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WP15 - Thin Film for Superconducting RF (TF-SRF)

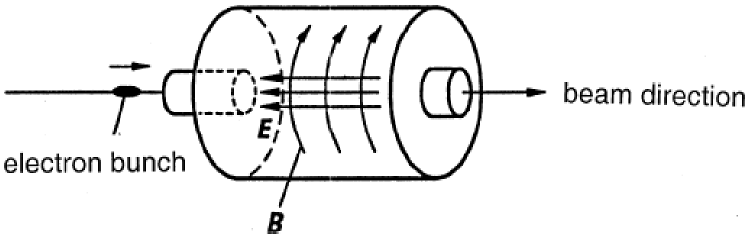
Oleg Malyshev
WP15 coordinator

ARIES Kick-Off Meeting , 4th May 2017, CERN, Geneva

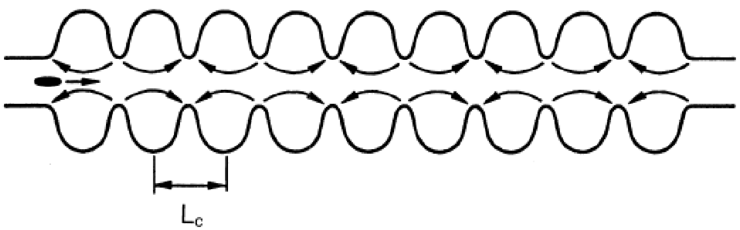
Superconducting RF cavity

RF cavities are designed to accelerate bunched particle beams in modern machines

Electric and magnetic field in a pillbox cavity for the accelerating mode TM010



Schematic cross section of a 9-cell cavity with electric field lines

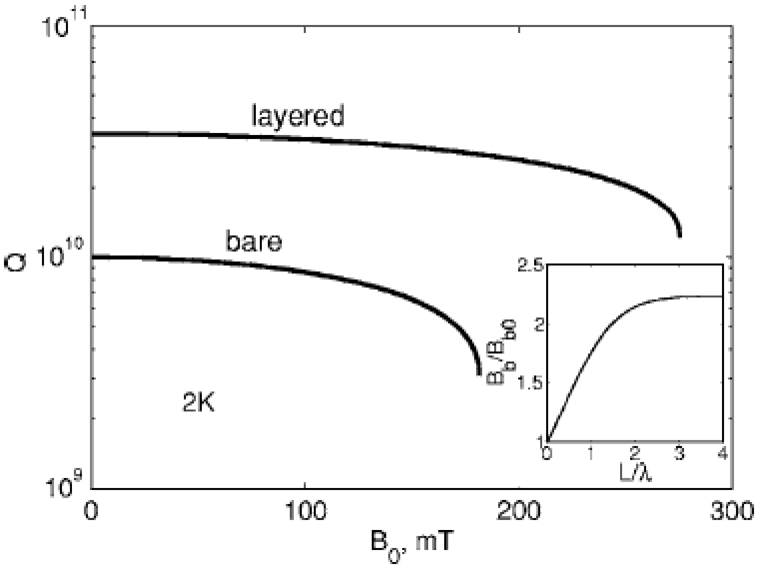


The quality factor Q_0 is an important parameter of a resonating cavity.

$$Q_0 = \frac{2\pi f_0 U}{P_{diss}} = \frac{f_0}{\Delta f}$$

- Nb bulk SC cavities perform near its theoretical limits
- The (low field) Q_0 affects an electricity cost for storage rings
- E_{max} is affects the cost of linacs
- Theory and experiments show the way to higher Q_0 and E_{max}
- Continuity to WP12 in EUCARD2

Quality factor of superconducting RF cavity as a function of B (or E)



A. Gurevich, Appl. Phys. Lett. **88**, 012511 2006

WP Description

- The aim of this work package is to intensify systematic studies and development of the coating technology of superconducting materials to enable the superconducting coated RF cavities with Q(E) characteristics better than for the bulk ones.
- The main emphasis will be on a systematic study of correlation between
  - surface preparation,
  - deposition parameters,
  - film structure, morphology, chemistry
  - as well as AC and DC superconductivity parameters
    - such as T_c, H_c, H_{fp}, H_{sh}, RRR
    - of superconducting material Nb, NbN, Nb_3Sn, MgB_2, etc.
    - deposited on copper and bulk Nb,
  - and, finally, the behaviour at radiofrequency with the test cavities recently built at CERN, HZB and STFC.

