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Thin Film Superconducting Cavities For Sustainable Accelerators

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The Cockcroft Institute
of Accelerator Science and Technology

Lancaster University

UNIVERSITY OF LIVERPOOL

iFAST

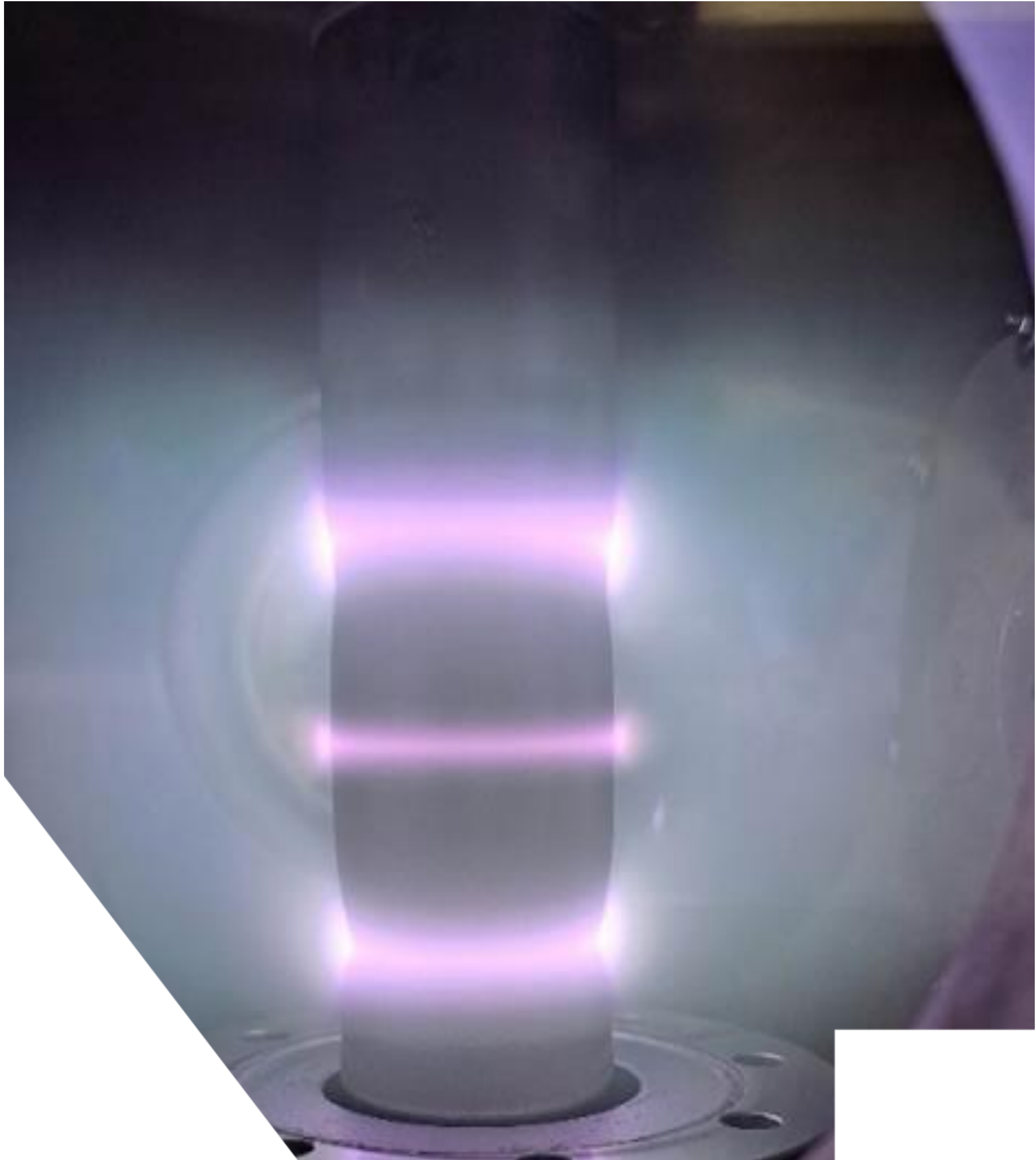
Agenda

1. Our Goal

2. Thin Film Development

3. Thin Film Testing

4. Future



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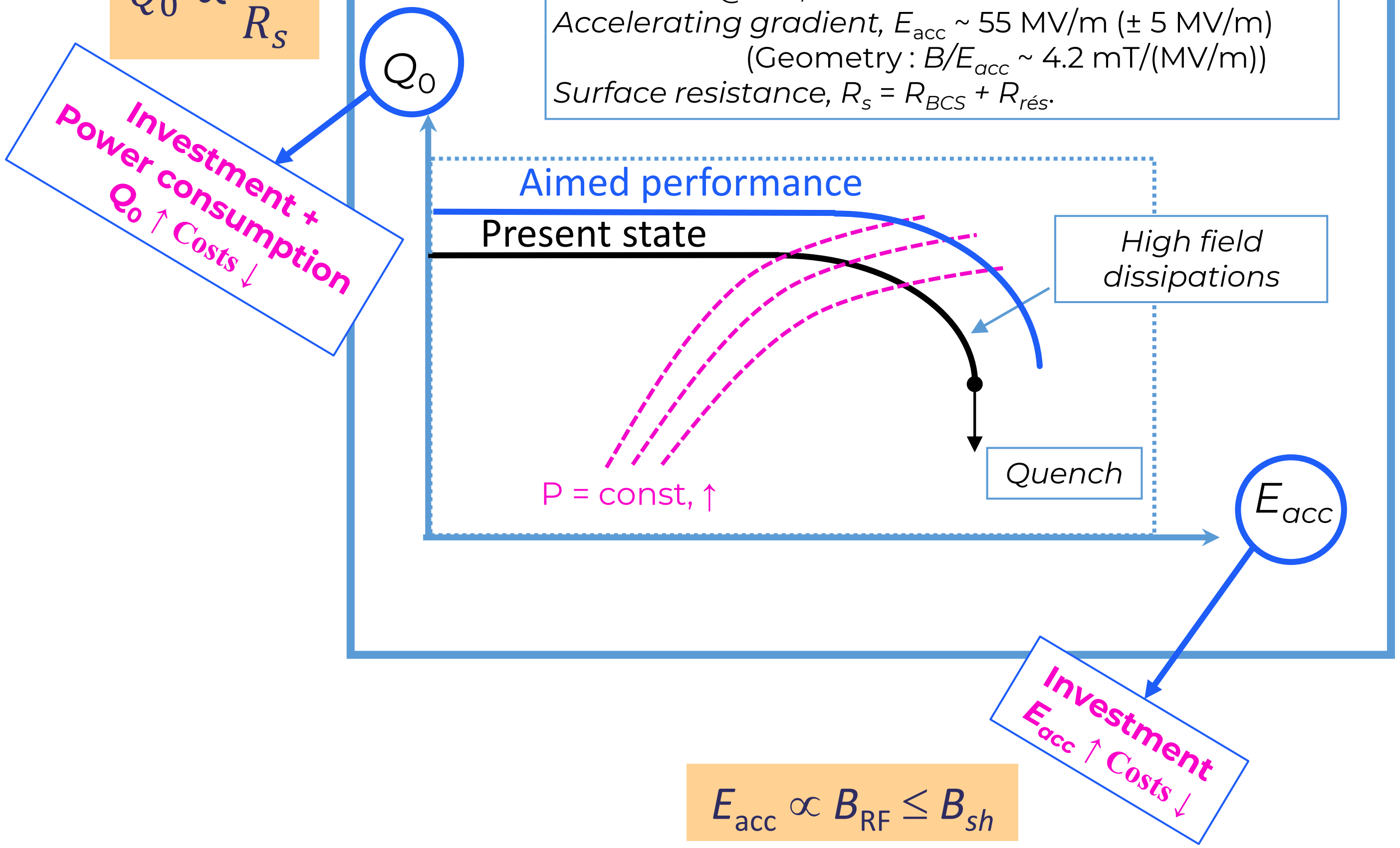
1. Our Goal

Bulk Nb Dominates SRF

- **Bulk Nb**
  - Highest T_c, B_{c1}, B_{sh} of any element
  - Large Q_0 (10^{10}- 10^{11})
  - CW operation

