C.N.R.S. - IN2P3 - UNIVERSITÉ PARIS-Saclay	**Pôle Accélérateurs** **Equipe MAVERICS**
M.FOUAIDY- 13/01/2021 Revised 25/01/2021	**Réf :** Report CSI _IN2P3-February 2021

Superconducting RF cavities R&D at IN2P3

Mohammed FOUAIDY, IJCLab

On behalf of SRF activities IN2P3 teams

I. Introduction

The R&D activities on Superconducting RadioFrequency SRF) Accelerating SYStems (SRFACCSYS) have been started at IN2P3 in 1986 for MACSE project in close collaboration with CEA: MACSE is the first French prototype of superconducting electron linac in the framework of R&D for a continuous electron beam machine dedicated to nuclear physics (e.g CEBAF physics program). The main objectives of MACSE are :1) design, develop and build a SRFACCSYS for electrons consisting of a horizontal cryostat housing multicell β=1 cavities with Fundamental Power Coupler, cold tuner, Higher Order Mode coupler, 2) gain experience in assembling and operation of SRF cryomodule with an electron beam, 3) Progress in the understanding RF superconductivity. Later, IN2P3 teams (IPN Orsay and LAL) in collaboration with Desy and CEA, were involved in the construction of Tesla Test Facility (TTF) with two major contributions: the electron injector (LAL and CEA) and the first SRF cryomodule (capture cryostat hosing non fully dressed 9-cell elliptical cavity) of TTF. As compared to normal conducting accelerating structures, SRF cavities have several advantages: high accelerating gradient (10-30 MV/m) even in continuous mode machine operation, higher acceleration efficiency (~factor 5-10) for high intensity beams. As consequence particle accelerators based on SRF cavities have the following features among others: 1) they are more compact resulting in shorter machine and cost saving, 2) ability to accelerate high current beam (storage rings, FEL), 3) they need a reduced peak RF power leading to reduced cost, increased reliability and availability and a better field regulation, 4) they produce better beam quality (i.e. reduced energy dispersion), 5) flexibility of operation. Due to the aforementioned advantages SRF cavities are the best technological choice for accelerators since many years: from LEP, HERA and TRISTAN to SPRAL2, XFEL, LCLS- II and ESS through CEBAF and SNS).

I. *State of the art and IN2P3 experience*

Most actual and future large particle accelerators, which are challenging in terms of their construction and operation, use high purity bulk niobium Superconducting RF (SRF) cavities as accelerating structures. This mature technology is widely used in accelerators for a very broad range of both fundamental research and applications: High energy Physics (ILC, …), Nuclear physics (SPIRAL-II, FRIB, SARAF…), High intensity protons linac based machines (SNS, JPARC, ESS, MYRRHA), X-Ray Light Sources (Soleil, Eu-XFEL, LCLS-II, ERL projects…). Thanks to a tremendous R&D effort around the world, the RF performance of SRF cavities were significantly improved: 1) for elliptical β=1 cavities, the accelerating gradient specification was increased from 5 MV/m (LEP, TRISTAN) to 24 MV/m and 33 MV/m for XFEL and ILC respectively, 2) the quality factor was increased by almost one order of magnitude. Furthermore, accelerating gradient of 52.3 MV / m, close to the theoretical limit value (52.8 MV /m) have been achieved in prototype one-cell β=1 elliptical cavities made of high purity bulk niobium. However, this fundamental limit, which is due to the critical magnetic of Nb ~190 mT, is far from being reached for the so-called low or medium β (β <0.5) such as quarter-wave (QWR) or Spoke resonators, which are used for SPIRAL2, ESS or MYRRHA, projects in which IN2P3 is very strongly involved. Thanks to the R&D effort for SRF accelerating systems supported by IN2P3, the IN2P3 teams acquired the technical and scientific know-how allowing to make a significant important contribution (Annex1) to SIPRAL2:1) design, development, construction and assembling of the 7 cryomodules of high energy section, 2) the cryogenics dedicated to the linac (helium refrigerator, 19 cold boxes, cryogenic distribution lines and cryogenic instrumentation). IN2P3 is now internationally recognized for the design, development, fabrication, preparation and assembling of superconducting cryomodules including: the liquid Helium (LHe) horizontal cryostat ant it's cold box, the cavities fully equipped with the cold tuner, fundamental power coupler, HOM coupler and magnetic shielding. IN2P3 contributes strongly to the main international projects (Eu-XFEL, ESS, MYRRHA) and have the facilities, know-how, expertise and technical skills (Annex1-Annex3) to participate to ILC if the project is approved and to future large scale project such as FCC.

II. *SRF accelerating system R&D main objectives and breakdown structure*

The SRF accelerating system R&D program has been significantly supported by IN2P3 for many years in terms of budget, equipment and human resources. The SRF R&D activity of the two IN2P3 laboratories (IJCLab and LPSC) contributing to the current projects (e.g ESS and MYRRHA) has always been kept to a minimum in order to meet the very demanding and stringent performance requirements of these electrons and proton linacs. In this context, due to lack of human resources, which are involved mainly in design, development, construction, testing and assembling of ESS and MYRRHA, the R&D activity on some topics is much reduced.