What is proposed

The main emphasis will be on a systematic study of correlation between

Surface preparation
- Cleaning, etching,
- Polishing, passivating

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

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

Superconducting properties measurement
- RRR, H_c, H_{fp}, H_{sh}, …
- AC and DC magnetic susceptibility,
- Field penetration facilities at ASTeC

Superconducting RF properties evaluation
- QR at CERN
- QR at HZF
- HW cavity at ASTeC

Real cavity measurement
- Cavity deposition

Excellence

- The bulk niobium RF cavities have been optimised for the past 50 years and has almost reached the theoretical peak performance.
- An improvement beyond the present day limitations can be achieved by employing thin film coatings of superconducting material.
- To realise this highly ambitious endeavour, this WP facilitates an essential joint effort of teams having an expertise in different fields (such as thin film deposition, surface analysis, superconductivity and RF) because no single lab can provide the required expertise and resources alone.

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Impact

- A significant outcome of the WP will be energy saving, since the successful implementation of thin film technology into accelerator manufacturing reduces both initial and running costs of the RF structure.
- Furthermore, the high costs of accelerating structures are one of the main reasons limiting the usage of accelerators outside scientific applications. Superconducting thin films would be an important milestone on economically feasible usage of particle accelerators in industry, medicine, security and other applications.

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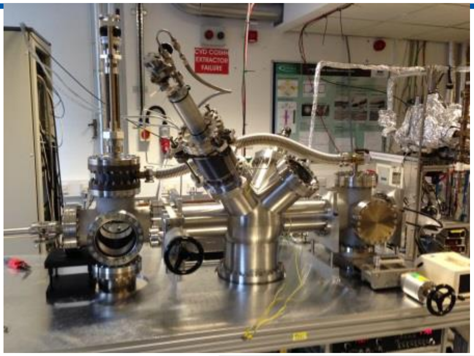
Thin Film Theme Partners

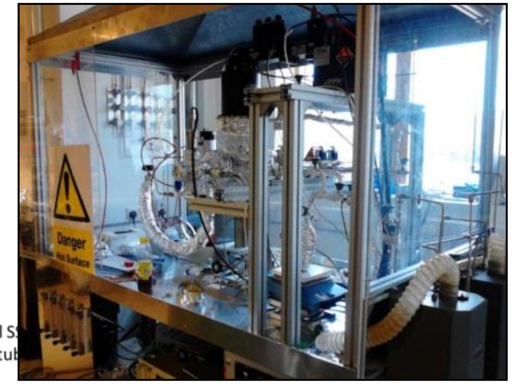
- **Participants:**
  1. ASTeC/STFC (Daresbury, UK)
     - Leading WP and Tasks 3, participating in all tasks
  2. *CERN (Geneva, Switzerland)*
     - participating in all tasks
  3. LNL/INFN (Legnaro, Italy)
     - Leading Task 2, participating in Tasks 1 and 3
  4. University Siegen, Institute of Materials Science, Surface and Materials Technology (Siegen, Germany)
     - participating in Task 2 and 3
  5. Helmholtz-Zentrum Berlin (Berlin, Germany)
     - Leading Task 4, participating in Tasks 1
  6. CEA (Saclay, France)
     - participating in Task 4
  7. IEE-SAS (Bratislava, Slovakia)
     - participating in Task 4
  8. RTU (Riga, Latvia)
     - participating in Task 2 and 3

ASTeC/STFC (Daresbury, UK)

- **Deposition facilities**
  - UHV PVD (planar and 3D): DC, Pulsed DC, RF and HiPIMS
  - (PE)CVD and ALD
- **Surface Analysis**
  - RBS, SEM, TEM, XPS, Auger, EBSD, XRD, AFM, SNMS.
- **Superconducting evaluation facilities**
  - Test Cavity 7.8 GHz,
    - Sample: 10-cm diam. disc
  - Magnetic field penetration,
    - Sample: a tube OD=12 mm, L=23 cm
  - RRR

