Science and Technology Facilities Council

The Cockcroft Institute of Accelerator Science and Technology

School of Engineering | Lancaster University

Overview of the thin film SRF programme at Daresbury Laboratory

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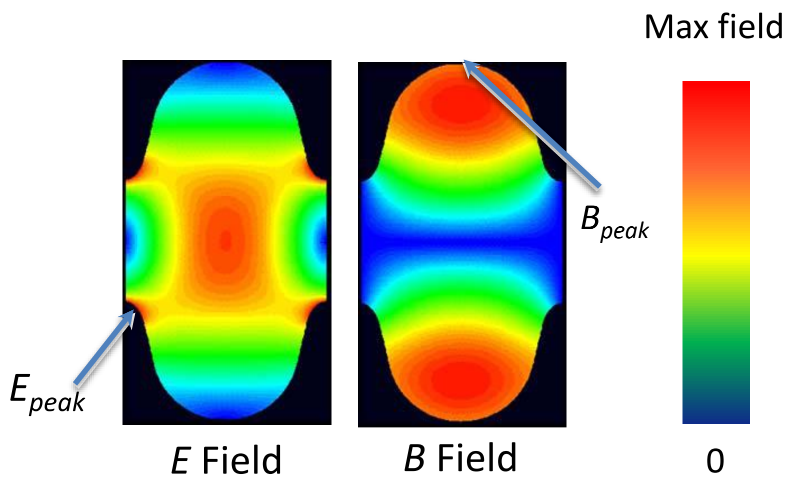
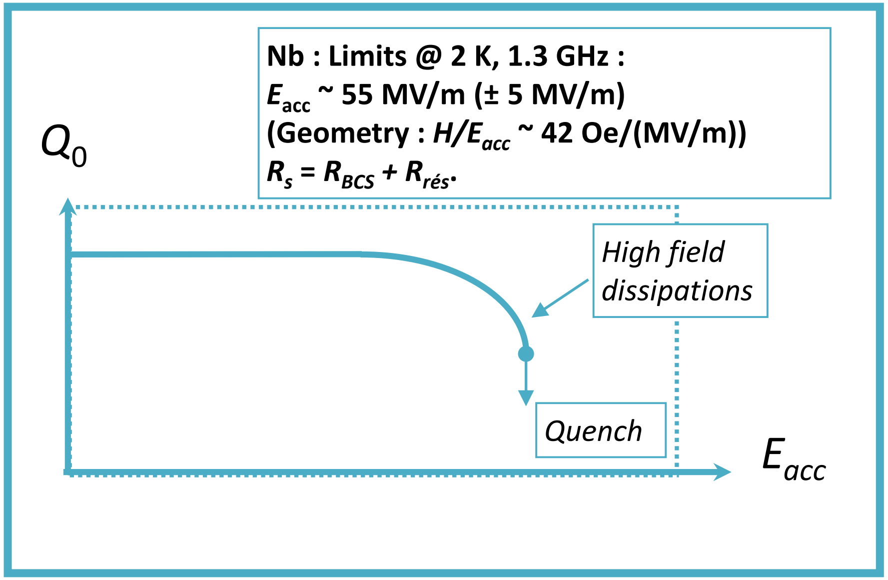
Bulk Nb SRF

- **Bulk Nb**
  - **Highest** T_c and H_{c1} of any element
  - **Large** Q_0 (10^{10}- 10^{11})
  - **CW operation**
- **Some figures of merit**
  - $E_{acc} \propto E_{peak} \propto B_{peak}$ - limitation = magnetic transition
  - $Q_0 \propto 1/R_S$ - limitation = thermal transition
  - Duty cycle (=> 100%) - limitation = cryogenic power
- **However,** bulk Nb cavities are close to reaching theoretical limits in E_{acc}!





