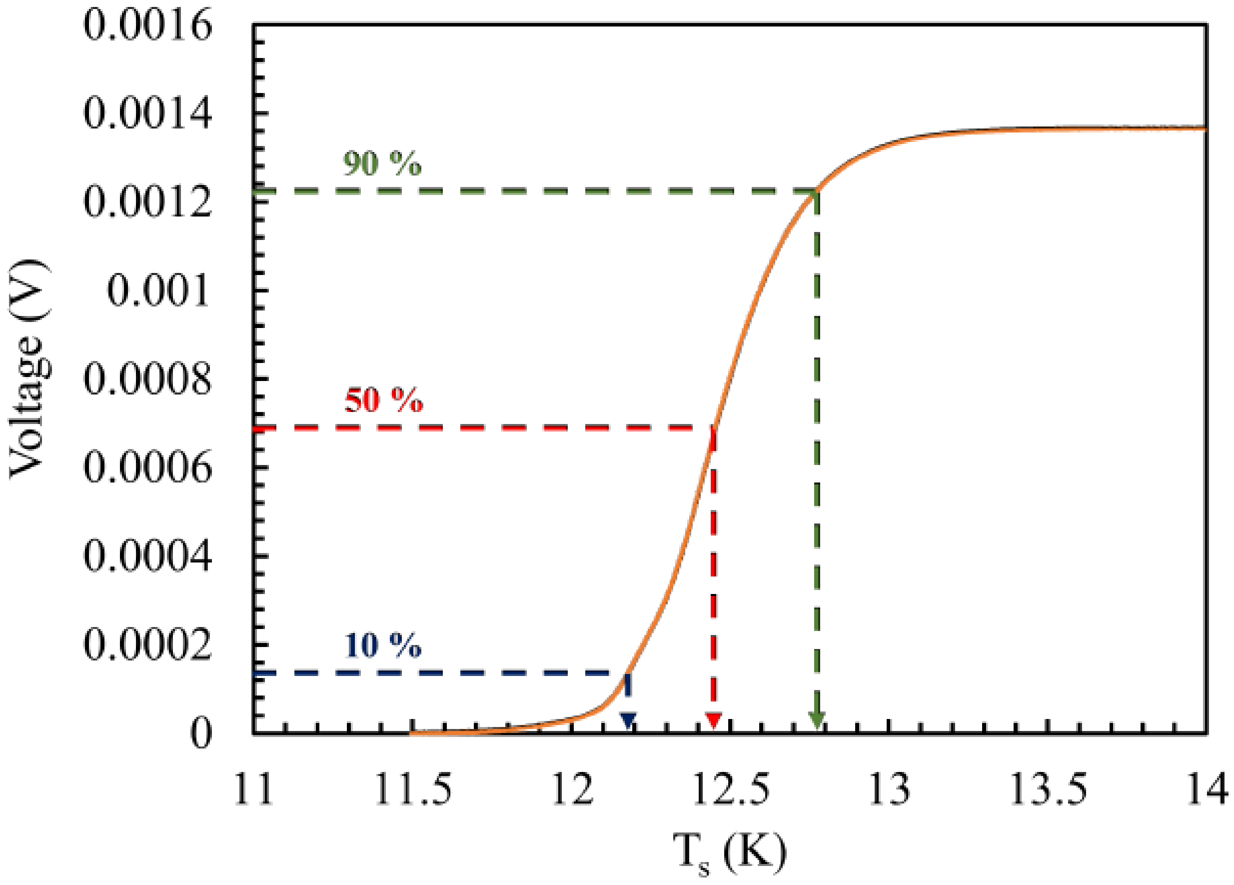
R_S measurements with a 7.8 GHz choked cavity and a 6 GHz split cavity

Thin film DC superconducting properties - 1

RRR and T_c measurements: (a) Cryostat, (b) insert, (c) sample holder



Resistance measurements for a V_3Si on sapphire sample indicating the 10, 50 and 90 % transition points