The development and construction of these large scale projects has a positive impact in terms of financial support, technical and scientific challenges addressed, improvement of technical skills and development of new facilities for SUPRATech platform (Annex 1. However, the pressure due to our involvement in these projects, has drastically reduced both the time and human resources allocated to basics R&D.

The main objective of SRF R&D program is to develop high functional performance SRF accelerating structures, at low cost with high production and process yield at large scale. The scientific program, which includes both generic/basics R&D and development in the framework of accelerators construction, addresses four main topics targeting the main objectives as described in Table1.

Topic	Goal or Objective	Parameter impacted and/or issues
Optimum design of SRF cavities	High accelerating field and acceleration efficiency Reduce anomalous RF losses High thermal stability High mechanical stability Increase Multipacting barrier level	Investment and operation costs RF performance and cryogenic load Achievable gradient and tolerance to normal defects Lorentz detuning, micro-phonics, RF power and regulation RF performance, reliability Robust design and reliability
Fabrication, preparation and processing	reliable manufacturing, preparation and processing at low cost	Cost, construction planning
Ancillaries and RF systems	Cryostat and cryogenics Power coupler Cold tuner Low Level RF (LLRF) Magnetic shielding	Cost, Cryogenic load, cost, reliability, assembling Power, Multipacting, RF conditioning Tuning range, Reliability, life time, regulation, RF power Tuning range, Reliability, availability, flexibility, regulation, RF power Residual surface resistance, RF losses
New fabrication techniques and cooling schemes of SRF cavities		Cost, cryogenic load, RF performance, vibrations and micro-phonics (*)

This topic is not yet started. It will be, largely supported by PACIFICS: a PIA3 equipex+ that have been approved

Table 1: Major SRF R&D topics at IN2P3

The aim of the basics R&D scientific program is to investigate and develop material, fabrication methods and optimized process for the treatment of SRF cavities in order to:

I. Increase significantly maximum achievable accelerating gradient and consequently increase beam energy and/or reduce accelerator length and cost,
II. Reduce dynamic RF losses and consequently the thermal load to the refrigerator resulting in an increase of acceleration efficiency and reduction of both investment and operation costs.

More precisely, the reduction of manufacturing costs and/or the improvement of the RF performances (i.e. E_{acc} and unloaded quality factor Q_0) of SRF cavities require an important generic R&D program devoted to:

1) Development and mastering of new advanced techniques for the treatment of RF surface and/or material with dedicated facilities and equipment (e.g. Ultra High Vacuum Heat Treatment (UHVHT), chemical and/or mechanical polishing, low temperature in-situ baking) in order to improve RF performances of SRF cavities. These topics are covered by two projects within the Master Project SRF namely HELOISE (IJCLab, M. Fouaidy) and PACCAS (IJCLab, D. Longuevergne).

2) Development of special sensing probes/electronics to diagnose and characterize (e.g. superconducting properties, DC and RF electrical and electromagnetic properties, thermal and mechanical properties…) performances of materials used for the fabrication of SRF cavities and their ancillaries (e.g. RF power couplers, fast cold tuning systems, magnetic shielding…) in cryogenic environment. These topic is also a part of HELOISE (IJCLab, M. Fouaidy).

3) Investigation of alternative material to bulk niobium namely superconducting thin films made with superconducting materials of higher critical parameters than niobium. More precisely, superconducting films (Nb_3Sn, NbN, MgB_2, …) will be studied for SRF application. These topic was initially covered by the project ECOMI within the Master Project SRF (IJCLab, G. Martinet). It is now a part of collaborative projects with CEA and SIMAP (CNRS).

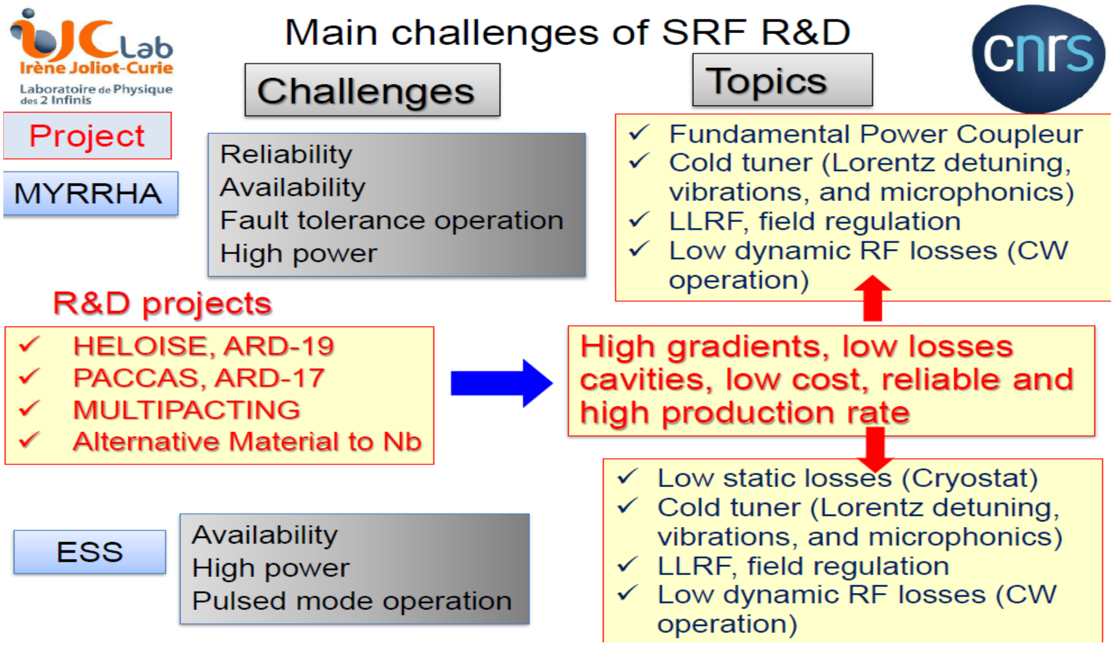
4) Multipacting studies concerning both SRF cavities and High Power coupler: a critical component having a strong impact on the performance and reliability of SRF accelerating system. This topic is covered by the Project Multipac (LPSC and IJCLab, Y. Gomez Martinez) within the Master Project SRF.