Courtesy of C. Antoine (CEA)

From bulk Nb cavities to thin film cavities

- **Superconducting films coated on copper:**
  - Lower production costs!
  - Copper substrate → higher thermal conductivity than Nb
  - **Keeps the SRF properties of the film with the thermal properties of the bulk**

- **Main goals for thin film SRF:**
  - Improve accelerator performance - higher Q_0 and E_{acc}
  - Explore various high T_c materials (Nb_3Sn, V_3Si, NbN, NbTiN, MgB_2, and multilayer structures)
  - **Reduce cost:**
    - Copper vs bulk Nb
    - Lower cryogenic power consumption (increased Carnot efficiency at higher T)
    - Shorter accelerator structures – total cost reduction

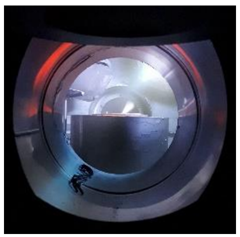
Superconducting thin film development

Key aim: Is there a correlation?

Surface preparation
- Cleaning, etching,
- Polishing, passivating

Thin film deposition
- **PVD**: DC, pulsed, HIPIMS…
- **Nb, NbN, Nb_3Sn**, MgB_2, etc.
- Laser treatment of Nb film

Film deposition

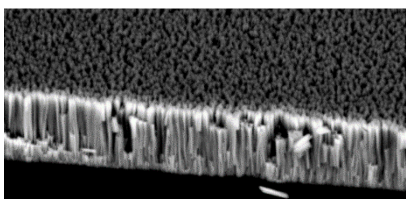


Film characterisation
- SEM, FIB, AFM,
- XPS, XRD, RBS, TEM…

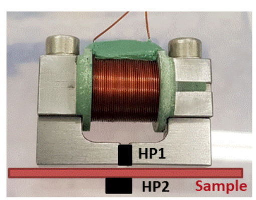
Superconducting properties measurement

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

SEM image of a NbN thin film

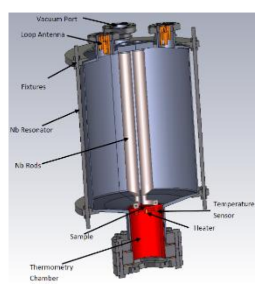


DC magnetisation

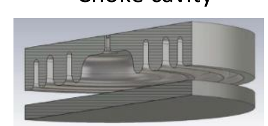


Superconducting RF properties evaluation
- QPR at CERN
- QPR at HZB
- Choke cavity at DL

QPR



Choke cavity



Mainly planar samples for easier analysis

Surface preparation → Thin film deposition → Film characterisation → Superconducting properties measurement → Superconducting RF properties evaluation

How is the substrate surface prepared?

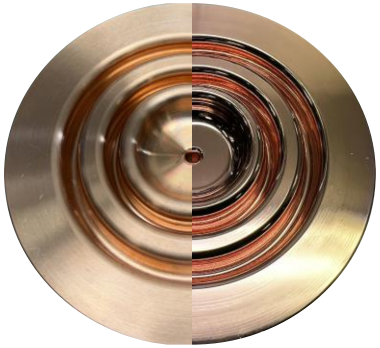
At Daresbury Laboratory

- Mechanical polishing

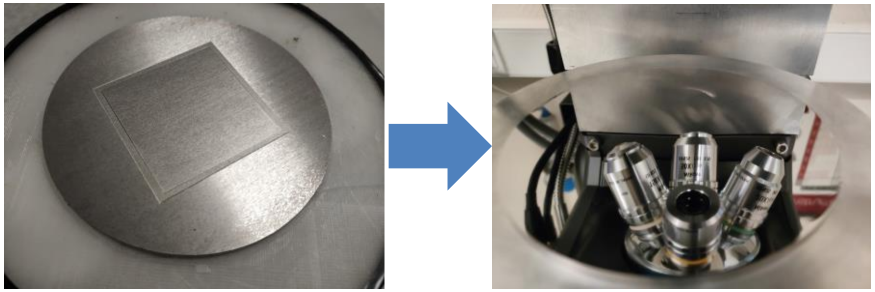
Elsewhere

- Fine mechanical polishing
  - tumbling
  - diamond turning
  - Metallographic
- Chemical polishing:
  - SUBU5 solution
  - Electropolishing (EP)
- Laser polishing for pre- and post-treatment (new technology!)
- Combination of different techniques