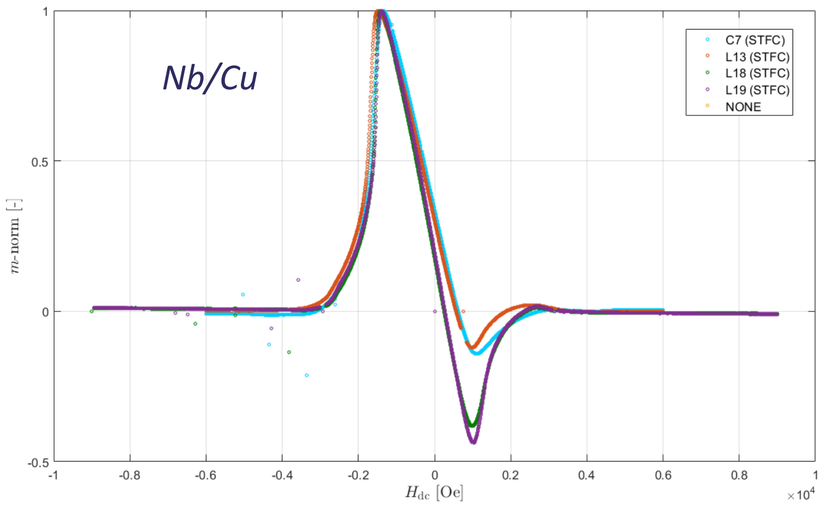


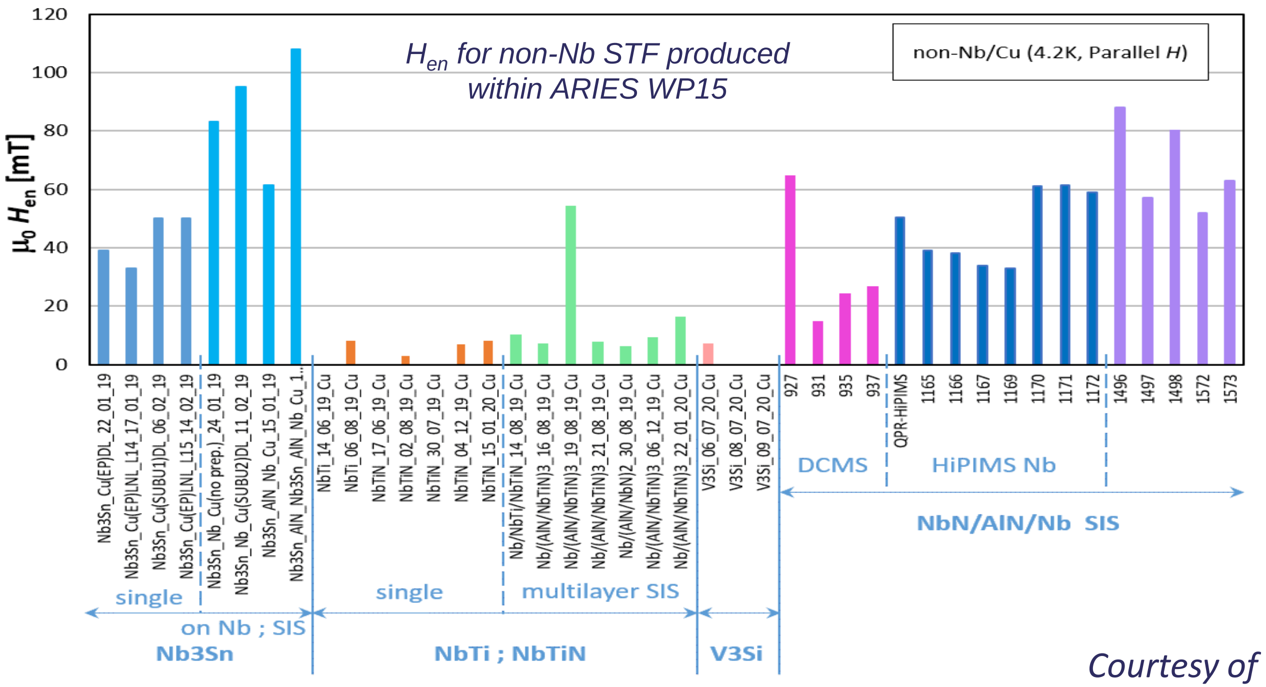
Courtesy of L. Smith (STFC)

Thin film DC superconducting properties - 2

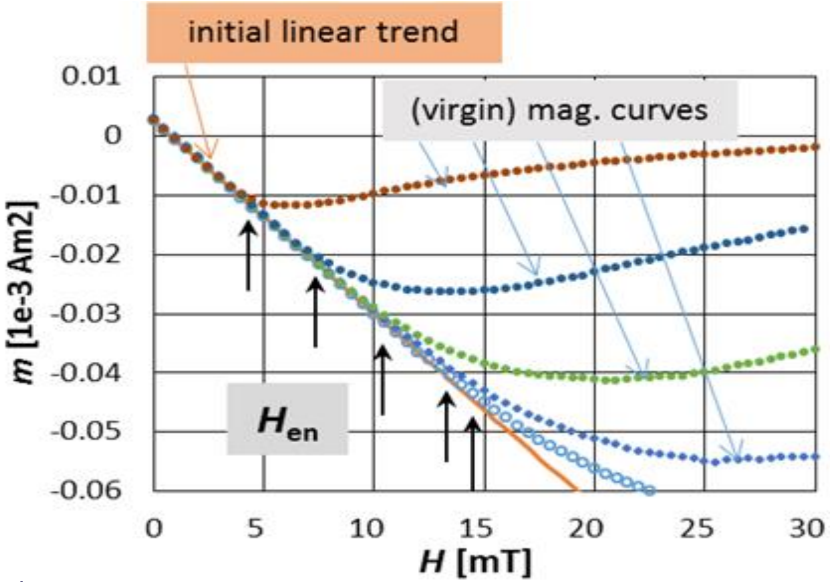
PPMS (Physical Property Measurement System)