Bulk Nb has reached limits:
$Q_0 > 10^{10}$
$E_{acc} > 50$ MV/m
(1.3 GHz, 2 K)

$$Q_0 \propto \frac{1}{R_s}$$

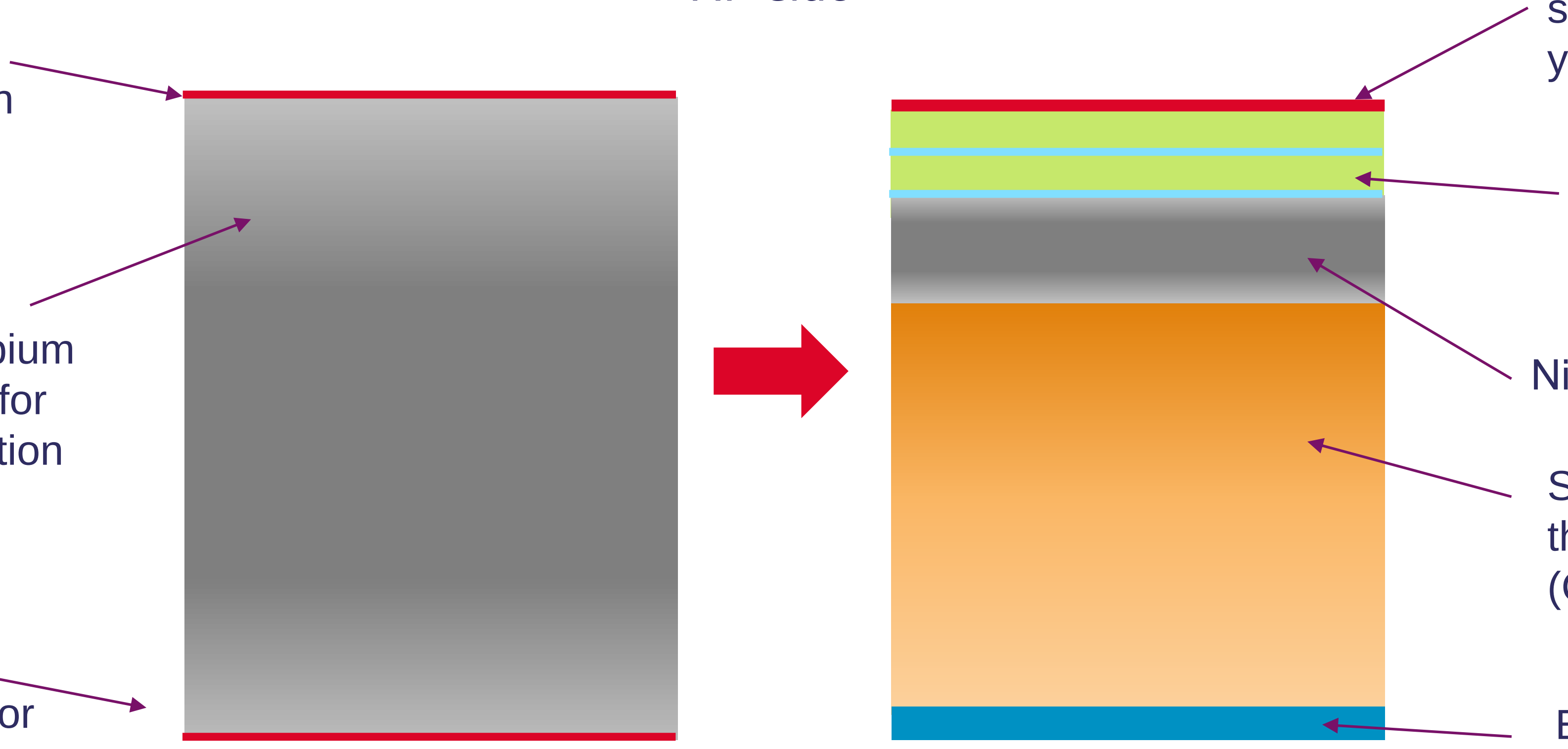


Nb : Limits @ 2 K, 1.3 GHz :
Accelerating gradient, E_{acc} ~ 55 MV/m (± 5 MV/m)
(Geometry : B/E_{acc} ~ 4.2 mT/(MV/m))
Surface resistance, $R_s = R_{BCS} + R_{rés}$.

$$E_{acc} \propto B_{RF} \leq B_{sh}$$

Courtesy of C. Antoine (CEA)

From Bulk Nb To Thin Films



Today

RF side

Future ?

Native oxide

Unstable upon annealing

High purity Niobium
Optimized only for thermal conduction

Native oxide

Not optimized for thermal transfer

Protection, low secondary emission yield

High T_c SC

S-I-S multilayers

Niobium or…

Structure, high thermal conductivity (Copper ?)

External layer, optimized for thermal transfer

Helium side

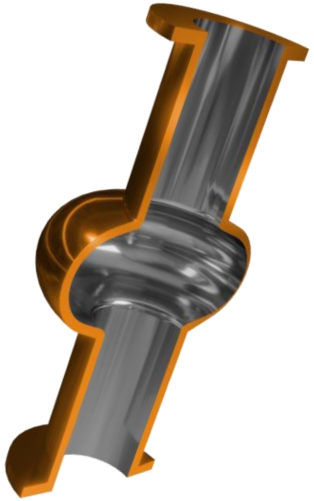
Courtesy of C. Antoine (CEA)

Superconductors Being Considered

Material	T_c (K)	B_{sh} (mT)@ 0 K
Pb	7.1	100
Nb	9.2	219
NbTiN	17.3	439
V_3Si	17.0	490
NbN	17.3	214
Nb_3Sn	18.3	425
Nb_3Al	18.5-19.1	
MgB_2	39.0	170

Courtesy of C. Antoine (CEA)

High B_{sh} → High E_{acc} → fewer cavities



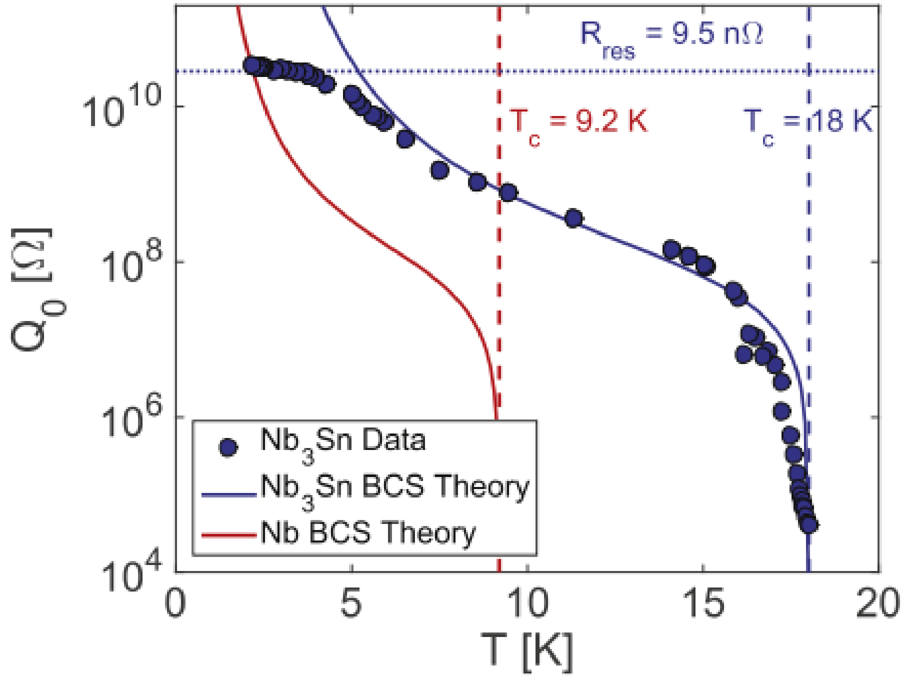
Why thin film on copper?

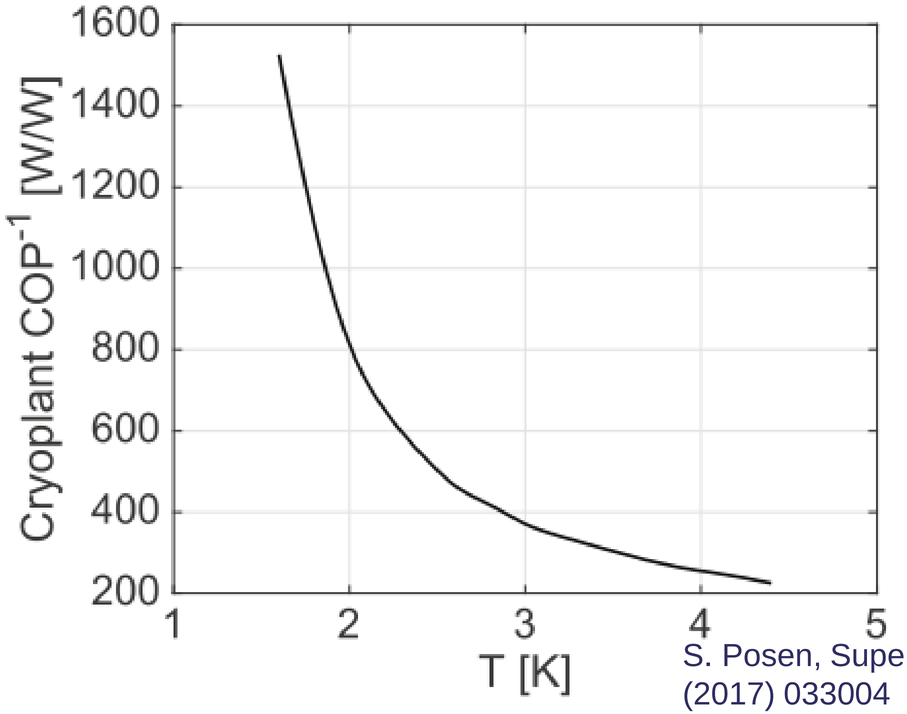
- Cheaper than Nb
- Higher thermal conductivity
- Easily machinable

High T_c → High Q_0 → less cooling

Saving Energy For Future Accelerators

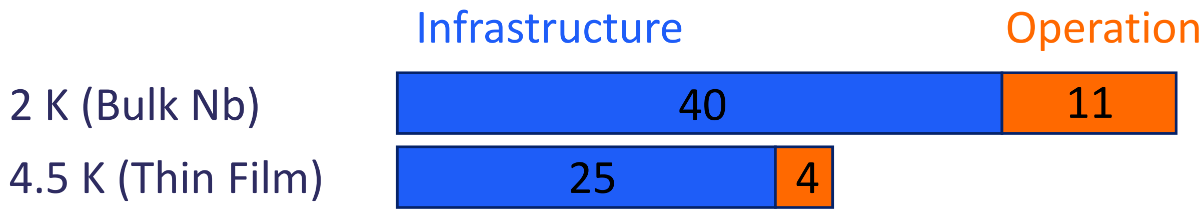
Moving from 2 K to 4.5 K reduces cryogenic power by factor 3!