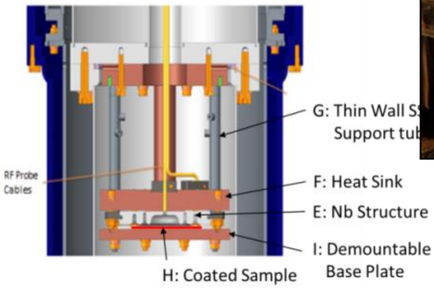


PVD deposition facility

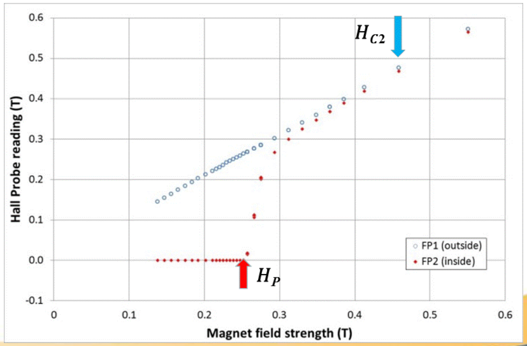


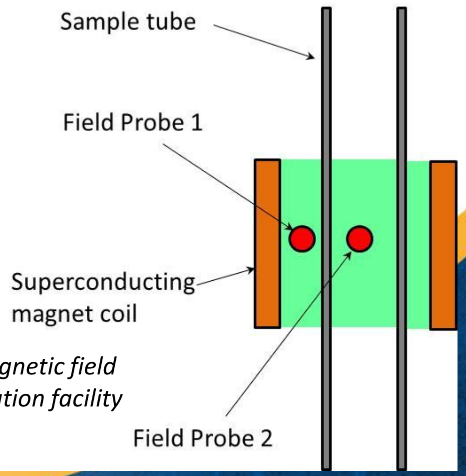
ALD/CVD deposition facility

SRF evaluation facility

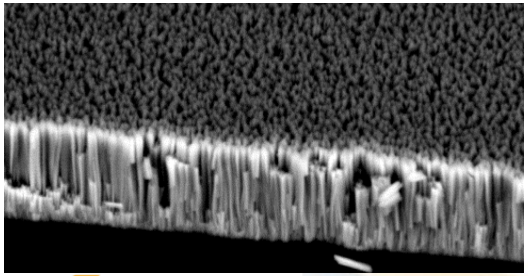


Field penetration measurements with Sample 1 (bulk Nb tube).





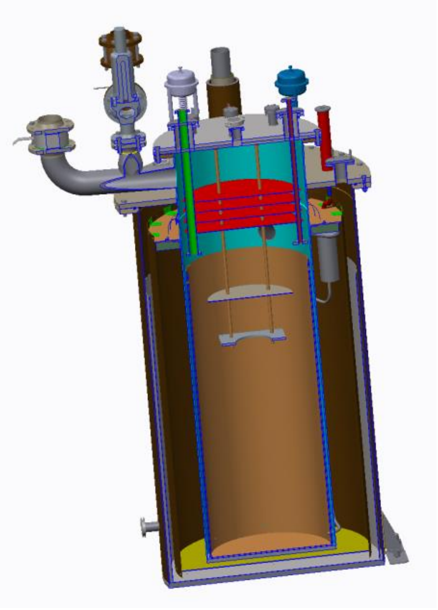
The magnetic field penetration facility



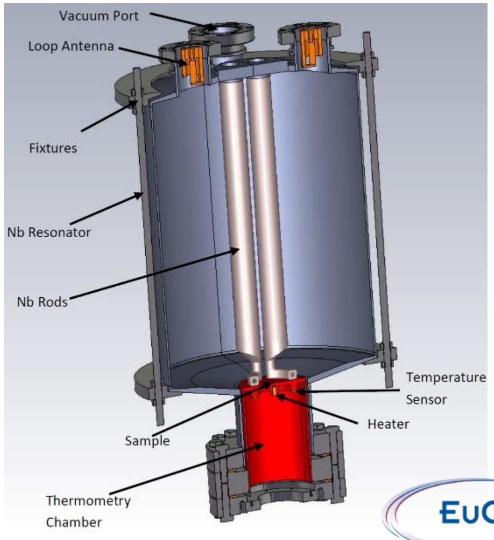
SEM image of a NbN thin film

Helmholtz-Zentrum Berlin (Germany)