- Virgin DC magnetisation curve: B_{en}(~$B_{c1\ perp}$), [B_p, B_{c2}]
- The Materials Characterisation Laboratory at ISIS (RAL)
- IEE-SAS (Bratislava, Slovakia)





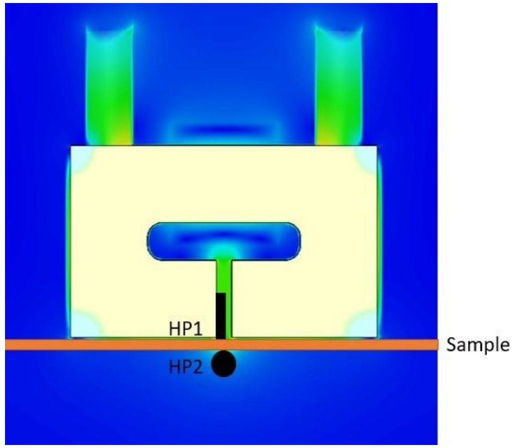
Courtesy of E. Seiler (IEE, Slovakia)

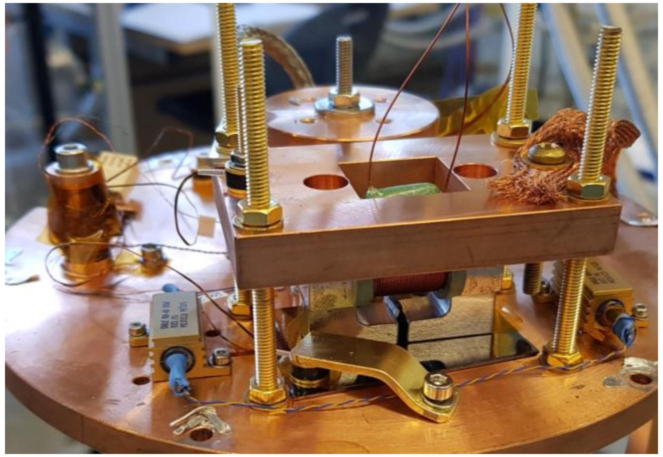


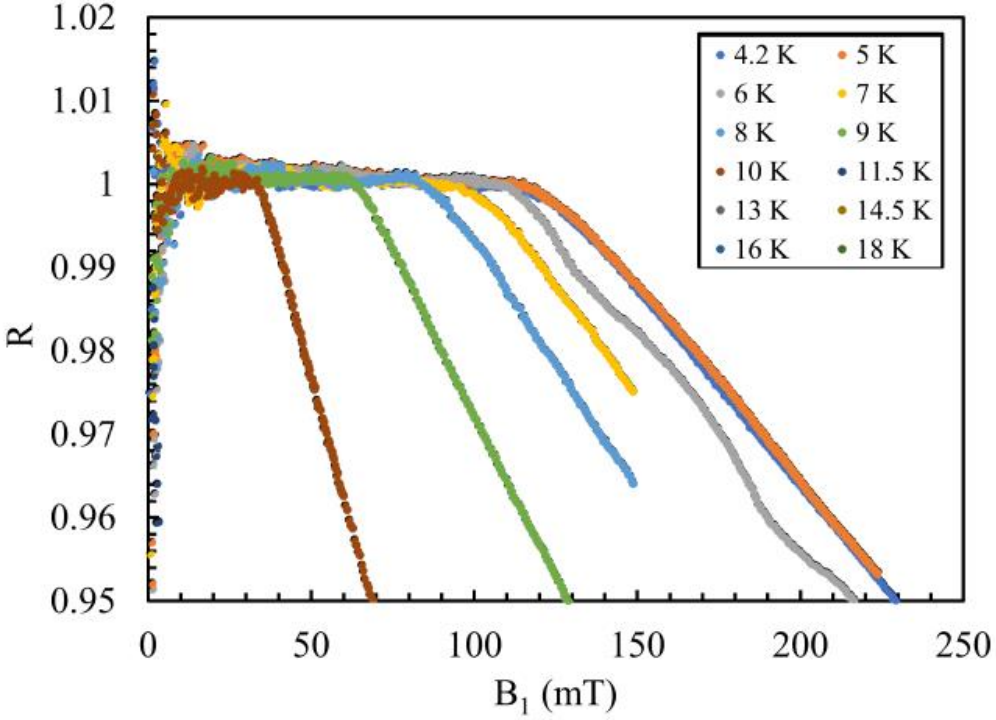
Determination of the characteristic field H_{en} from the virgin magnetization curves