The R&D activities concerning the other topics driven by machine development, namely the cold tuning System, LLRF and fundamental power coupler are included in the specific program of the concerned project (i.e ESS, MYRRHA).

It should be stressed that several new apparatus and experimental test stands that will be developed in the framework of the new project PACFICS which was recently accepted, will reinforce strongly the whole program. In particular, PACIFICS will allow IJCLab to initiate the topic #4 of table 1: this topic is an opportunity for addressing and launching R&D in cryogenics that will give to IN2P3 teams the development of a know-how and skills allowing them to actively participate to new R&D topics on superconducting high field magnets (FCC). As the proposed R&D program of PACIFICS is well detailed in the proposal it will not detailed in this report. Finally, the unique expertise of the scientists combined with the state of the art facilities (SUPRATech, Panama and PACFICS) in CEA/CNRS will strengthen the position of France as a world leader in SRF cavities for particle accelerators.

The diagram of Fig. 1 show the scientific and technological challenging topics addressed in SRF R&D activities at IN2P3, either in synergy with the ongoing projects or in view of future accelerators projects. The structuration, organization along with the different financial supports, the main collaborations, the technological platforms or facilities and IJCLab Accelerator Department teams or groups involved in SRF R& D are illustrated in Fig. 2 of these activities.

Fig. 1 Main challenges of SRF R&D at IN2P3



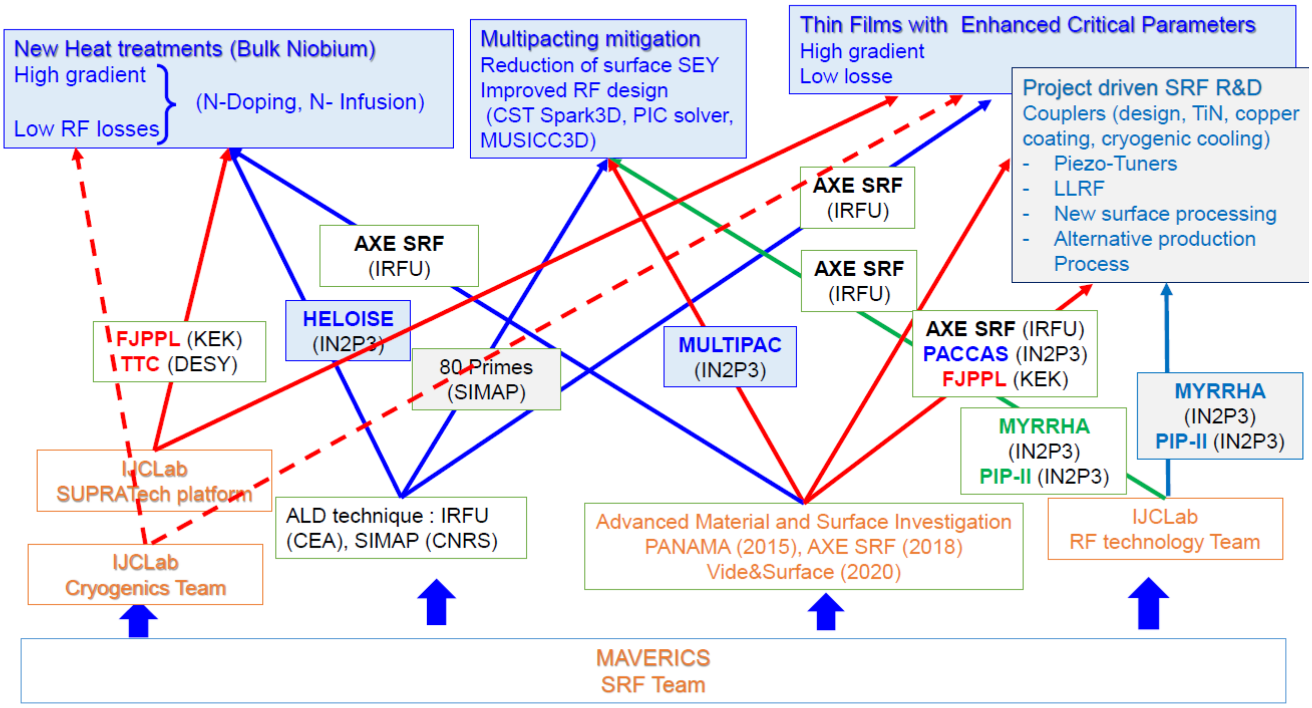


Fig. 2 Diagram of SRF R&D organization at IN2P3 showing the different teams involved, collaboration and other financial supports.