Would like to develop these at DL



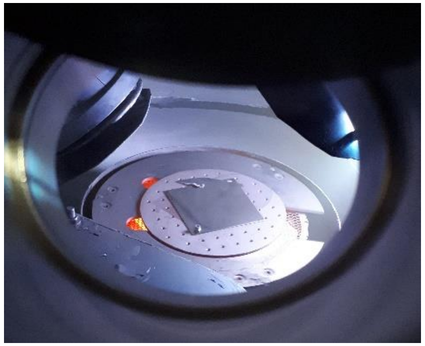
SUBU5 polishing at INFN courtesy of E.Chyhyrynets, C. Pira



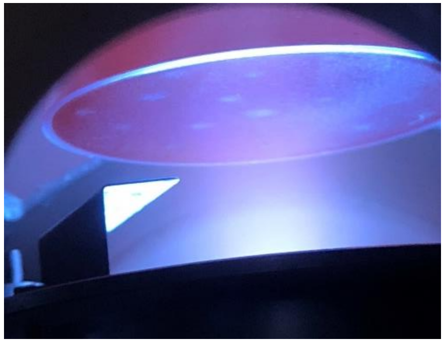
Metallographic polishing at IJCLab courtesy of O. Hryhorenko

How is a thin film developed?

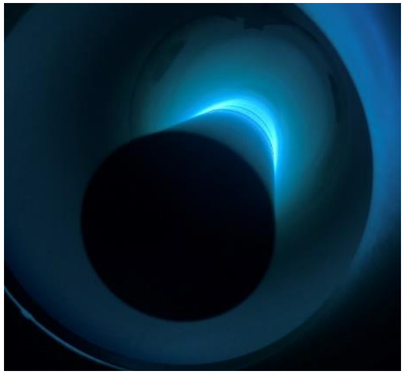
- **Techniques:**
  - **Physical Vapour Deposition (PVD)** - DC, pulsed, High-power impulse magnetron (HIPIMS)…
  - **Chemical Vapour Deposition (CVD)**
  - Plasma-enhanced CVD (PECVD), plasma-enhanced Atomic Layer Deposition (PEALD) – under development
  - Combined: PCVD
- **Materials:**
  - **Nb**
  - **NbN, Nb_3Sn**, NbTiN, V_3Sn, MgB_2, etc.
  - Multilayer structures
- **Deposition facilities at DL**
  - For planar samples
  - For Quadrupole Resonator (QPR) samples
  - For cavities



A planar sample during the Nb deposition



A QPR sample during Nb TF deposition

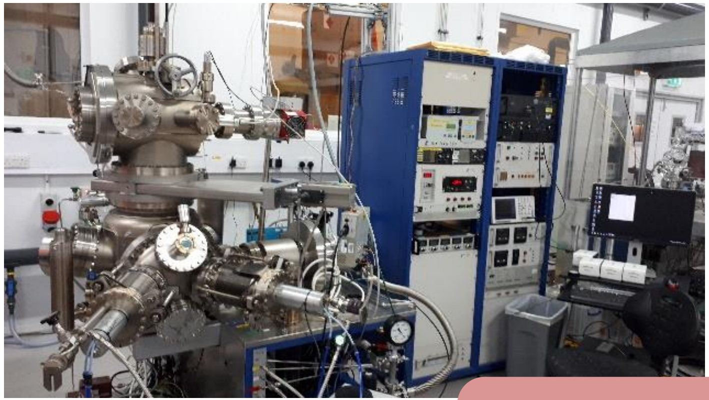


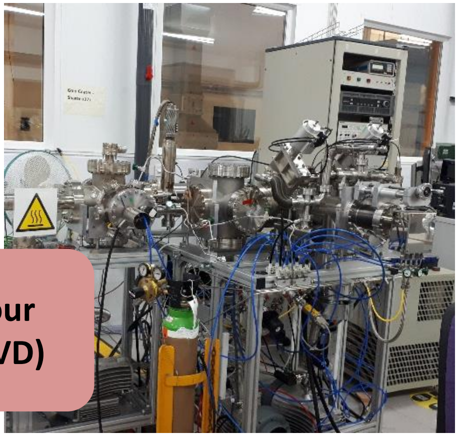
Cavity prototype deposition

Courtesy of R. Valizadeh (STFC)