Thin film DC superconducting properties - 3

- Magnetic field penetration facility for the planar samples
  - TF samples can be compared in conditions similar to ones in the cavity
    - DC magnetic field parallel to the surface
    - Magnetic field applied from one side of the sample (similar to an SRF cavity)
  - Applied and penetrated field measured by Hall probe sensors
  - $R = 1 - \frac{B_2}{B_1}$,
    - i.e. SC is in Meissen state when $R = 1$



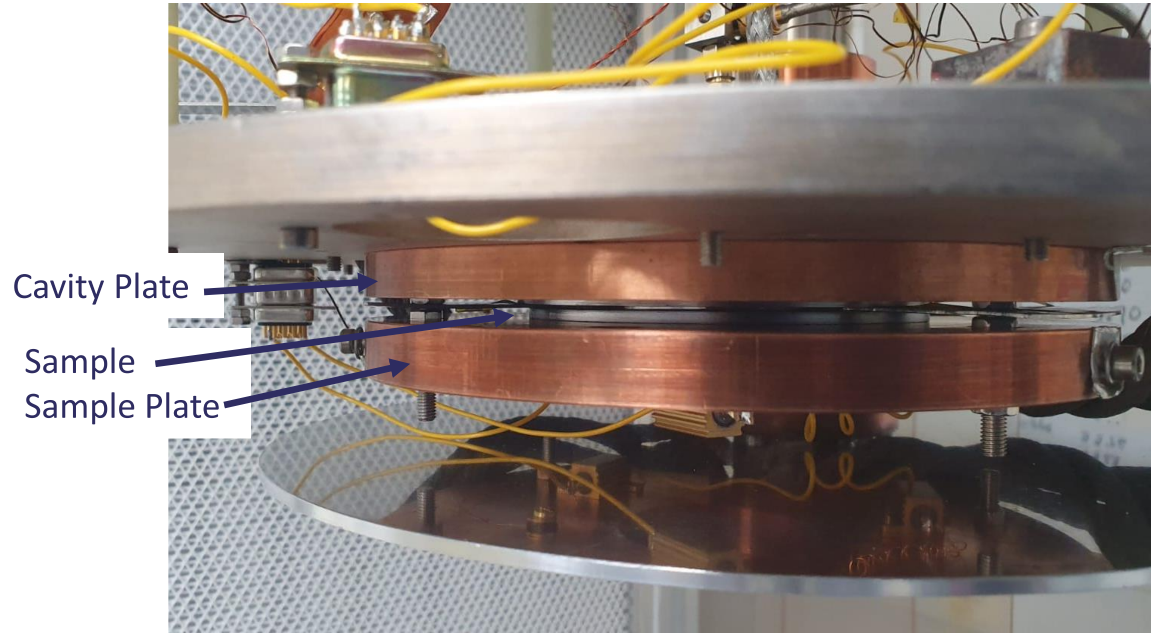




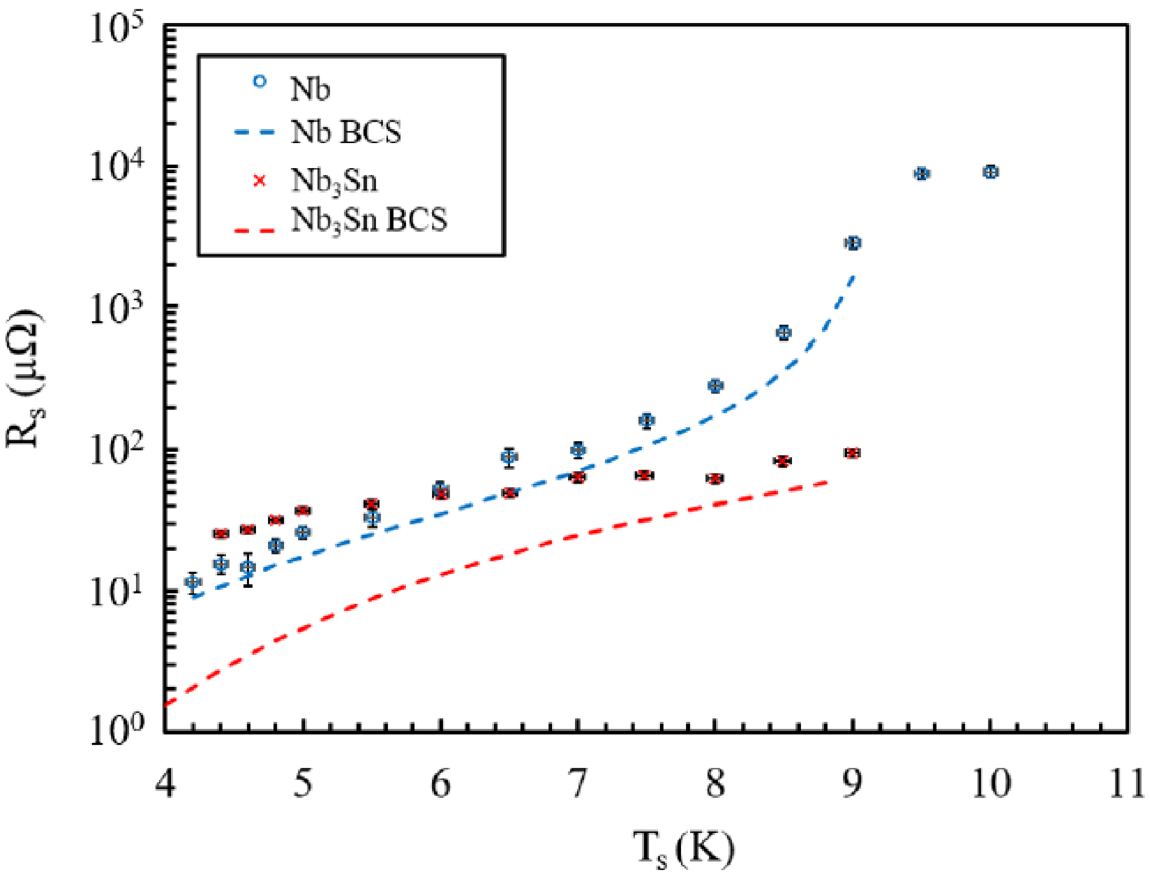
Courtesy of L. Smith (STFC)