IV. HELOISE

The main goals of the project HELOISE (High tempErature anneaLing, low temperature baking and dOpIng for low LoSses CavitiEs) is two folds: 1) investigate the various heat treatments processes in order to progress in the understanding of the complex physico-chemical phenomena involved, 2) optimize the parameters which impact these new advanced heat treatments processes in order to apply them reliably to ongoing and/or future SRF cavities based projects. Vacuum Nitrogen Doping (VND) technique was recently and successfully applied for processing bulk Nb SRF 1.3 GHz cavities at FNAL and JLAB (USA). The main results of VND process studies at these 2 institutes are: a) reproducible improvement by a factor 2 to 5 of the unloaded quality factor Q_0 of processed cavities, as compared to the initial value prior to VND, b) systematic reduction of the maximum achievable accelerating field up 40%, c) maximum achievable accelerating field limited by the cavity quench. The surface studies of these VND Nb cavities revealed unusual features as compared to Nb samples treated with the standard processes: a) presence of N atoms dopant (100's of ppm) in a surface layer of ~100 nm, b) an almost ideal, homogeneous superconducting Density Of States (DOS) at the surface, c) a very thick and dense protective oxide layer. In contrast, Low Temperature Baking (LTB) at θ= 120°C in N_2 atmosphere or in air showed an improvement of up to 20% but with an unchanged value of Q_0. In order to improve both reliability reproducibility and high yield production rate of high RF performances SRF cavities, the in-depth understanding of the correlations between Q_0 and materials properties becomes more stringent down to 10-100 nm scale is necessary. New and precise characterization methods together with a high level of tight control of Heat Treatment (HT) process are then needed. These heat treatments processes (e.g. High Temperature Vacuum Annealing (HTVA) at θ=600 °C-800°C, VND at 600 °C-800°C, LTB at θ=100 °C-200°C) are performed with the dedicated IJCLab facilities and equipment namely SUPRATech (Annex 1).The scientific program is devoted to : 1) Design and development of test stands for the measurements of several important physical properties of superconducting materials on samples, either at low temperature (e.g. critical temperature Tc, transport properties (electrical and thermal conductivities) or at room temperature (e.g, microstructure, residual mechanical stresses, impurities concentration profiles), 2) Cold RF tests of various shape SRF cavities covering a wide range of resonant frequencies f (e.g, accelerating Quarter Wave Resonator (QWR):f= 88 MHz, Spoke type Resonators (SR): f=352 MHz, Elliptical Resonators (ER):f=1.3 GHz, and TE011 Resonator (TER) f_1=3.85 GHz and f_2=5.12 GHz. Note that the tests on cavities will include in particular, RF surface resistance R_S (e.g.) measurements (Q_0 α1/R_S) in both the so-called Bardeen Cooper Schrieffer (BCS) regime and residual regime. Moreover, cold RF test of 1.3 GHz cavities is performed at the facilities of collaborating (Fig. 2) institutes (CEA, Desy, KEK). The complex Nb surface modifications after a HT process hinder our understanding of the involved phenomena and many questions remain unsolved; What is the effect N-doping on the Nb superconducting parameters (Δ,TC, H_C, effective penetration depth λ and coherence length ξ) at scales in the range $\lambda - 100\,\lambda$ under the applied surface RF field? Is the increase of Q_0 after N-doping process due to the reduction of normal electrons mean path l_e? Is quench field decrease due reduction of l_e at depth ~100μm resulting in a dramatic decrease of k(T) at T~2 K (e.g phonon peak depression)? What are the role and impact of deleterious phase formation (NbH_x, NbC_x…), interstitial impurities (e.g. N, O), and the native oxide properties (density, thickness, transition with the underlying metal) on Δ, T_C, H_C, λ andξ.. Theoretical investigation and numerical simulation are also a part of the program. This program will allow French institutes to progress in SRF cavities to a level comparable to USA institutes by exploring a wider doping parameters phase space resulting in advance toward mastering HT doping processes and a dramatic improvement of bulk Nb SRF cavities RF performances (both Q_0 and E_{acc}^{max}) beyond what is currently achievable.

Two approaches are considered:

1. Better understanding of N doping process (e.g. new procedures using gases as doping sources).
2. Beyond N Dopant: The use of solid thin films as controlled sources for new dopants.

The topic 'Beyond N-Dopant', which included in the program focused on Thin films with enhanced critical parameters, will be described in next section.

The project will enable a strong and coordinated R&D effort, focused on the doping control in order to improve significantly Nb SRF cavities performances. Such effort is, to our knowledge absent in Europe: it will be a basis for long term R&D opportunities for future European accelerator projects namely FCC. Furthermore, a part of our continuous collaboration with CEA, we have started two collaboration programs on two important R&D topics included in HELOISE and coordinated by M. Fouaidy: 1) With Desy (Nitrogen infusion and Quench detection) in the framework of Tesla Technology Collaboration, 2) With KEK (Nitrogen infusion, Quench detection and residual magnetic field sensors (AMR)) in framework of ARD-19 project supported by TYL-FJPPL.

The development of diagnostic tools for SRF cavities is focused on thermal quenches detection and location and residual magnetic field mapping.