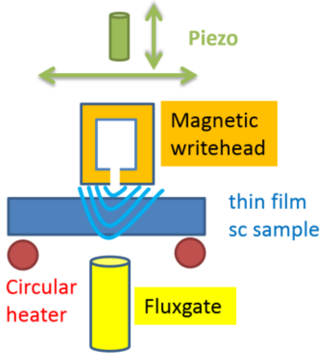
- Able to provide **RF characterization** of thin films samples deposited on a Nb disc (or any other metal if the sides of the disc can be coated as well
- The chamber has been fully developed within EuCARD2 and is ready for tests.
- Since the Nb discs/sample holders are pricey (10k€) some money are required to purchase more holders.



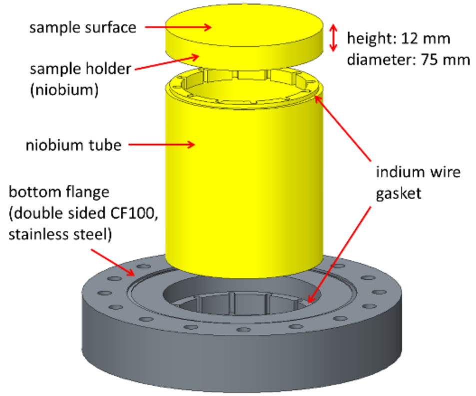
vertical cryostat



HZB quadrupole resonator



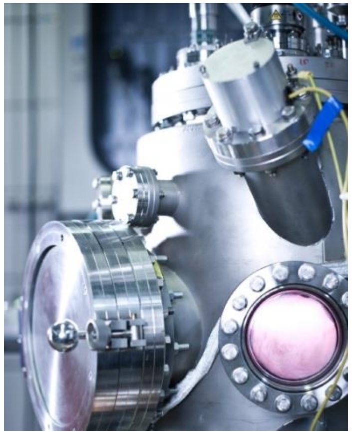
flux mobility measurement

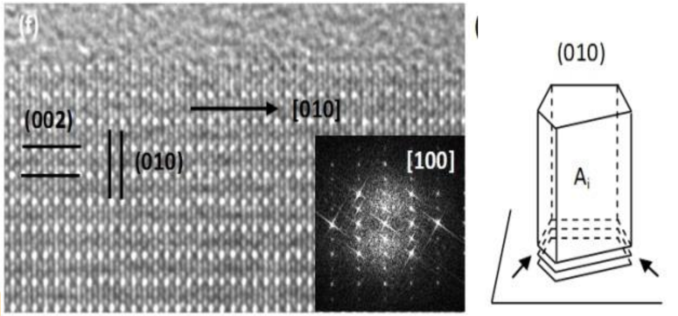


alternative sample holder

University Siegen, Institute of Materials Science, Surface and Materials Technology (Siegen, Germany)

- **Substrate preparation**
  - In-situ (meaning just before deposition) plasma pre-treatment: MF-Plasma cleaning/sputtering by Ar, Xe, O_2,…
  - Plasma etching (dry etching) in a dedicated plasma etching tool via Ar, O_2, H_2, N_2, …-plasma.
- **Superconducting thin films synthesis**
  - DCMS, HiPIMS in an industry standard coating machine
  - Project pending: Option of high temperature synthesis (T_S > 1200°C) of Nb_3Sn coatings.
- **Materials Characterization**
  - SEM, TEM, FIB, SIMS, XRD, FTIR, RAMAN, AFM, Nanoindentation, Pin-on-disc, Scratch-Test,
  - SEY-Measurements (developed in collaboration with CERN and HZB)