Thin film RF superconducting properties

- A radiofrequency (RF) cavity and cryostat dedicated to the measurement of superconducting coatings at 7.8 GHz (CrabLab/DL/STFC)
  - Operation with a closed-cycle refrigerator:
    - T_{cavity} = 4.0 K and T_{sample} = 4.0 K
  - Low power (≤1.0 W) measurements with an emphasis on fast turn-around time (~2 days for each sample).
  - **Flat Sample** – a disk diam. 90 - 130 mm



An example of $R_s(T_s)$ measurements for Nb and Nb_3Sn TF planar samples with the choked cavity.



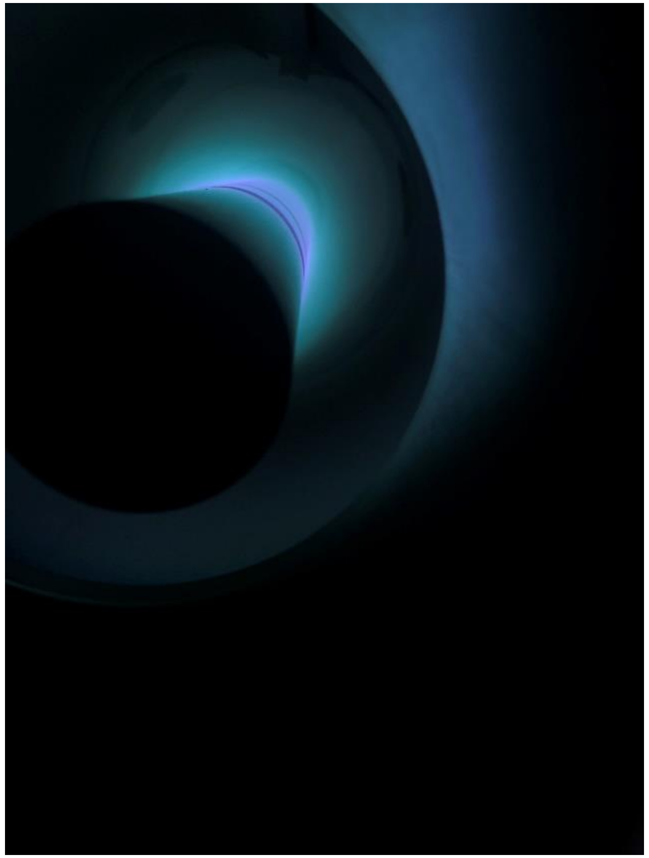
Courtesy of D. Seal (STFC/LancU)

A path towards the goal

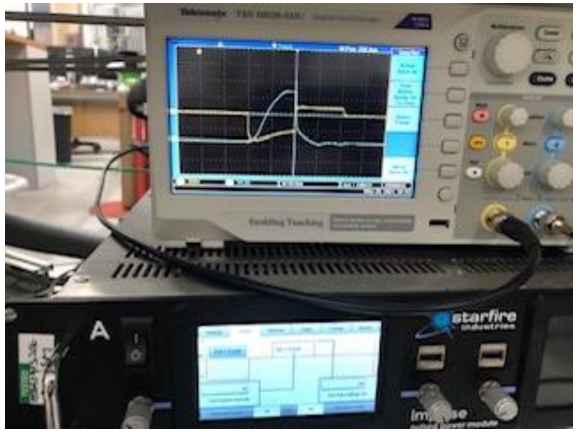
(2) Superconducting thin film coated RF cavity