- Investigation of thermal quenches of SRF cavities (IJClab, M. Fouaidy)

The maximum accelerating fields E_{acc} achieved with bulk Nb SRF cavities are often limited by the so-called anomalous losses due to Joule heating of normal-conducting defects imbedded onto niobium surface by the strong RF magnetic field. At high surface magnetic field BS (e.g. B_S>63 mT corresponding to E_{acc} >15 MV/m for elliptical cavities of ILC type), the temperature of these defects increases dramatically with E_{acc}, leading to a thermal breakdown of the whole cavity or quench resulting in a fast and decrease (5 or 6 order of magnitude) of the quality factor Q_0 of the resonator. This dramatic decrease of Q_0 during cavity quench is naturally due to the phase transition of the hot spot area from superconducting to normal resistive state. Sensors, dedicated to the detection, locating and characterization of these quench sources are a powerful diagnostic tool for investigating these phenomena. The first generation sensors (1980s) are surface thermometers for measuring heating of liquid helium cooled wall of the SRF cavity. Second generation of quench detectors in superfluid helium (He II), namely OST (Oscillating Super-Leak Transducer), were used to diagnose thermal breakdown of SRF cavities since nearly 15 years. The OST are capacitive quench detectors, based on second sound (e.g. temperature wave) transient events measurement in He II: second sound events are induced by pulsed heat release from the hot spot of the quenching SRF cavity. Recently, we suggested to use low response time (<< 1ms) resistive thermometers as quench detectors sensing second sound in He II. Thanks to IN2P3 financial support, we developed and constructed several OST quench detectors and used low response time industrial thermometers for detecting SRF cavity quench experimentally simulated precisely and in controlled way by localized and pulsed various heat sources. The cryogenic insert for their calibration and characterization in a wide temperature range (e.g. 1.6 K-2.2 K) was operated successfully. The main goals of these studies are: 1) Development of diagnostic tools dedicated to in situ quench detection and location in SRF Cavities in order to get more insight into quench phenomena and anomalous RF losses. 2) Thorough investigation of the dynamic response of the actual OST detectors when the thermal sources are subjected to various excitations as function of several parameters (helium temperature and pressure, heat pulse shape width, and height, pulse duration, …) in order to optimize these sensors. 3) Use

of OST detectors to investigate (locating and characterization) thermal quenches in SRF bulk Nb cavities of various shape, geometrical and frequencies f_0 (e.g., spoke type cavities: f_0=352 MHz, Quarter Wave Resonator (QWR) cavities: f_0=88 MHz, elliptical cavities at f_0=352 MHz, 704 MHz, 1300 MHz, 1500 MHz and 3000 MHz) at different superfluid helium temperatures.
4) Study of quench dynamics and critical size of normal resistive area leading to SRF cavity quench. 5) Use OST thermal quench map of SRF cavities as guides for repairing the resonator and/or improving their RF performances. 6) Improvement of spatial resolution of OST sensors (size reduction) and sensor signal to noise ratio by integrating the signal conditioning system onto OST quench detectors (e.g. developing of fast charge amplifier operating at Low Temperatures (LT)). 7) Development of experimental test-cells dedicated to study of transient heat transfer in superfluid helium subjected to high flux density thermal pulses, including second sound resonators for low temperature metrological applications (e.g. precise cryogenic temperature sensing in the vicinity of the transition temperature T_{λ}, liquid helium range temperature scale). 8) Development and optimization of Low Response Time (LRT, e.g.<< 1ms) and high resolution resistive thermometers as quench detectors by sensing second sound signal in He II. 9) Development of fast cryogenic electronics (e.g. bandwidth >100kHz) for conditioning LRT thermometric signals. 10) Study the possible use of other type of LRT (e.g. Superconducting Thermal Sensors STS, Transition Edge Sensors, Kinetic Inducting Detectors KIDs...). All the goals from 1 to 7 were achieved and we published several papers on this topic. We have also successfully tested and fully characterized our first prototype of fully digital large band high sensitivity (10^{-5}) signal conditioner for low level signals (i.e < 100 mV). We performed also several successful tests at a temperature of 77 K of some critical electronic components as well as prototypes of operational amplifiers.

We have a collaboration with Desy on quench detection and location: several sensors, electronics, calibration heaters, were shipped to Desy for the test with 1.3 GHz elliptical cavities. Finally, we have also a collaboration (FJPPL TYL ard-19 project, coordinated by M. Fouaidy for the French team) with KEK on this topic.

- AMR sensors for magnetic field mapping at cryogenic temperatures (IJClab, G. Matinet)

The residual magnetic flux in the SRF cavities environment is responsible of residual surface resistance degradation on superconducting materials used in SRF technologies. The trapped magnetic flux during the transition from normal conducting state to superconducting state is a part of the increase of residual resistance. Indeed, to characterize this effect on superconducting samples, compact sensors are required to mount on sample characterization devices. Several sensors could be used at helium liquid temperature. Since wide spread of shape of RF characterization devices (TE011 cavity, mushroom cavity, QPR cavity, microstrip resonator, multi-mode cavities, …), a compact cryogenic magnetic sensor is required. Results from HZB laboratory with commercial AMR sensors have demonstrated the interest of these class of probes. To adapt these sensors to our requirement, we have started in 2019 to work on this topic in order to develop triaxial probes to measure magnetic vector near the surface of superconducting samples or cavities. The objectives is to identify triaxial AMR chip which is compatible with cryogenic environment (vacuum and/or liquid helium), with high accuracy and sensitivity (0.1 – 100 mG range, 0.5 mG of resolution) and high sampling rate (> 1kHz of sampling rate). Although HZB laboratory has shown good overall performances of AMR sensors to measure the magnetic field map in the vicinity of SRF cavities, it is not straight forward to use it for sample cavities. The tested sensor is a mono-axis from Sensitec company which requires 3 sensors to achieve a magnetic vector measurement. This configuration is not suitable for sample cavities because of the size of the system.