Surface preparation → **Thin film deposition** → Film characterisation → Superconducting properties measurement → Superconducting RF properties evaluation

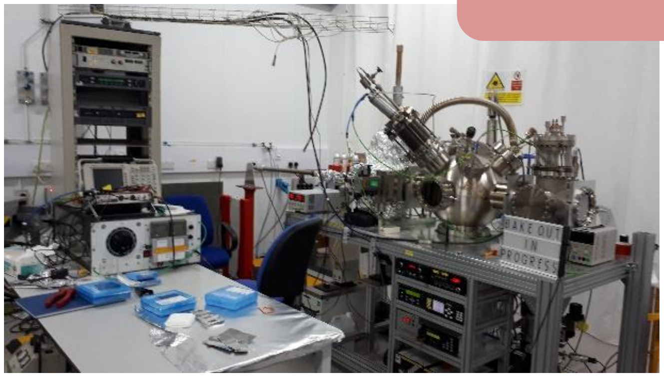
VISTA Laboratory





Physical Vapour Deposition (PVD)

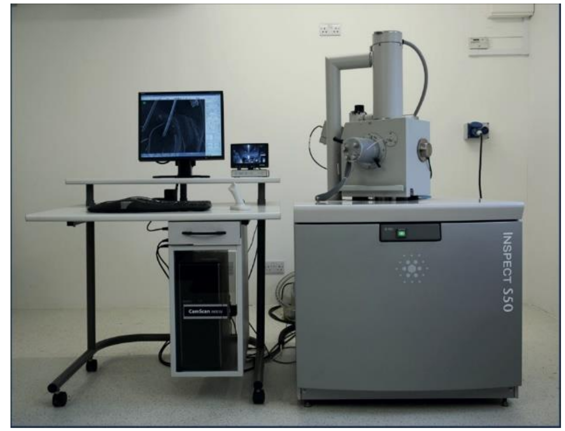
Hybrid Physical Chemical Vapour Deposition (HPCVD)



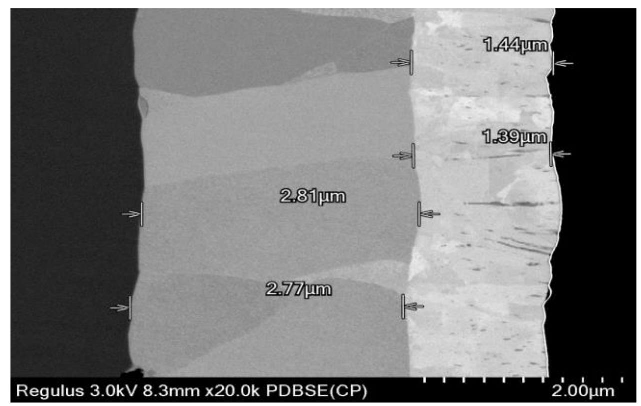
Chemical Vapour Deposition (CVD)

How are films characterised?

- **Films are sensitive to defects**
- **A wide range of techniques:**
  - Scanning Electron microscope (SEM)
  - Focused Ion Beam (FIB)
  - Atomic Force Microscope (AFM)
  - X-ray Photoelectron Spectroscopy (XPS)
  - X-ray Diffraction (XRD)
  - Rutherford Backscattering Spectrometry (RBS)
  - Transmission Electron Microscopy (TEM)
  - Energy-Dispersive X-Ray Spectroscopy (EDX)



FEI inspect S50 SEM

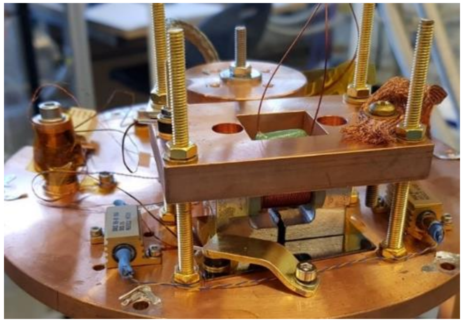


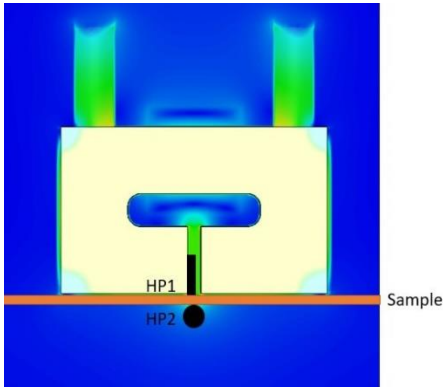
X-section SEM of Nb_3Sn with a Nb underlayer as double structure on Cu