Development of 6 and 1.3 GHz cavity coating

- Cylindrical Magnetron has been built
- Nb thin film depositions on cylindrical and cavity shaped surfaces are ongoing



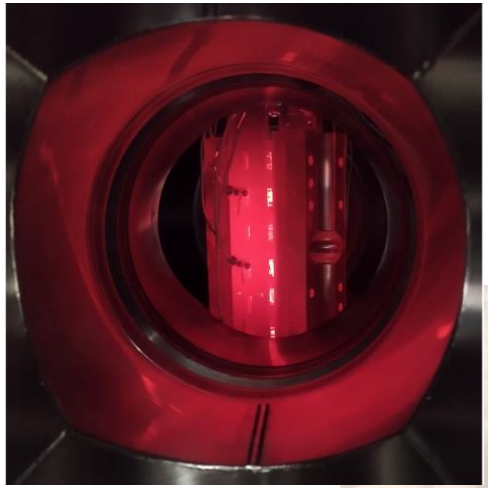
Cylindrical magnetron in low power (**DC**) sputtering mode
Plasma dominated by *argon* emission



Cylindrical magnetron in high power (**HIPIMS**) sputtering mode
Plasma dominated by *niobium* emission

6 GHz split cavity

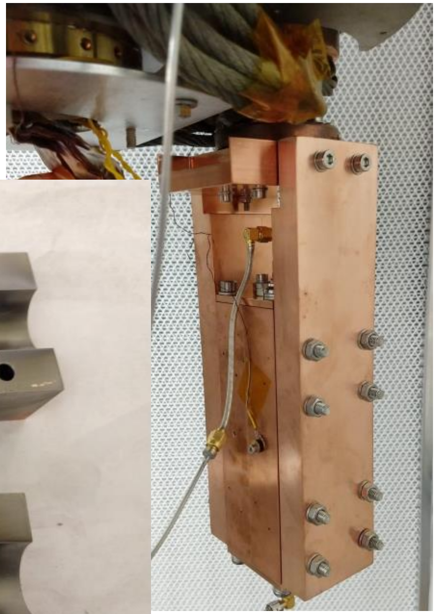
- An idea suggested by G. Burt (CI)
- The cavity cut is along the electric field lines, i.e. electric current is not crossing the cut
- Easy to coat with either conventional planar magnetron or in tubular geometry used for RF cavities
- Easy to inspect
- Two 6 GHz cavities were Nb coated and tested at 4.2 K ≤ T ≤ 11 K