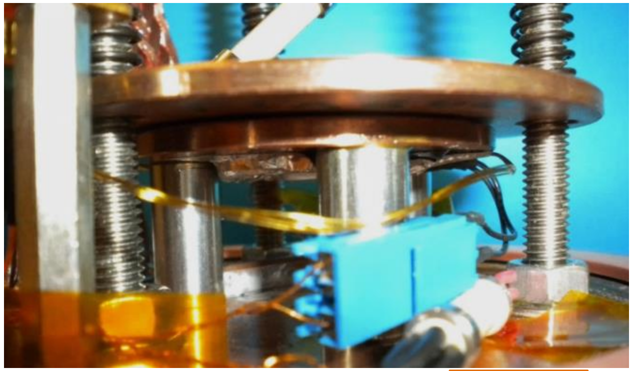


LNL/INFN (Legnaro, Italy)

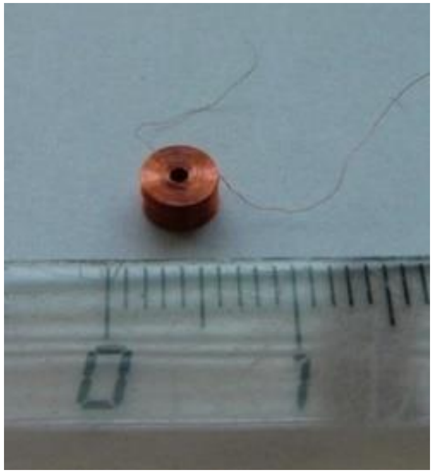
- Service of “Material Science and Technology for Nuclear Physics applications”
  - Treatment system for cavity Electropolishing
  - Clean room (class 1000) for SRF cavity mounting
  - Chemical plant for copper cleaning
  - The sputtering facilities
  - Cryogenic laboratory

CEA (Saclay, France)

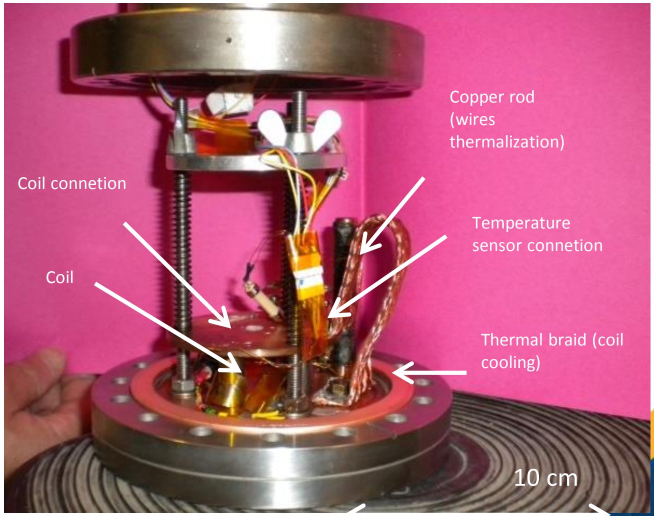
- Sample characterization program and exchanges with other labs in the loop
  - DC superconducting properties (T_C, RRR..)
  - Local magnetometer under development under EUCARD2 (allows measuring the1st transition field of sample and hence estimate the possible accelerating gradient of new materials)



Sample holder detail



Coil



150 mT, 2K set-up

Institute of Electrical Engineering IEE-SAS (Bratislava, Slovakia)

- Superconducting property characterization
  $H_{c1,2}$, H_{fp}, AC&DC mag. susceptibility, AC losses

  – PPMS with VSM insert

  14 T, AC&DC magnetization,
  sample space Ø = 5 mm, h = 15 mm

  – Custom AC susceptometer insert in 12 T sc. magnet

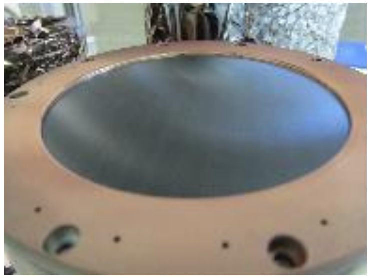
  max AC field ~100 mT, sample space Ø=10 mm, h=10mm

Custom AC susceptometer

PPMS

CERN (Geneva, Switzerland)