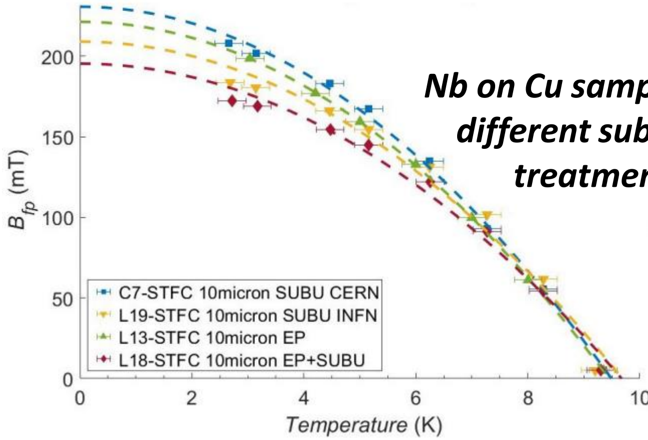
Courtesy of R. Valizadeh (STFC)

Magnetic field Penetration

- **Similar to cavity conditions:**
  - DC magnetic field parallel to surface
  - Field only from one side of sample
- **Field local to the sample surface:**
  - Avoid edge effect
  - Allow possibility of sample scanning
  - Applied and penetrated fields measured by Hall probe sensors
- **Facility is easy to operate:**
  - **T_{min} = 2.5 K, B_{max} ~ 612 mT**
  - LHe free system
  - Data acquisition fully automated
  - Field of full flux penetration, B_{fp} *vs T*







Nb on Cu samples with different substrate treatments

Courtesy of D. Turner (DL/Lancaster)

See D. Turner et al. 2022. A facility for the characterisation of planar multilayer structures with preliminary niobium results. Superconductor Science and Technology.

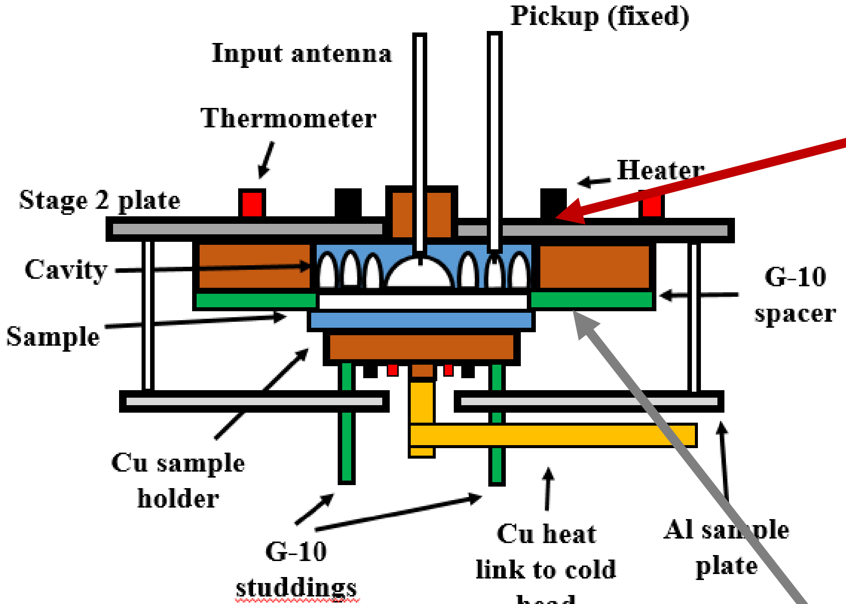
RRR and T_c

- Residual-resistance ratio is essentially a measure of material purity,

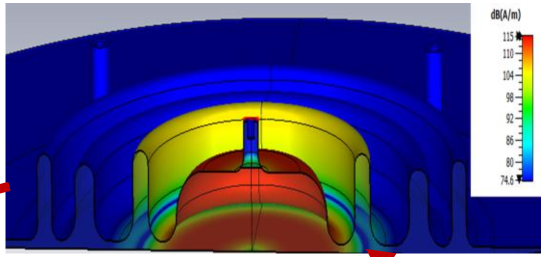
$$RRR = \frac{\rho(300\text{K})}{\rho(T \gtrsim T_C)}$$