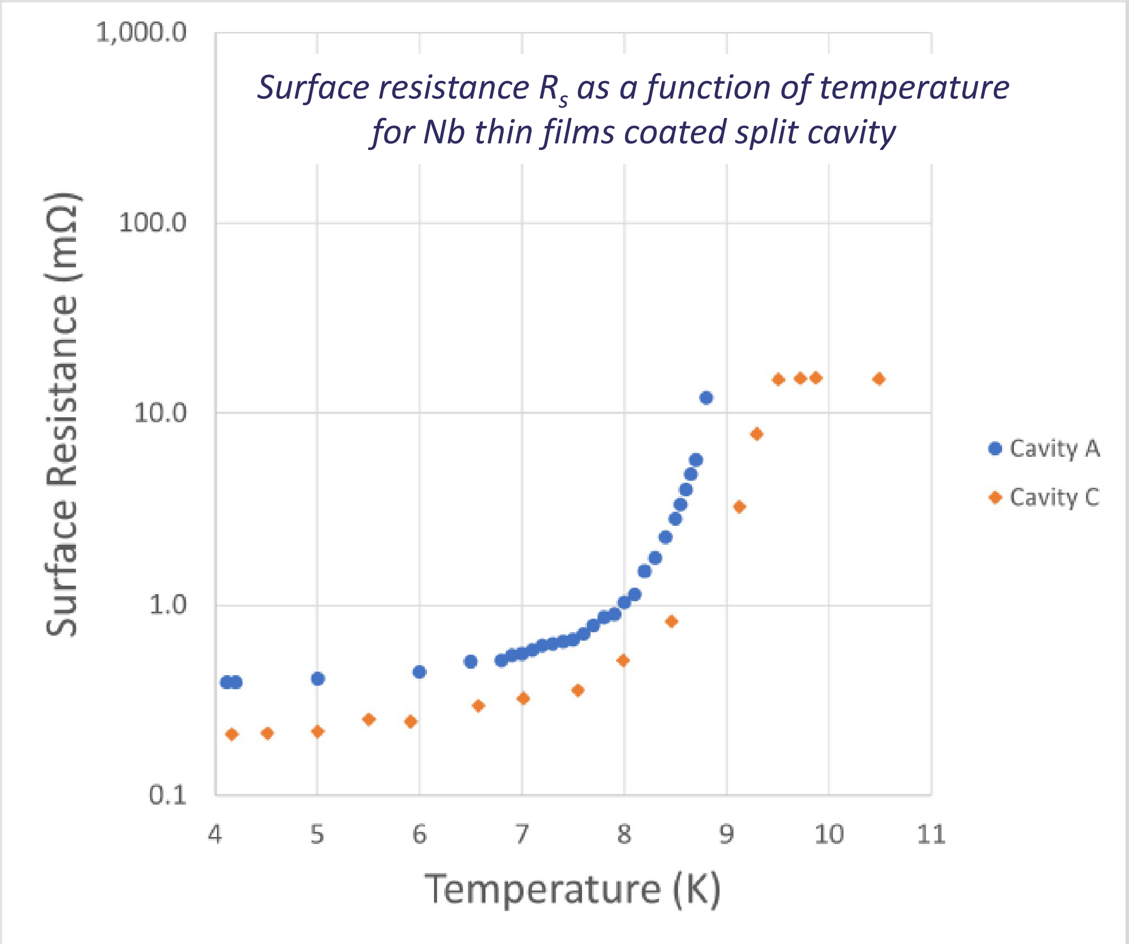


A split cavity during thin film deposition

Nb thin films coated split cavity

Split cavity mounted on the cold head for cryogenic measurements

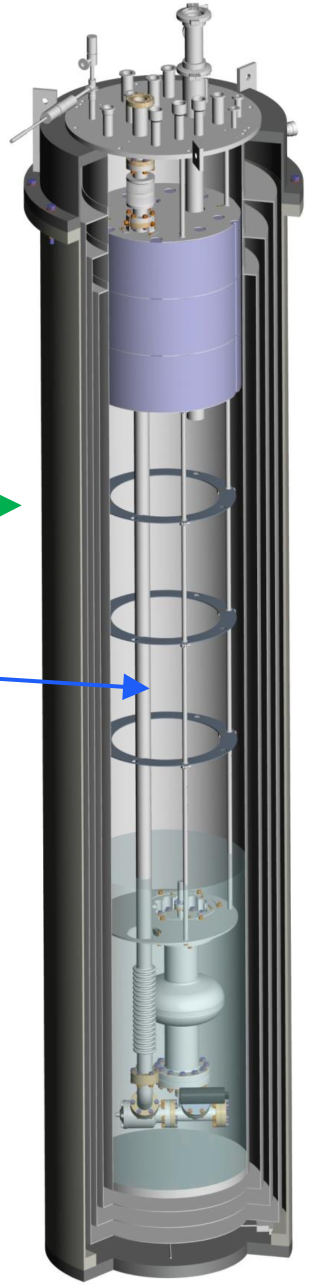




Courtesy of N. Leicester (STFC/LancU), T. Sian, and J. Conlon (STFC/LancU)

1.3 GHz cavity testing

- **Aiming a high power test**
  - **Required fully operational by end of 2023**
    - Main Delivery for IFAST WP9: a non-Nb SC coated prototype testing (by March 2025)
  - Cryostat and insert:
    - Cryostat is available
    - New insert is designed, parts manufactured, assembling in process
  - Copper cavity:
    - will be provided by I.FAST partners: Piccoli and LNL/INFN
    - looking for UK industry as well
    - Coating with STF at STFC/DL
  - Clean room for assembling the cavity – TBD
  - RF amplifier – under development
  - Bunker and cryogenics:
    - SuRF lab infrastructure is available