Based on these results as starting point, we are looking for other sensors which are respecting requirements. Sensors from Honeywell have been selected because of the specifications which are similar to Sensitec sensors with 2-axis and 3-axis in one chip. The qualification process is based on the following roadmap:

- Systematic measurement of magnetic field in a Helmholtz cell from 0 mG up to 200 mG for temperature in the range of 1.8 to 300 K
- Measure the calibration curve of each sensor in these magnetic field range and temperature range.
- Measure the reproducibility and the cycling effect as it has already done for temperature sensors

First test of AMR sensors shows the efficiency of these components. 1-axis sensor from Honeywell presents no issues during the test form 295 K down to 4.2 K. The behavior is comparable to the Sensitec sensor. Further investigations are led on 3-axis sensor to conclude if it could be used in cryogenic environment and to fix the conditioning of the chip. Despite the lake of results Honeywell sensors, overall results are very promising to find a compact 3-axis sensor to measure residual magnetic field on small superconducting samples. We are now preparing systematic measurements to establish the calibration curve and cycling effect.

V. Thin films with enhanced critical parameters

SRF cavities based on superconducting thin films (e.g., Nb, Nb3Sn, NbTiN) sputtered onto OFE copper substrate are still considered as an alternative fabrication scheme to standard high purity bulk niobium cavities produced by deep drawing and electron beam welding for future high energy accelerators and colliders. Thin films SRF cavities are economically attractive and offer several technical advantages, as compared to bulk niobium resonators (e.g., lower BCS losses, no quench or thermal breakdown, cost effective and especially for large scale applications, much reduced sensitivity to Lorentz detuning due to their highest stiffness). Unfortunately, the poor RF performances (i.e., high losses) obtained 20 years ago with sputtered Nb thin films cavities hamper their use for high gradient applications (e.g., for ILC E_{acc}>30 MV/m is required) and/or low loss machines (e.g., C.W machines and Energy Recovery Linacs). More precisely, the RF losses in the residual surface resistance regime increases strongly with E_{acc}: typically the observed unloaded quality factor Q_0 decreases by one order of magnitude when E_{acc} is increased from zero to 25 MV/m at a T≅1.7K. More recently, new coating methods (i.e. Pulsed High-power impulse magnetron sputtering – HiPIMS) developed at CERN and JLab allow to improve significantly the RF performance, critical parameters and transport properties of thin films (i.e Nb, Nb_3Sn V_3Si). Moreover, theoretically due to the well-known dimensional effect, the critical magnetic of material which is an intrinsic property a superconducting bulk material, can be increased when the thin film thickness δ is lower than the London penetration depth λ_L: for Niobium λ_L= 40 nm. We are exploring, in collaboration with CEA (IRFU) a new development based on this dimensional effect. This original approach in order to improve the performance of bulk Niobium RF cavities rely on surface engineering with Atomic Layer Deposition (ALD) technique. It will be used for producing superconducting multilayers. These MultiLayers (ML) consist in a stack of superconducting 40-40 nm thick films separated by a 5 to 10 nm thick insulating layer (structure similar to SIS or Josephson Junction). The ML have two major roles: 1) achieve accelerating fields well beyond the bulk niobium substrate intrinsic limit (i.e ~190 mT) quench limit by enhancement of the critical field ($H_{CML}=H_{Cbulk}/\delta$), 2) screening efficiently the magnetic fields and therefore inhibiting vortices penetration in Niobium SRF cavities. Atomic layer deposition (ALD) is a very promising deposition technique able of providing high structural and chemical homogeneity over large surfaces with complex shapes. As a first step for the multilayer, we aimed till now at replacing the deleterious niobium native oxide by a clean interface between an insulator synthesized by ALD (Al2O3, Y2O3 and MgO) and the Niobium metal. This surface passivation is expected to provide some improvements similar to nitrogen doping. Extensive sample study showed so far that ALD deposited films are a good diffusion barrier, resist to thermal treatments at 650 °C and reduce significantly the presence of the niobium native oxide on the surface. Low Secondary Emision Yield (SEY) material such as TiN was also deposited on top of the insulator film to reduce multipacting phenomena. RF test on ALD coated cavities performed at IRFU shows already a slight improvement of the superconducting performances. IJCLab is strongly involved in this collaboration. A PhD student is financed by IN2P3 and IJCLab and co-directed with IRFU since 2018. IRFU has developed and operates an ALD deposition set-up. The PhD work focuses on 4 tasks:1) Standard surface characterization of ALD deposited samples by XRD, XPS, TEM, SIMS on instruments available at IJCLab (Panama Platform, Jannus-scalp Platform) and on Orsay Campus (ICMMO, LPS), 2) Heat treatment of samples and cavities in IJCLab High Temperature Vacuum Furnace (Supratech Platform) dedicated to SRF activities, 3) Specific surface analysis of the Secondary Electron Yield (SEY) of Al2O3, Y2O3 and TiN deposited by ALD, 4) Cryogenic RF test on ALD coated sample compatible with HZB Quadrupole Resonator set-up (QPR).