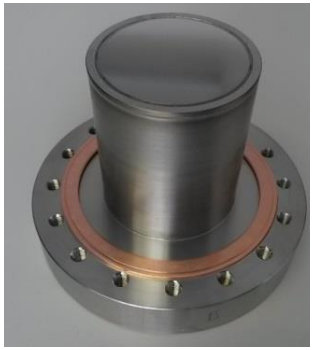
- **Copper substrate standardized preparation procedure**:
  - provide a unique and reproducible substrate preparation procedure for all thin film production labs in the WP.
  - Facilities: chemical and surface preparation laboratory.
- **Thin film sample production**:
  - DCMS/HiPIMS with pure (Nb) and alloy targets (Nb_3Sn and V_3Si).
  - Facilities: Thin film coating laboratory
- **SC/RF measurements**:
  - Quadrupole resonator and cold superconducting parameters measurement
  - Facilities: Cryolab.



Nb-Sn target mounted on planar magnetron

View of the samples facing the cathode during sputtering

Quadrupole resonator cavity



QRC sample holder

Riga Technical University (Riga, Latvia)

- RTU will perform three laser based tasks on selected samples:
  - substrate laser cleaning and polishing to improve film-substrate interface,
  - evaluation of long term thermal induced stability of the films deposited by other WP partners and film-substrate interface influence on the phase transitions, providing mapping over the whole specimen surface
  - the film deposited by WP partners can go through the laser annealing to increase the grain size and anneal the defects.
- This can subsequently characterise on topography (AFM) and analysed with XRD to determine the change of grain size at RTU

How the WP15 is structured

Workpackage Thin Film SRF
(WP Coordinator - Oleg Malyshev (STFC))

Task N.1
Coordination and Communication

Task Leader:
Oleg Malyshev (STFC)

Partners:
Enzo Palmieri, Cristian Pira (INFN);
Oliver Kugeler (HZB);
Giovanna Vandoni (CERN);
Reza Valizadeh (STFC).

Task N.2
Surface preparation

Task Leader:
Enzo Palmieri (INFN)

Partners:
Alban Sublet (CERN);
Michael Vogel (Universität Siegen);
Reza Valizadeh (STFC).

Task N.3
Thin film deposition and analysis

Task Leader:
Reza Valizadeh (STFC)

Partners:
Alban Sublet (CERN);
Michael Vogel (Universität Siegen);
Artur Medvid, Aleksej Katašev (RTU)
Enzo Palmieri (INFN).

Task N.4
Superconductivity evaluation

Task Leader
Oliver Kugeler (HZB)

Partners:
Walter Venturini (CERN);
Oleg Malyshev, Philippe Goudket (STFC);
Claire Antoine (CEA);
Eugen Seiler, Fedor Gömöry (IEE/SAS);
Sebastian Keckert (HZB).

Production of Milestones and Deliverables

Task 15.1: Coordination and Communication

Participants (beneficiaries):

<u>Oleg Malyshev (STFC)</u> – WP coordinator and Task 15.1 Leader,

Enzo Palmieri (INFN), Reza Valizadeh (STFC), Oliver Kugeler (HZB) – Task 15.2-15.4 leaders,

Giovanna Vandoni (CERN)

Objectives

- Define the global system taking inputs from different work-package (WP) tasks
- Coordinate and schedule WP tasks, to monitor work progress and inform the project management and WP participants
- Follow up the WP budget and resource use and prepare internal and deliverable reports

Description of work and role of partners

- This task will oversee and co-ordinate the overall activities, ensure the consistency of the work with the project plan and coordinate the WP technical and scientific tasks with tasks carried out by the other work packages when relevant.
- It includes organization of WP internal steering meetings, setting up of proper reviewing, reporting to the project management and distribution of the information within the WP and to the Project, and organisation of possible activity workshops or specialized working sessions.

Task 15.2: Substrate surface preparation

Participants (beneficiaries):

Enzo Palmieri (INFN) - Task Leader,

Alban Sublet (CERN), Michael Vogel (USIEGEN), Reza Valizadeh (STFC), Artur Medvid (RTU)

Objectives

- Coordinate the surface preparation for all samples.
- The surface treatment (mechanical, chemical and electrochemical, laser cleaning and polishing to improve film-substrate interface) of the substrate used for thin film deposition in Task 15.3 and the following measurements of surface resistance in Task 15.4.
- Define optimum cleaning and polishing procedure.
- Identify what could cause of delamination, lose thermal contact, etc.