S. Posen, Supercond. Sci. Technol. 30 (2017) 033004

Estimated cryogenic costs of ESS (M€):



C. Z Antoine: IPAC2023

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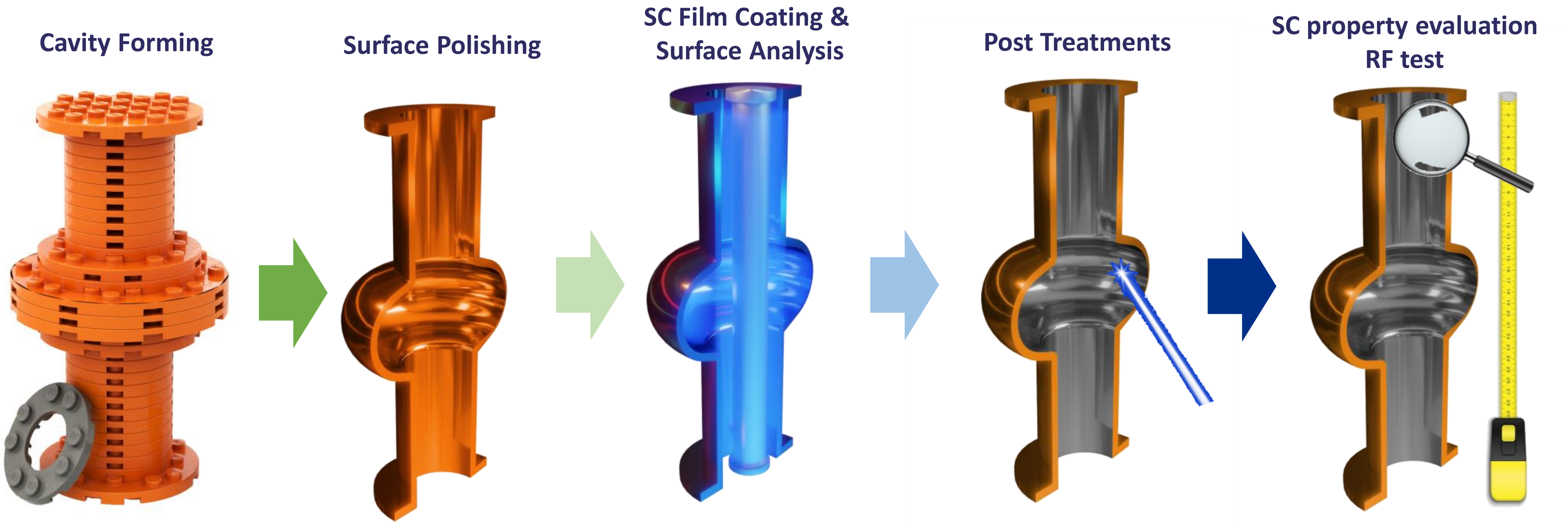
2. Thin Film Development

Thin Film Pathway

Initial testing on planar samples



Cavity Forming

Surface Polishing

SC Film Coating & Surface Analysis

Post Treatments

SC property evaluation RF test

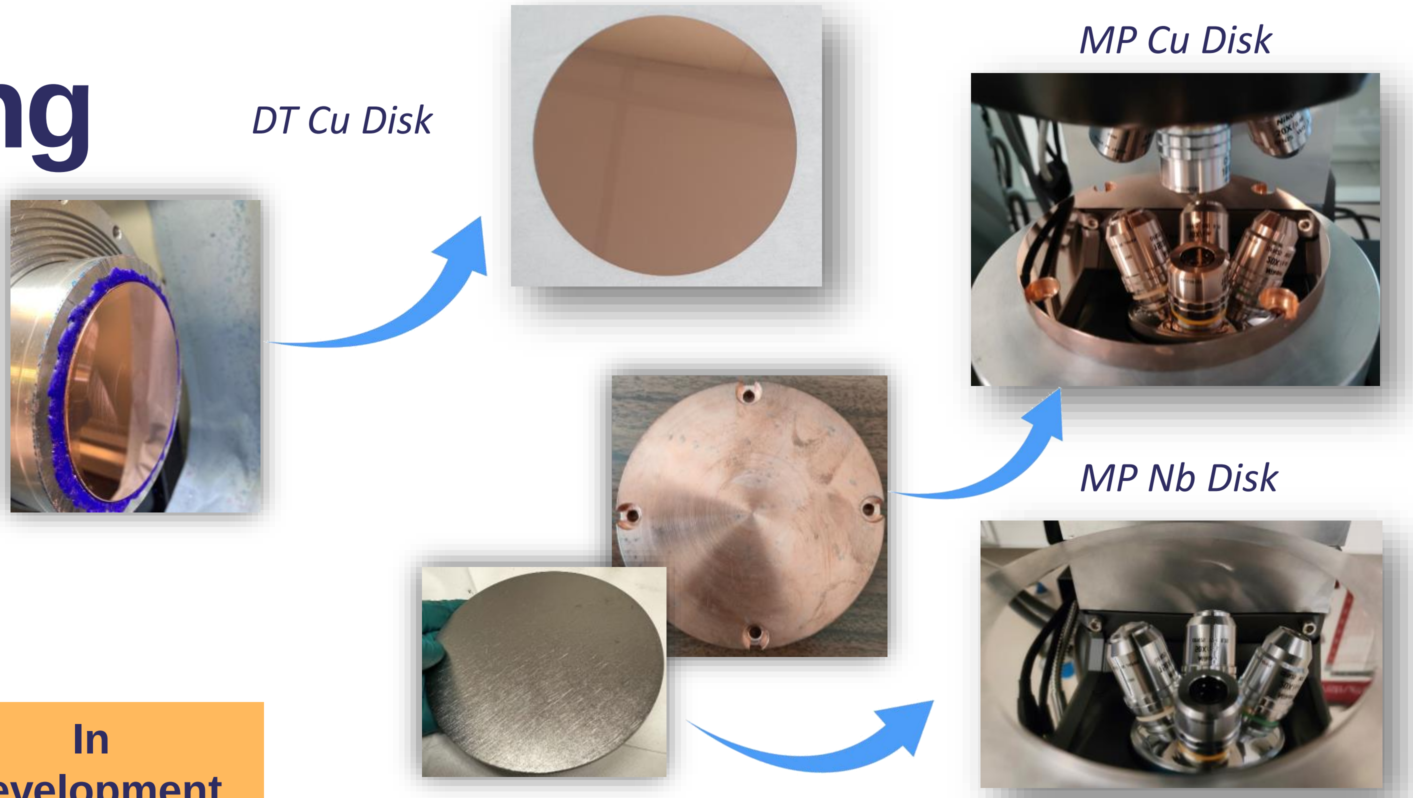
Aim: Produce a prototype, high performance 1.3 GHz thin film SRF elliptical cavity $Q_0 > 10^{10}$ @ 4.5 K

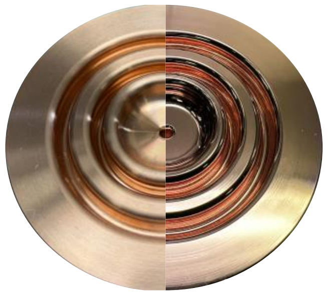
Surface Polishing

- **At STFC:**
  - Some mechanical polishing
  - Diamond turning (DT)
- **IFAST Partners:**
  - Mechanical polishing;
    - Tumbling
    - Metallographic (MP)
  - Chemical polishing
    - SUBU
    - Electropolishing (EP)
    - Plasma Electrolytic Polishing (PEP)

In development at STFC

Green alternative





SUBU Cu Choke Cavity

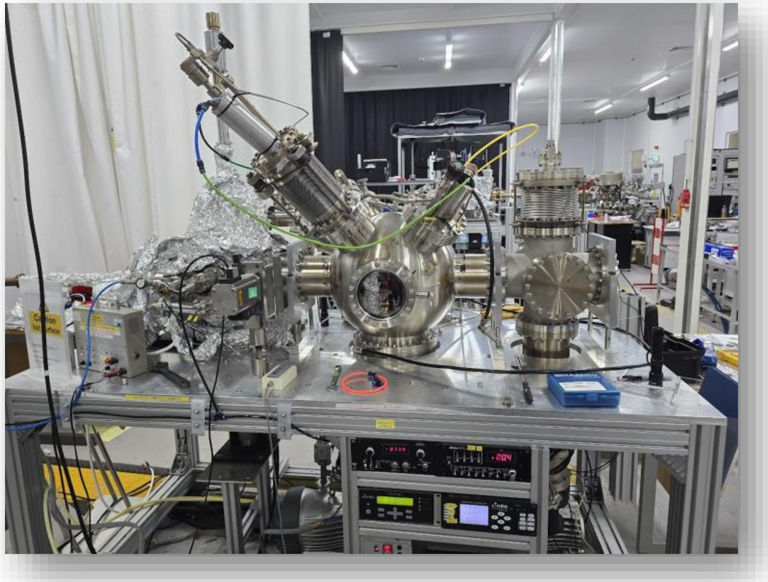
PEP Quadrupole Resonator (QPR)