- Check if material is superconducting and measure T_c
- Variable temperature inserts:
  - LHe-free cryostat
  - Individual vacuum tubes filled with He gas
  - Multiple sample tests/day

RF Evaluation



Bulk Nb 3 Choke Cavity



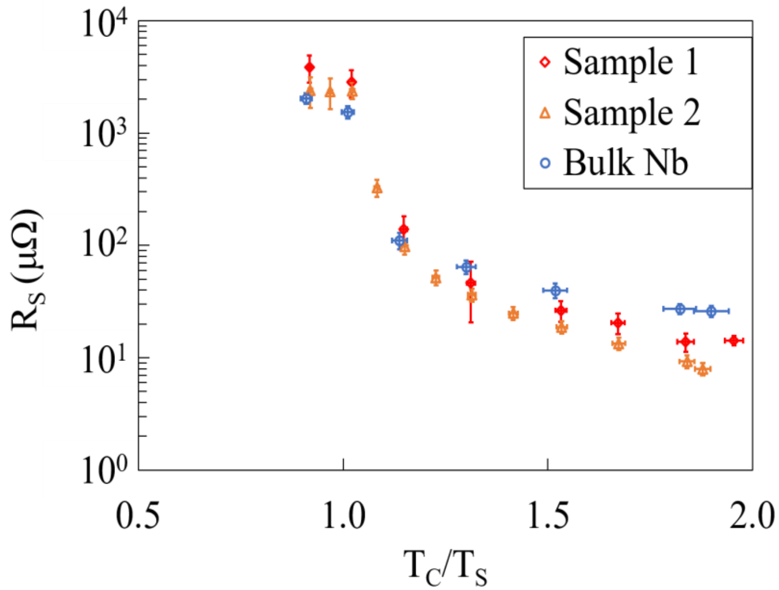
- **No physical welding** between cavity and sample required!
- Direct measurements of sample R_s

An **RF choke** is designed to reflect the cavity's fundamental mode frequency back into the cavity

Surface preparation → Thin film deposition → Film characterisation → Superconducting properties measurement → Superconducting RF properties evaluation

- Low power measurements of $R_s(T,B)$, of flat samples **90 – 110 mm** diameter
- **Parameters:**
  - Frequency = 7.8 GHz
  - Sample temperatures, T_S > 4 K
  - *B*-fields ≤ 0.8 mT
  - RF power ≤ 1 W

- Simple to operate and change sample (1 PhD student!)
- Simple sample design (low cost)
- LHe-free system
- ~ **2-3 sample tests per week** (fast turnaround)



More details in poster

Commissioning with bulk Nb (no treatment yet!) and Nb on Cu samples

What next?

Surface preparation

Thin film deposition

Film characterisation

Superconducting properties measurement

Superconducting RF properties evaluation

Ultimate Goal: produce a 1.3 GHz thin film coated cavity

Real cavity measurement

6 GHz split-cavity

1.3 GHz cavity

Conclusions

- Significant progress since the programme started in 2014
- An ongoing systematic study of correlation between deposition parameters and superconducting properties:
  - Small sample depositions, characterisation and testing
  - Mastering Nb deposition
  - Development in non-Nb films, e.g. Nb_3Sn, NbTiN, Mg_2B, …
  - Depositing multilayer structures, e.g. Cu-Nb-AlN-Nb_3Sn
- Ultimate goal: beyond Nb coated cavity:
  - 6 GHz split cavity tests
  - Develop a 1.3 GHz deposition and RF testing facility

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Thank you for listening

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