Description of work and role of partners

- This task is focused on defining an optimum cleaning and polishing procedure which dictates the optimum RF properties of the films and on providing the partners with the sample substrates prepared exactly in the same surface chemical state and mechanical topographical finish, in order to minimise the substrate effect on the final film properties.
- The samples prepared at INFN will be used for deposition at other partner's laboratories.
- This task will include an intense coordination and exchange of information between partners.
- The results will be compared to the ones obtained with in-house prepared substrates.
- This task will provide samples or optimum cleaning and polishing procedure for sample preparation for Task 15.3.

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Task 15.3: Thin film deposition and analysis

Participants (beneficiaries):
Reza Valizadeh (STFC) - Task Leader,
Alban Sublet (CERN), Michael Vogel (USIEGEN), Enzo Palmieri (INFN), Artur Medvid (RTU)

Objectives

- Coordinate the type of material, thicknesses and multilayer structures to be deposited with different deposition techniques available at the participating parties.
- Perform characterisation of deposited films with available surface analysis and characterisations tools.
- Define optimum deposition techniques and parameters.

Description of work and role of partners

- This task involves evaluating the best technique coming out of earlier programmes (EuCARD-2 WP12) for depositing new materials either in single or multiple layer(s).
- Partners (STFC, CERN and USIEGEN) will deposit various materials employing the deposition technologies and facilities available in their labs on the sample substrates prepared and provided by Task 15.2.
- RTU will perform three laser based tasks on selected samples: evaluation of long term thermal induced stability of the films deposited by other WP partners and film-substrate interface influence on the phase transitions, providing mapping over the whole specimen surface and, finally, laser annealing of superconducting films to increase the grain size and anneal defects on the films.
- All deposition and treatments techniques will need to be applicable to (planar) large (up to 100-mm) scale substrates as required by the RF testing devices in Task 15.4. This fairly large geometry of the sample was agreed as the testing standard – it forces the coating technique to function on a realistically large area but avoids the problem of coatings on curved surfaces as required for a resonator which is to be addressed at a later point.
- Subsequently, the mechanical, chemical, morphological properties and topography of the bare substrates and the deposited films will be analysed by all the partners and the results will be correlated with the ones obtained in Task 15.4.

Task 15.4: Superconductivity evaluation

Participants (beneficiaries):

Oliver Kugeler (HZB) - Task Leader,

Walter Venturini (CERN), Oleg Malyshev (STFC), Claire Antoine (CEA), Eugen Seiler (IEE/SAS)

Objectives

- Coordinate superconducting RF evaluation experiment in three laboratories (HZB, CERN and STFC)
- Perform experimental RF tests on selected samples of superconducting films deposited on copper discs on three facilities at CERN, HZB and STFC. Analyse the results obtained at different frequencies and different facilities.
- Upgrade the HZB QPR developed in EuCARD2 to enable flux penetration and flux mobility experiments
- Perform magnetic field penetration experiments of superconducting films deposited either on copper tubes to be studied on a dedicated facility at STFC or on a planar copper substrate to be studied on dedicated facilities at CEA and IEE/SAS to find the optimum film for single or multilayer coatings.
- Define criteria and evaluate the best technology for producing superconducting film for RF cavities.

Description of work and role of partners

- This task deals with the characterisation of the DC and RF superconducting properties of samples prepared within Task 15.2 and 15.3.
- H_{c1} *measurements* (Saclay, IEE/SAS) and *DC resistance measurements* (CERN, IEE/SAS) yield macroscopic information and can provide an exclusion criterion for the functioning of a manufacturing procedure.
- *Full penetration magnetic field* H_{fp} (STFC, IEE/SAS) provides an essential input for the multilayer films.
- Based on these, *RF tests are performed with the QPR/RF-testing facilities* (CERN, HZB, STFC) measuring BCS and residual resistance at different RF frequencies (400 MHz to 8 GHz), temperatures (from 1.5 K up to T_c) and fields up to 120 mT. Most conceivable cavity operation conditions are covered by this parameter space.
  - Due to the limited throughput of RF tests - realistically not more than 6 samples per year per facility - it is necessary to have 3 installations dedicated to RF testing within the task performing tests in parallel.
  - It is also planned to upgrade the HZB QPR that was funded by EuCARD2 with the capability to measure flux migration which is an important issue when aiming at the highest Q_0 values.