PEP 6 GHz Cavity

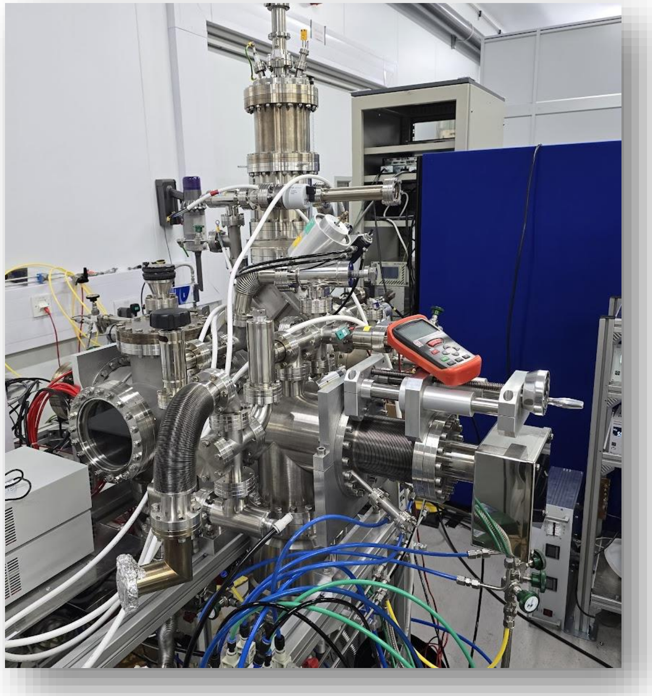
Courtesy of E. Chyhyrynets & C. Pira (INFN)

Thin Film Depositions - Planar Samples

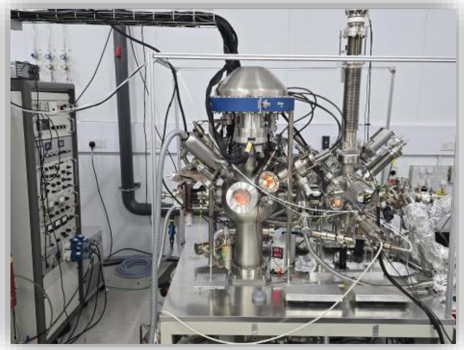
Planar samples provide a cost-effective pathway for thin film R&D



Sample disks for mass parameter optimisation



QPR samples for high RF field analysis



X-ray Photoelectron Spectroscopy

Secondary Ion Mass Spectrometry

Scanning Electron Microscopy

White Light Interferometry

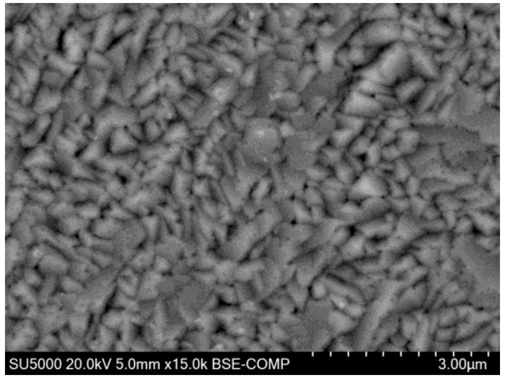
Thin Film Depositions - Planar Samples

Can Nb_3Sn sputtering match or exceed performance of Sn vapour diffusion into bulk Nb?

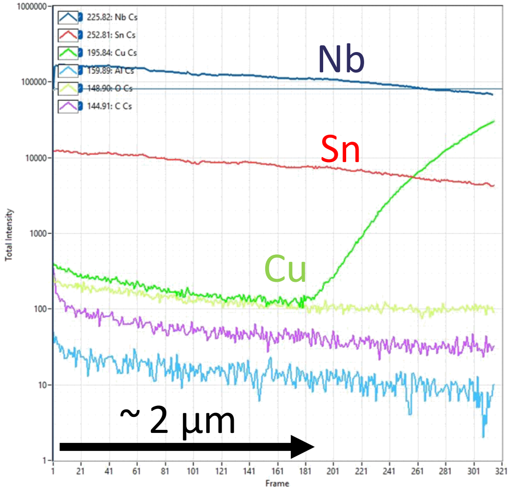
Nb_3Sn on 50-100 mm substrates

- Theoretical T_c = 18 K
- DC, HiPIMS
- Effect of magnetron power, deposition temperature

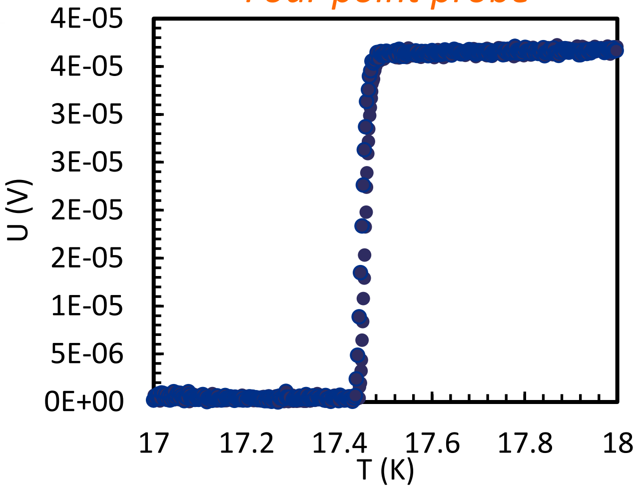
SEM – high grain density

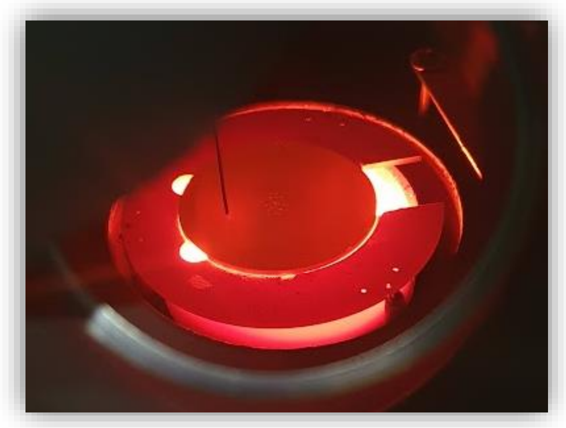


SIMS on 100 W HiPIMS

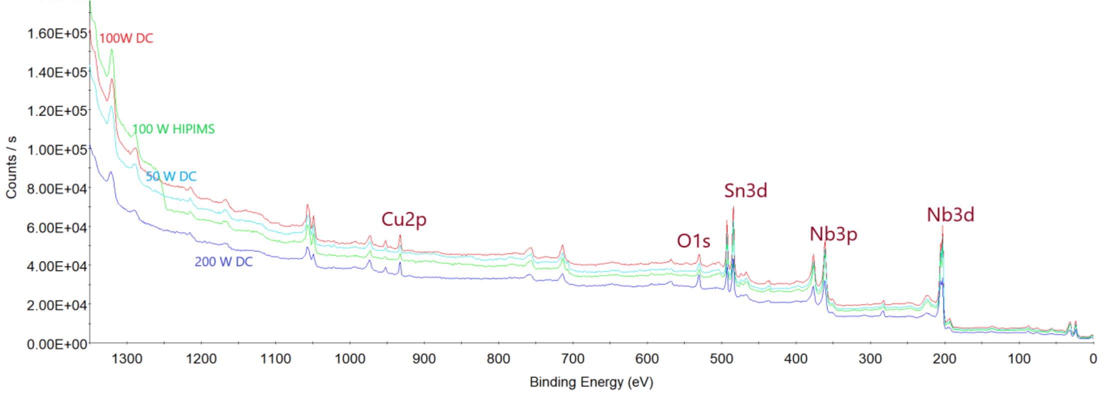


Four point probe

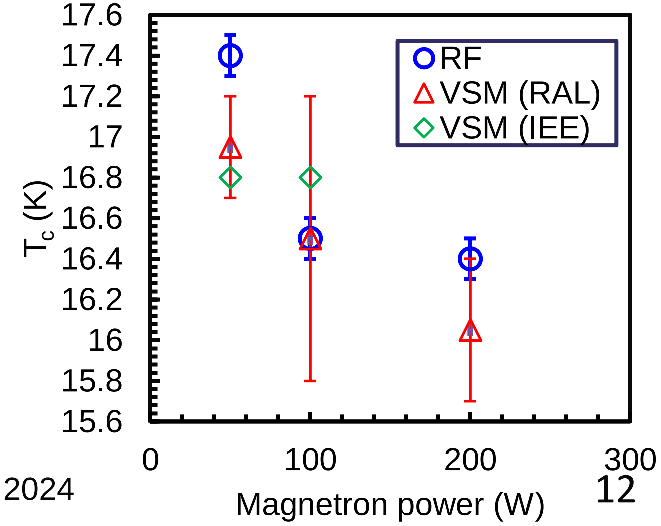


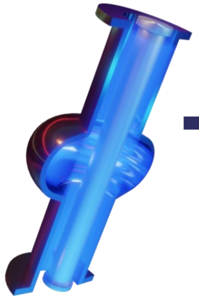


XPS comparison of Nb_3Sn/Cu (~ few nm depth)