Moreover, in order to characterize thin films and ML and get more insight into the physics, we have developed a dedicated test stand. It is based on a cylindrical bulk niobium cavity, operating at two frequencies (TE011 mode at f_1= 4.04GHz and TE012 mode at f_2=5.6GHz) and equipped with a removable test sample, was used for this purpose. This cavity allows measurements of the surface resistance R_S of various materials (bulk Nb, Nb, NbTiN and Nb3Sn films and ML). The first measurements with this cavity is performed by the standard RF method. However, this technique, which is called end plate differential method requires a comparison to a reference bulk niobium disk and is limited by a poor accuracy (i.e., $\pm$1500 nΩ) in terms of surface resistance measurement at 4.2K. For material of high RF performance, it is then necessary to develop another method with improved accuracy and sensitivity in both BCS and residual resistance regime. A new device, based on a calorimetric method, was designed and successfully used for measuring both local and absolute value of surface resistance for temperature T in the range 1.7K-4.2K In addition to improved accuracy, reliability and sensitivity in measuring RF properties of new materials, the main motivations to develop a new instrument are two folds: 1) measure exclusively the RF losses of the test-sample by excluding any extra RF losses, 2) perform local measurement and therefore R_S distribution. Notice that the extra RF losses, inherent to the end-plate replacement method, are due to the rest of the host cavity, lead gasket and RF coupling loops. Further, the main advantage of the actual calorimetric method, as compared to the usual RF technique, are: 1) it is absolute, direct and local method, 2) as no reference disk is needed, it is faster and the reliability is improved, 3) vacuum insulation of the heater and thermometers resulting in precise measurement of temperatures and thermal power, 4) in-situ measurement of substrate thermal parameters.

VI. PICASU - PACCAS

Large-scale production of superconducting radio-frequency (SRF) cavities is an industrial challenge, not only because of the increasing number of units for future projects but also because the very demanding requirements in term of yield rate, reliability, reproducibility and RF performances. For the International Linear Collider more than 10000 SRF bulk niobium high purity 9 cell elliptical cavities are the needed. The main RF performances requirements in order to achieve a center-of-mass energy of 500 GeV with two 11-km long main linacs for ILC cavities are: 1) accelerating gradient of 31.5 MV/m and unloaded quality factor Q_0 =8.10^9 in average with an allowable spread of < ±20%, 2) vertical test acceptance gradient of 35 MV/m at Q_0 =8.10^9. The Future Circular Collider (FCC), which is in the roadmap of future HEP machines, is also very challenging for the high field magnets but also for the RF performance of the SRF resonators. For such demanding large-scale facilities, the reduction of investments and operation costs are absolutely needed in order to keep the allocated budget within acceptable limits. An alternative pathway to reduce the production and processing costs of SRF bulk niobium elliptical cavities while improving the performances has been proposed by C. Antoine (CEA). Firstly, it consists in applying directly on Niobium sheets an optimized metallographic polishing process aiming at removing the damaged layer generated during Niobium sheet manufacturing. This process has been studied for several years at IN2P3 in the project PICASU (Polissage Innovant pour les Cavités Accélératrices SUpraconductrices) and in the framework of H2020 European program, European Nuclear Science and Applications Research - 2 (ENSAR2) in collaboration with CEA/IRFU. Results obtained, thanks to the very fruitful and close collaboration between IN2P3, CEA and LAMPLAN (French company specialized in metallographic lapping and polishing), were very positive and lead to successful polishing of large Niobium disks with surface roughness below 100 nm. It has to be pointed out that this R&D on alternative polishing offers the possibility to also address the question of the role of surface roughness on the limitation of SRF performances in cavities and at last but not least provides very smooth surfaces as substrates for the quest of alternative SRF materials deposited as thin-films (S-I-S multi-layer deposition by Atomic Layer Deposition (ALD) technique. Secondly, polished Niobium sheets have to be formed and welded to build an elliptical cavity. However, conventional forming techniques might not be applicable as this process would damage too significantly the pre-polished surfaces. All the benefits of the high-quality metallographic polishing would then be lost as a conventional chemical treatment would need to be performed. Collaborative project with CEA since 2018 (AXE SRF) and with KEK since 2020 (TYL-FJPPL program) have been initiated to address this problematic of cavity forming of pre-polished Niobium disks for the fabrication of 1.3 GHz elliptical cavities. KEK has the experience, ability and facilities to build elliptical cavities. IJCLab/IRFU have the ability and equipment to perform the optimized metallographic polishing procedure for SRF applications and proceed with surface characterization. Sharing and combining both experience and effort will allow us to address, in a very efficient manner, the second step of this alternative pathway.