Schedule of milestones and deliverables

		Year 1				Year 2				Year 3				Year 4			
Task	Description	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	1st WP meeting.	M1															
2	Evaluation of cleaning process for surface preparation for Cu and Nb substrate for Nb coating - (INFN).		M2		D1												
2-4	Evaluation of system 1 & 2 (e.g. NbN and Nb_3Sn coating) - STFC					M3			D2								
2-4	Evaluation of system 3 (e.g. MgB_2 and SIS multilayer coating)									M4			D3				
1-4	Final report.																D4

List of milestones and deliverables

Type	Delivery date (month)	Lead beneficiary	Related task/ responsible	Description
M1	m1	STFC	*Task 15.1*	1st WP meeting. Analysing outcome from EuCARD2 and current state of the field, finalising a detailed plan for WP
M2	m6	INFN	*Task 15.2*	First sample substrates cleaned at INFN for depositing at partners (Report to StCom)
D1	m12	INFN	*Task 15.2*	Evaluation of cleaning process. Report defining an optimum cleaning and polishing procedure for surface preparation for Cu and Nb substrate for Nb coating minimising the substrate effect on the final film properties.
M3	m14	STFC	Task 15.3, 15.4	First samples exchanged (system 1 and 2) and deposited at partners (Report to StCom)
D2	m24	STFC	Task 15.3, 15.4	Evaluation of systems 1 and 2. Report on deposition, surface and structural analysis, DC and RF superconductivity evaluation of systems 1 and 2 (e.g. NbN and Nb3Sn) and Superconductor-Insulator-Superconductor (SIS) multilayer coating
M4	m26	HZB	Task 15.3, 15.4	First samples exchanged (system 3 and SIS) and deposited at partners (Report to StCom)
D3	m36	HZB	Task 15.3, 15.4	Evaluation of system 3. Report on deposition, surface and structural analysis, DC and RF superconductivity evaluation of system 3 (e.g. MgB_2) and SIS multilayer coating
D4	m46	STFC	Task 15.3, 15.4	Final report on thin film technology [46] Report summarizing the results on the evaluation of cleaning and coating procedures for highest Q_0 and E_a

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Performance indicators

Key Performance Indicator (KPI)	Description	Method to measure	Estimated target
Q_0 (or surface resistance)	Q_0 and surface resistance of thin films measured in Task 15.4 will be compared to ones with bulk Nb	Report	Q_0 with thin film sample is equal or higher than Q_0 with bulk Nb sample
Raise of RF critical field with thin films	Increase of E_a is coupled with a raise of RF critical field with thin films.	Report	20% higher than for bulk Nb

Critical risks for implementation

Description of risk	Likelihood	Impact	Proposed risk-mitigation measures
Change of management team or WP Coordinators during the project	Medium	Medium	Anticipate potential staff changes in the project management and WP coordinators and select suitable replacements within the consortium as soon as possible
Withdrawal of beneficiary (ies)	Low	Low	Other beneficiaries take over the responsibilities of the withdrawing partner or new beneficiaries are included in the project from the pool of collaborating institutes
Reduced or undelivered contribution by one or more of the beneficiaries to the work programme of the project	Low	Low	Redistribution of work and budget to other members of the consortium, with possible rescheduling of milestones and deliverables if needed
Failure of equipment for film deposition, surface analysis or superconductivity evaluation	Medium	Medium	Each task involves at least two teams with similar capability. In the case of such a failure the project will continue running with slower progress. There is a contingency in the WP deliverables which allows fixing failed equipment
Chosen film system does not provide the required SRF parameters	Medium	Medium	The WP team will work in tree directions: (1) In additional to traditionally used Nb film three other types of film systems will be studied as hot candidates (such as NbN, Nb_3Sn, MgB_2) (2) Pre- and post-deposition laser treatment to improve film adhesion and grain size. (3) The SIS multilayer coating with both Nb and new types film systems will be investigated

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