Effect of DC magnetron power



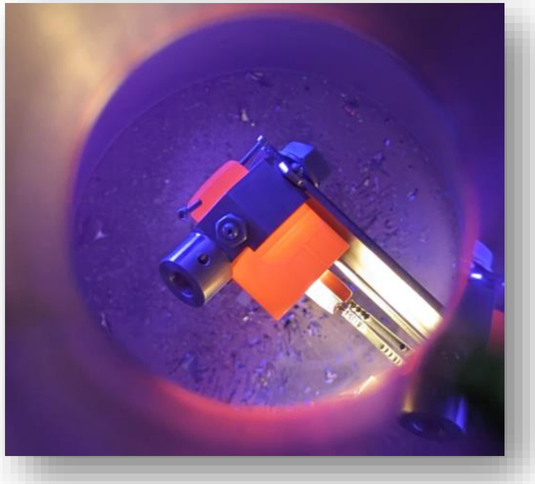


Thin Film Depositions - Planar Samples

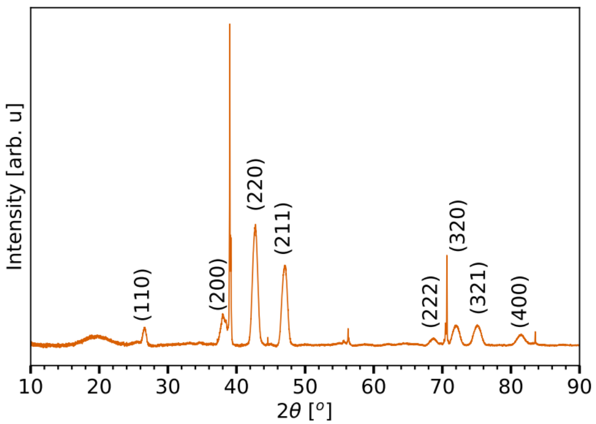
Is V_3Si a viable alternative material?

V_3Si on 10 mm substrates

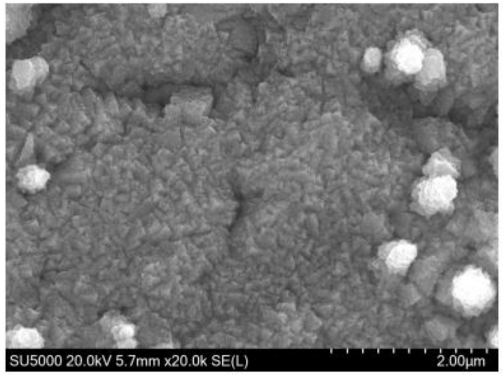
- Theoretical T_c = 17 K
- Initial steps to improve T_c and consistency of growth
- Post-annealing required – furness, laser, flash lamp



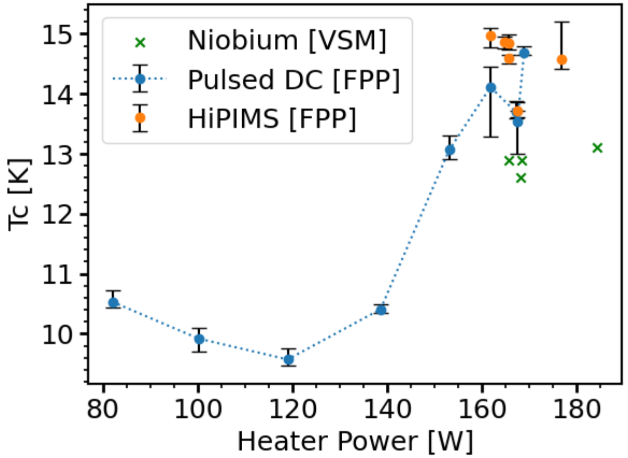
XRD V_3Si/Nb



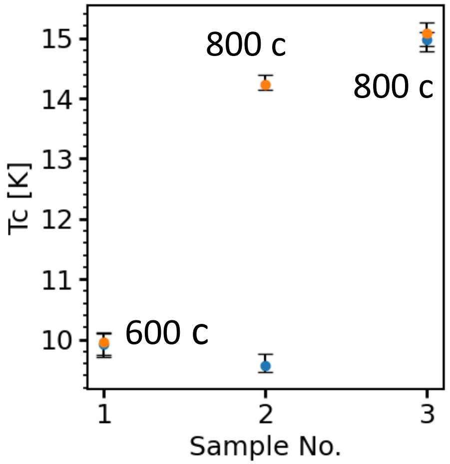
SEM – small crystallites



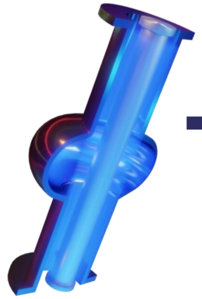
Effect of heater power on T_c



Effect of post-deposition annealing



C. Benjamin et al. V3Si: An alternative thin film material for superconducting RF cavities, IPAC 24



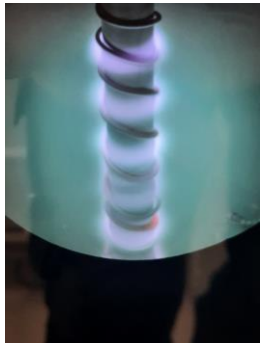
Thin Film Depositions – 6 GHz Cavities

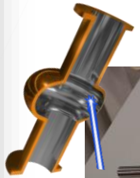
Are performances on flat geometries repeatable on curved geometries?

Closed Seamless Cavities

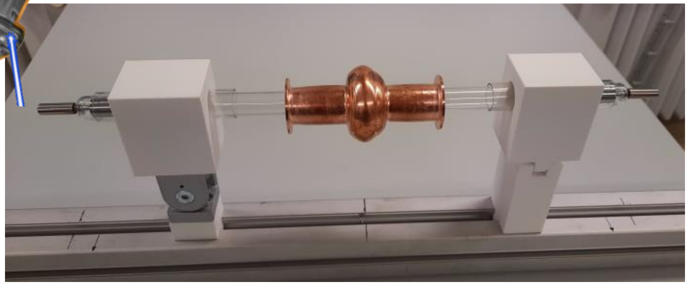
Deposition facility

Nb target with Ti wire





ms-Flash Lamp Annealing at HZDR



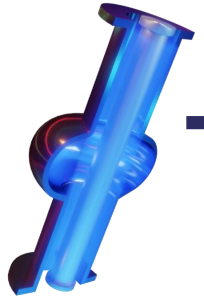
Courtesy of S. Prucnal & S. Zhou (HZDR)

Open Split Cavities

Planar magnetron

Cylindrical magnetron

Nb, NbTiN, Nb_3Sn, V_3Si



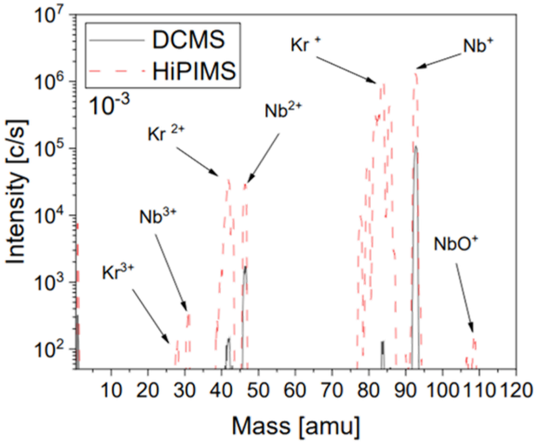
Thin Film Depositions – 1.3 GHz Cavities

Can we achieve uniform coatings on larger cavity structures?

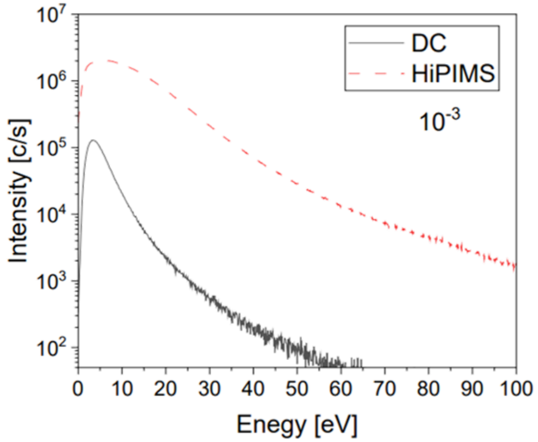
Optimising thin film deposition parameters

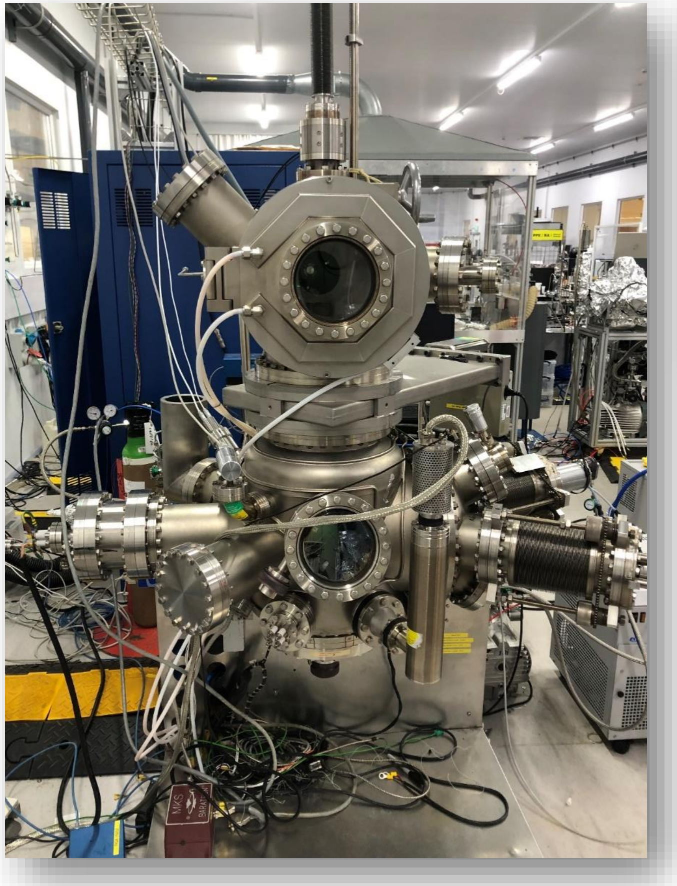
- Mainly Nb thin films so far
- Comparing deposition techniques (DCMS, HiPIMS)
- Plasma diagnostic studies