Superconducting Cavity Evaluation in SuRF lab

This STFC/DL infrastructure

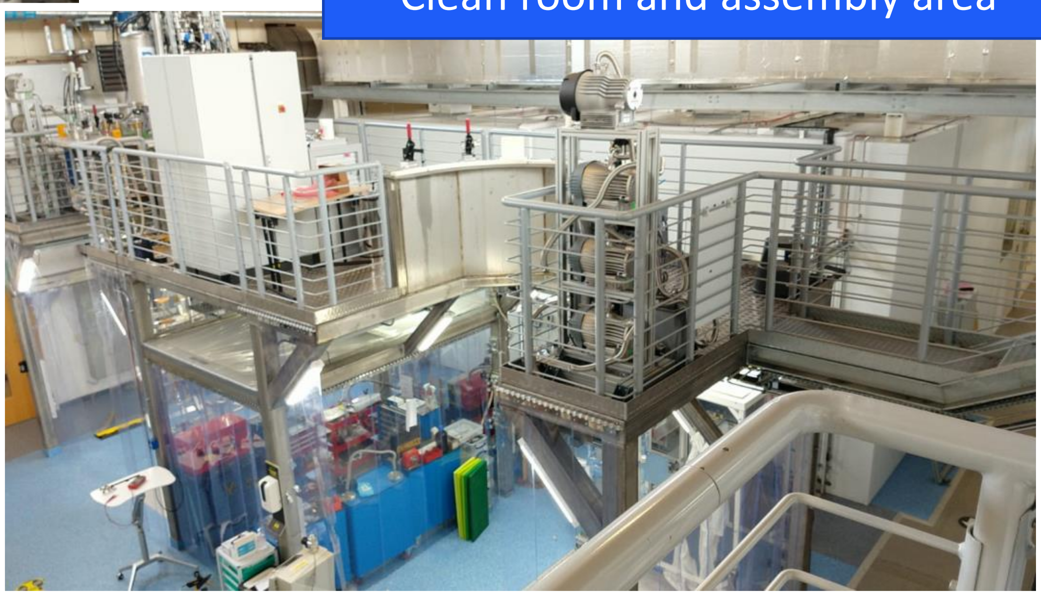
- is being used for the full power SRF testing of >160 cavity modules for ESS and
- will be used for SRF testing of PEP-II cavities

He liquefier and
LHe storage Dewar

This infrastructure can be used in future for the full power SRF testing of superconducting thin film coated RF cavities

SRF bunker

Clean room and assembly area



Courtesy of T. Sian

Future for TF-SRF cavities in UK

Development

- Single layer coating:
  - Nb
  - Nb_3Sn, NbTiN, V_3Si, Mg_2B
- Multilayer coatings
  - SS, SIS, SISIS…
- Multicell cavity coating
- Split cavity development
- Low and high power RF testing at STFC/DL

Possible applications

- RF loaded test in CLARA
  - Multicell cavities
  - Split cavity
  - LHe-free cryo-cooling
- UK-XFEL
- ISIS-II
- …
- Possible involvement in international projects (e.g. ILC, FCC…)

Conclusions

A significant progress since the programme started in 2014

1) Developing coating technology for **superconducting thin films**: an *ongoing systematic study* of correlation between deposition parameters and superconducting properties:

- Mastering Nb deposition *Ongoing*
- Development in non-Nb films: Nb_3Sn, NbTiN, V_3Si, Mg_2B… *Ongoing*
- Developing deposition targets for non-Nb films *Ongoing*
- Deposition of SIS structures (e.g. Nb_3Sn/AlN/Nb/Cu) *Ongoing*
- Thin film characterisation: SEM, FIB, XPS, XRD, AFM, RBS… *Ongoing*
- DC/AC superconductivity evaluation with *in-house* built and commercially available facilities *Ongoing*
- RF superconductivity evaluation with 7.8 GHz choked cavity test for planar samples *Ongoing*

2) Developing **cavity deposition** expertise

- Copper cavity production (incl. EB welding) *Looking for industry partners*
- Polishing and cleaning of copper cavities *In plans (industry or in-house)*
- Building and commissioning deposition facilities *Ongoing*
- Optimising deposition parameters for 1.3 and 6 GHz cavities *Ongoing*
- Plasma characterisation *In progress*
- Developing deposition targets *In progress*

3) **SRF testing** at DL

- 6 GHz split cavity low power testing *Ongoing*
- Full power testing facility for 1.3 GHz cavity *Nov. 2023*
- Scaling up to a routine cavity coating and testing *In plans - 2025*
- Multicell cavities *In plans - 2028*

4) **Applying TF-SRF cavities**

- UK projects: UK-XFEL and ISIS-II *In plans - 2025*
- International projects, for example: FCC *In plans – 20??*

Acknowledgments

- STFC/ASTeC:
  - R. Valizadeh, C. Benjamin, L. Smith, A. Hannah, T. Sean, J. Conlon, F. Goudket, S. Wilde, S. Pattalwar, N. Pattalwar, A. May, P. Smith, J. Wilson, K. Dumbel, …
- STFC/ISIS:
  - G. Stenning
- Liverpool University:
  - J. Bradley, V. Danak, S. Simon, F. Lockwood Estrin, F. Walk
- Lancaster University:
  - G. Burt, H. Marks, D. Turner, D. Seal, N. Leicester
- CEA:
  - C. Antoine, …
- CERN:
  - A. Sublet, W. Venturini, G. Vandoni, M. Taborelli, …
- IEE:
  - E. Seiler, R. Ries and F. Gömöry
- IJClab:
  - D. Longuevergne and O. Hryhorenko
- INFN
  - C. Pira, E. Chyhyrynets, …
- HZB:
  - O. Kugeler, S. Keckert, D. Tikhonov, …
- RTU
  - A. Medvids, P. Onufriev …
- Siegen University
  - M. Vogel, A. Zubtsovskii …
- …