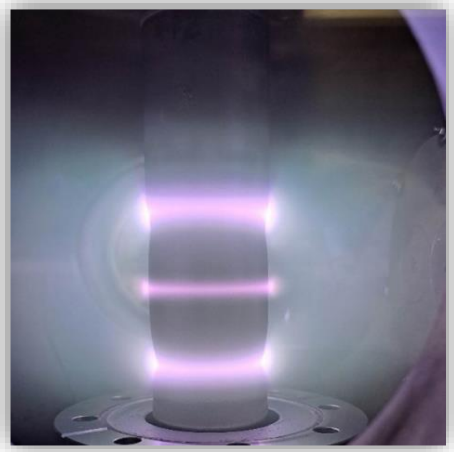
Mass scan at 10^{-3} mbar



Ion energy distribution function of Nb^{+} at 10^{-3} mbar







S. Simon et al. Tailoring the production of Nb superconducting films for SRF cavities: mass/energy spectroscopy and film characterisation, IPAC 24

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3. Thin Film Testing

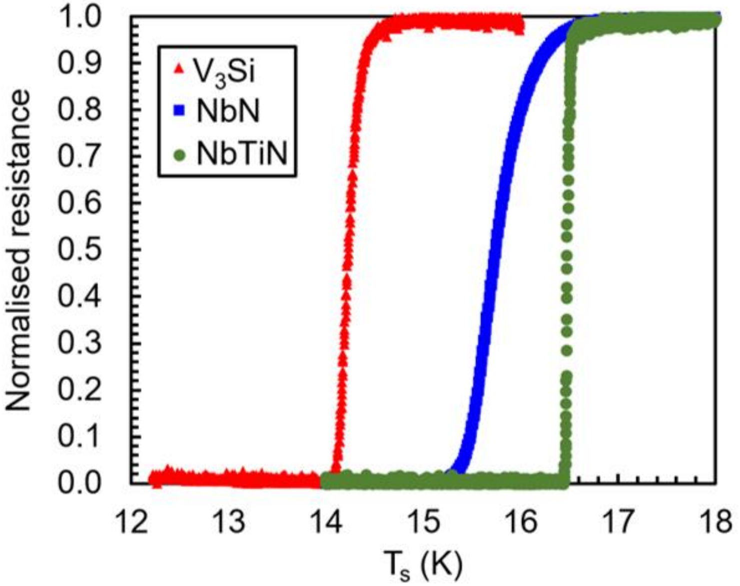
DC Superconducting Properties

Rapid sample tests with multiprobe inserts

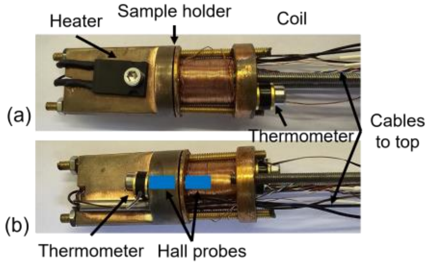
- Is the sample superconducting?
- What is its T_c?
- What is its behaviour under high magnetic fields?

20 tests per week!

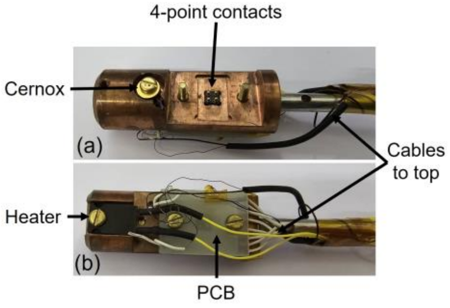
Four-point probe measurements with alternative materials



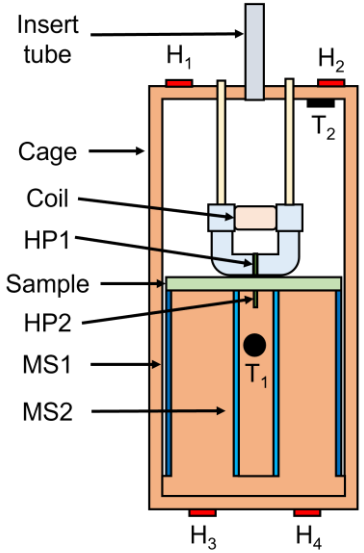
Magnetic T_c



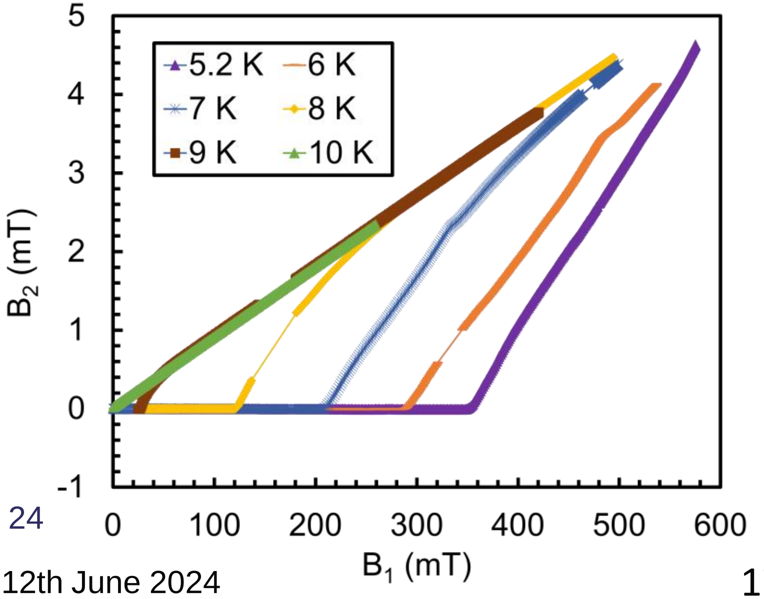
Four-point probe



Magnetic Field Penetration



Magnetic field penetration with Nb



D. Seal et al. Upgraded multiprobe sample inserts for thin film SRF cavity developments, IPAC 24

DC Magnetic Field Penetration

3 tests per week!

Is there a correlation between DC & RF performance?

Cavity-like DC fields applied:

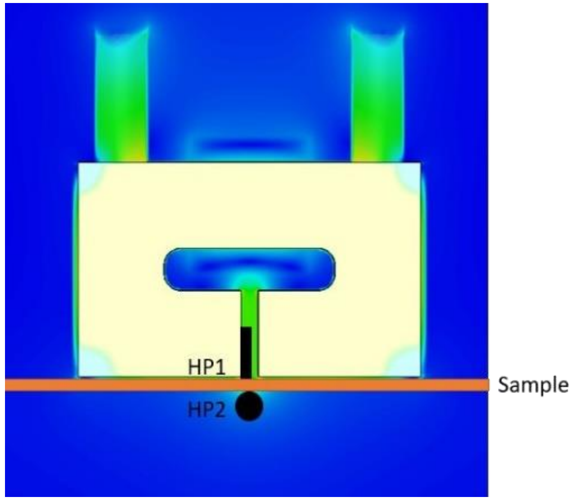
- Parallel
- From one side (unlike SQUID VSM)
- $B < 600$ mT

Recently upgraded facility:

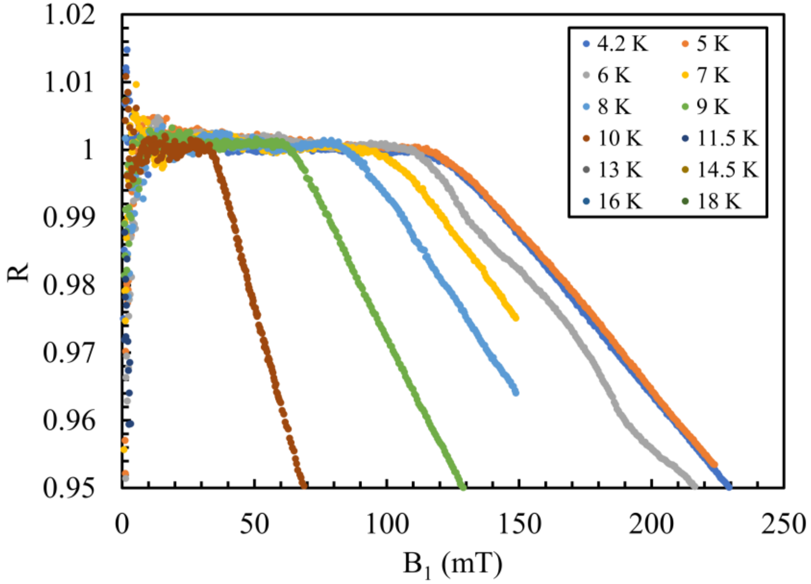
- Test 10 cm samples size and 6 GHz split cavities
- Magnetic shields
- Minimal damage to films

$$R = 1 - \frac{B_2}{B_1}$$

Meissner state when $R = 1$



V_3Si/Nb/Cu Sample



RF Test With Choke Cavity

Most importantly, how does the thin film perform under RF conditions?

7.8 GHz Choke Cavity

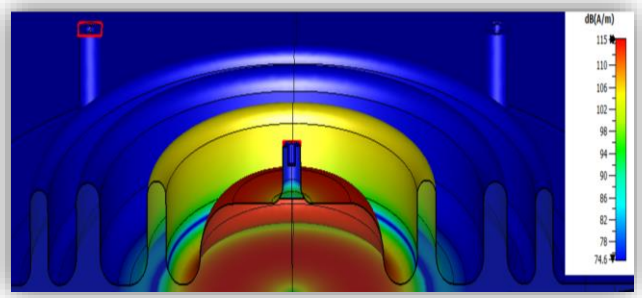
Low field measurements:

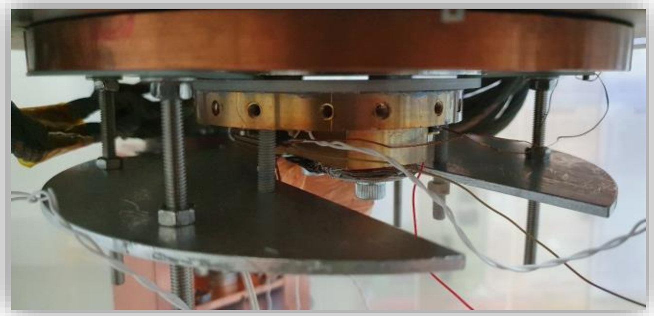
- *R_s* vs *$B_{\text{sample, pk}}$*
- *R_s* vs *T_{sample}*
- *Penetration depth* vs *T_{sample}*

Mass parameter optimisation prior to:

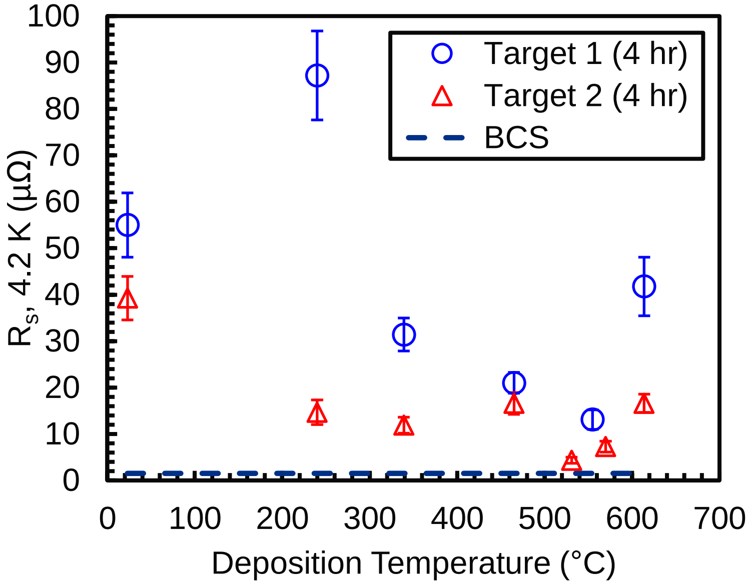
- High field/low frequency tests with QPR
- Cavity tests

3 tests per week!

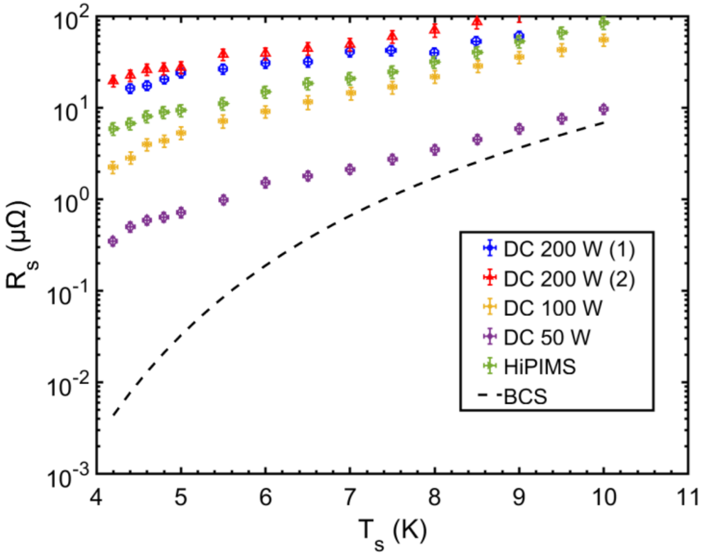




Effect of deposition temperature on Nb/Cu



Effect of magnetron power on Nb_3Sn/Cu



Low Power Cavity Testing

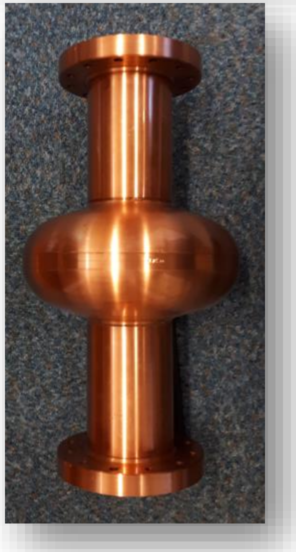
First tests autumn 2024!

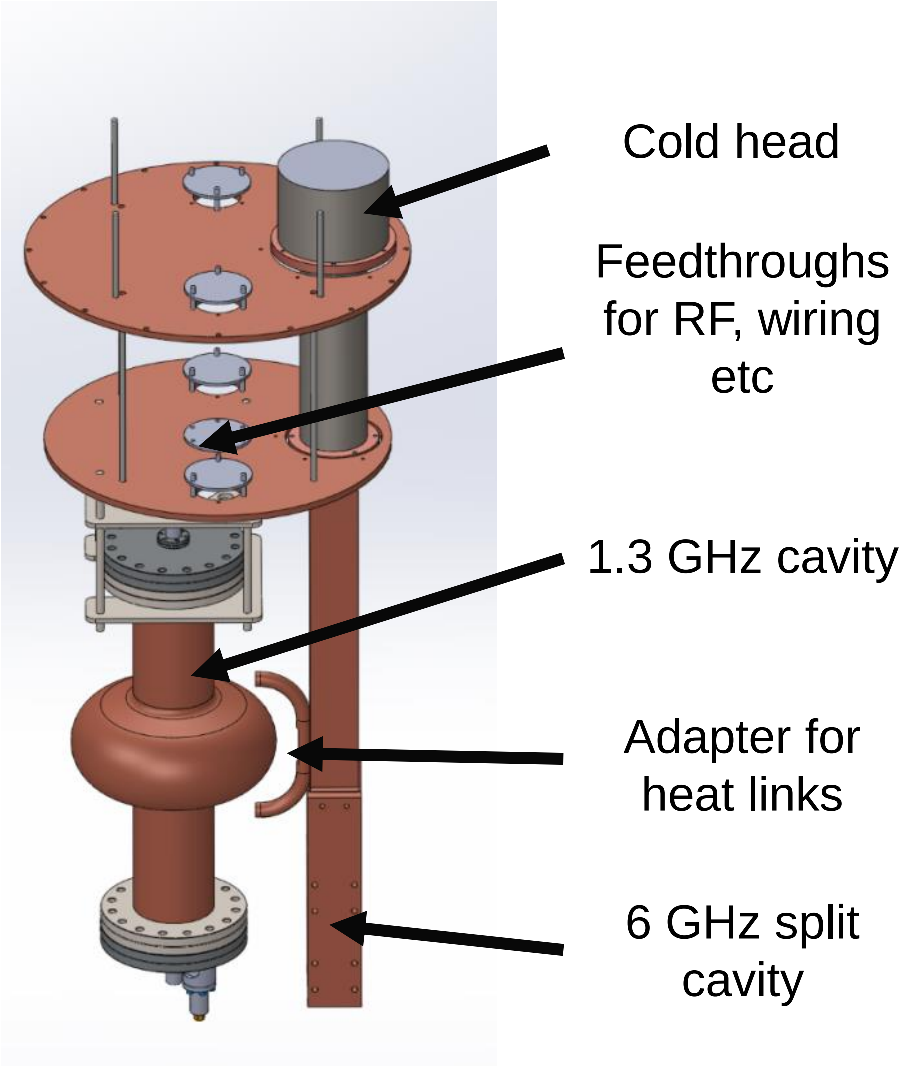
Cryocooler based facility

- $P < 2.5$ W, $T > 4$ K (est.)
- Quick first cavity test
- Good cavities will have high power test in LHe

4 types of cavity

- 1.3 GHz closed
- 1.3 GHz split (in development)
- 6 GHz closed
- 6 GHz split





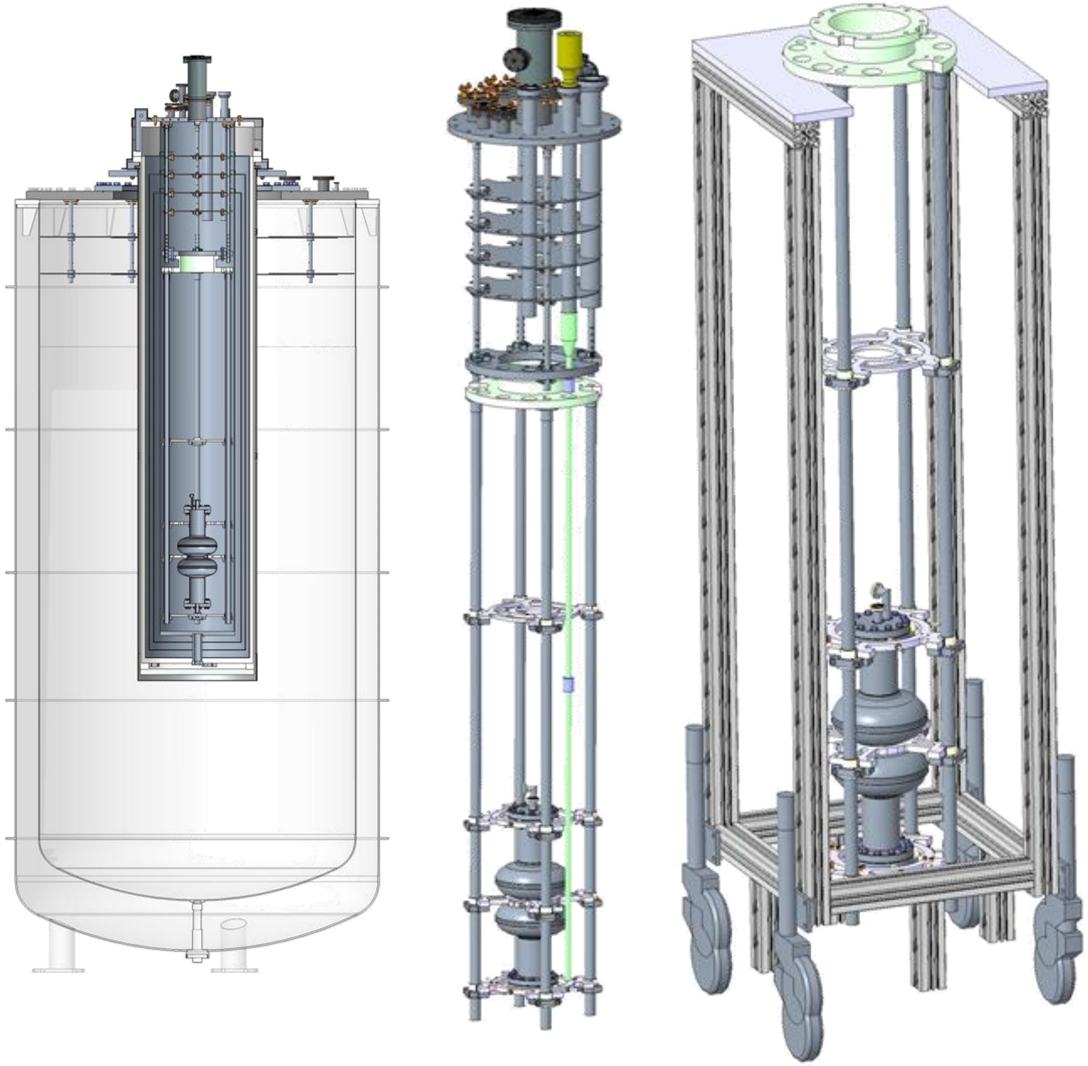
Courtesy of O. Poynton & J. Rigby

High Power Cavity Testing

First tests summer 2024!

- Full Q_0 vs E_{acc} test with LHe
- Testing with existing STFC/DL LHe infrastructure mainly used for ESS & PIP-II cavity tests
- **Upgrades now allow for:**
  - A RF single system for 650 MHz, 700 MHz and 1.3 GHz
  - $P \leq 200$ W, $T = 2$ K & 4.2 K
  - Capability for 9-cell tests

Existing SRF Test Facilities at Daresbury Laboratory



Courtesy of T. Sian & C. Hill

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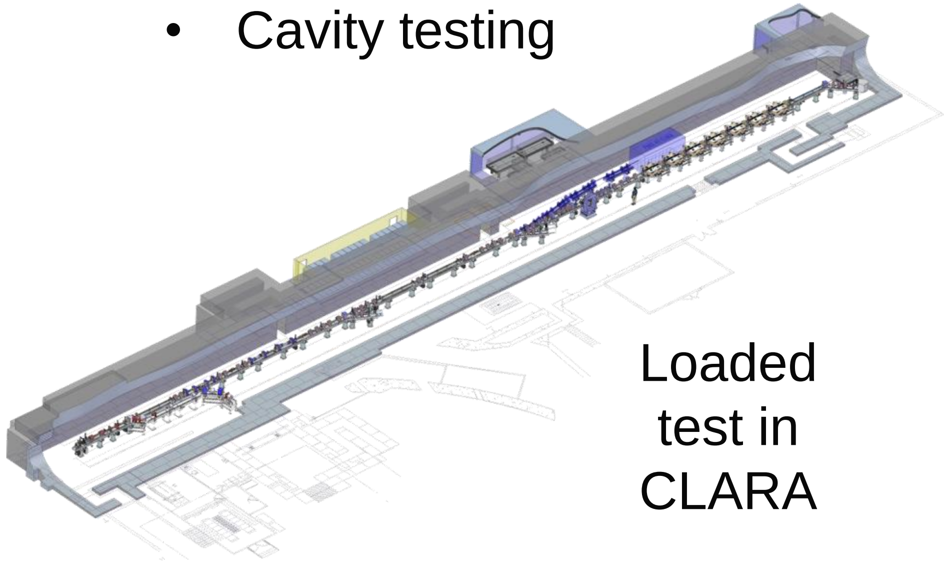
4. Future

The Future of Thin Film SRF in the UK

Reduce capital and running costs of accelerators!

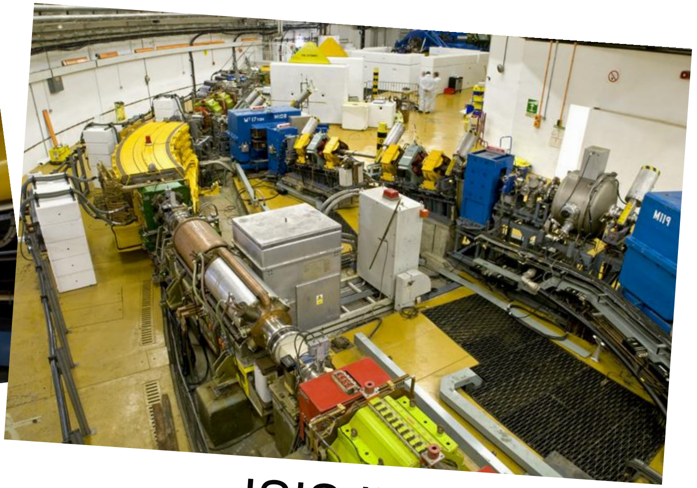
Continuing R&D

- Thin film coatings
- Post-processing
- Quick sample testing
- Split cavities
- Multi cells
- Cavity testing



Loaded test in CLARA

UK XFEL



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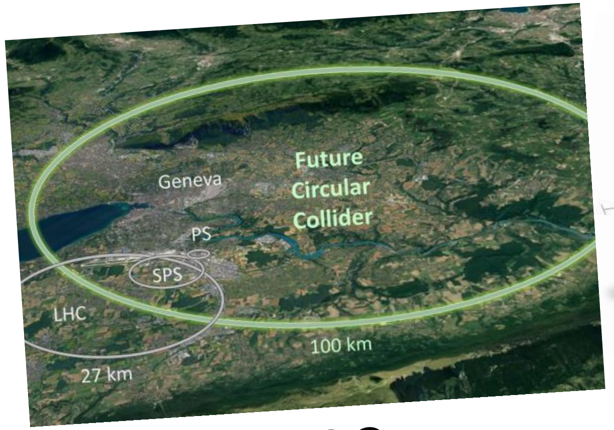

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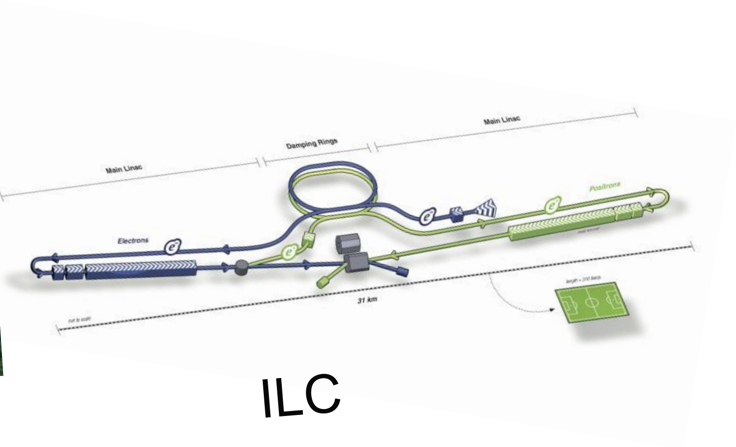

ILC

Acknowledgements

STFC/CI: O. B. Malyshev, R. Valizadeh, C. Benjamin, O. Poynton, J. Rigby, A. Akintola, T. Sian, L. Smith, J. Conlon, C. Benjamin, S. Pattalwar, G. Miller, A. Blackett-May, A. Vick, C. Hill, M. Pendleton, M. Jones, P. Smith, A. Wheelhouse, D. Mason

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University of Liverpool/CI: S. Simon, J. Bradley

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Thank you

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