VII. *Multipac: a project devoted to multipacting studies*

Multipacting (MP) is an unwanted phenomenon occurring in some RF components (SRF cavities, Fundamental Power Coupler (FPC), High Order Mode (HOM) coupler) when subjected to RF field under certain conditions in high vacuum. In contrast to electron field emission, MP is an avalanche resonant phenomenon characterized by uncontrolled and strong electron loading of the RF structure. In SRF cavities, Multipacting induces anomalous RF losses which are much higher than the intrinsic RF losses (i.e Joule heating to the finite surface resistance). In SRF resonators, MP induced losses lead to a dramatic decrease (more than factor 10) of the quality factor resulting in accelerating field limitation (i.e multipacting barrier): all the forward RF power is absorbed by MP electrons which impact the cavity wall and generate heat. Furthermore, MP losses limits the SRF resonator performance (quench, maximum achievable gradient) and could even lead to a breakdown and/or irreversible damages to FPC. Multipacting is observed when two conditions are fulfilled:1) a kinematic condition: the phase of primary electrons (emission) and secondary electrons (impact) with respect to the electrical field should be an odd multiple of π, 2) a multiplication condition: the Secondary Emission Yield (SEY) should be higher than unity. Due to the aforementioned arguments, multipacting is one major topic addressed in RF components (cavities, FPC) design and development. Multipact is a project that brings together the LPSC, IPN O and LAL laboratories (IJC Lab) and which will materialize the studies that since 2003 have been carried out at LPSC and since several years at IPN Orsay and LAL, now IJC Lab.
Thus, at the IJC Lab the TiN sputtering bench will be put into operation to be able to carry out the deposits for the study or more. And the secondary emission coefficient bench (SEC or SEY) that will be put into operation and with the PANAMA platform the deposits can be characterized. The main objectives of multipacting studies are threefold: 1) progress in understanding the physical processes involved and thoroughly characterize them, 2) develop surface treatment, preparation and conditioning (i.e. ramping the RF power in the device)

procedure for RF components in order to reduce or ideally avoid multipacting, 3) develop numerical simulation tools allowing the engineering and design of nearly multipacting free RF components. Although multipacting is a phenomenon observed and studied since several decades, more investigation is needed to understand and quantify the effect of the following parameters: surface conditions (i.e. chemical composition, roughness, adsorbed species) of materials subjected to RF field, foreign dust particles, residual gas pressure and chemical composition. An experimental set-up dedicated to multipacting studies was developed and successfully operated at LPSC. The RF component (e.g copper tube or alumina window) to be tested is inserted in this test-stand. The experimental device consists of a variable frequency coaxial copper cavity made up of two coaxial lines, of different lengths and connected by a tee. It is 3λ / 2 in length, where λ is the wavelength corresponding to the RF device frequency in the range 100 MHz - 1000 MHz. This device is aimed at investigating the effect of various surface treatment and TiN coatings (standard material used for reducing multipacting) on the behavior (i.e. multipacting levels and intensities) of the RF component. Moreover, the prediction of this phenomenon (i.e. determination of multipacting barriers) remains empirical or through 3-D numerical simulation codes. Few years ago, IJCLab developed a unique and useful tool the software MUSICC3D: it is a 3D code dedicated to numerical simulation of multipacting in RF components (cavities, FPC, HOM coupler). MUSICC3D was successfully used at JICLab for the design and optimization of the shape of ESS and MYRRHA spoke cavities. It allows the prediction of multipacting barrier in these resonators. Obviously it will be useful for future projects were a careful design and optimization of cavities and couplers is mandatory. In this project, the experimental measurements obtained will be compared to theoretical models and MUSICC-3D. For running MUSICC-3D, SEY of materials is an important input parameter: the output is the virtual charge produced by multipacting. We plan to perform new measurements of SEY of different materials using the PANAMA facility: the corresponding data will be implemented in MUSICC-3D database. We will also study the correlation between the measured electron currents and the "virtual charge" issued from MUSICC3D code and determine the critical value of the current prior to RF component breakdown or damage. Obviously the damage of RF component should be avoided: MUSIC-3D could help in predicting and evaluating the risk level of multipacting.In order to reduce the multipactor SEY , anti-multipactor thin (~1nm) coatings are used, especially for alumina windows of FPC. Due to their small thickness, the production of such coatings is challenging. More precisely, If the thickness is too small the deposit does not achieve the needed performance (i.e. significant reduction of SEY) and if it is too thick, the dielectric losses (proportional to the volume) are increased resulting in the material overheating and damage (thermomechanical stress). We use 10 nm thick TiN coating. However, several open questions and issues about TiN coating are still addressed. How to perform precise measurement of the TiN thickness, which is a critical parameter? What are the optimum values in term of composition of Ti and N species? The technical method and the process parameters for producing TiN coating have an impact of the chemical composition of the deposits (Ti, N, O) (Fig 1). This chemical composition, which is a critical parameter for the coating performance depend strongly on the thickness. Furthermore, it may vary with time (chemical stability). It is then needed to we develop and qualify the process for keeping the coating characteristics stablein time and at the various steps (brazing, cleaning, storage, removal of oxydes) of FPC production and preparation. Moreover, our observation showed some foreign elements such as carbon in the stoichiometry of the coating: what is the carbon source and what is the effect of carbon on the coating performance and lifetime? We will fully characterize the coating (thickness, stoichiometry, SEY, conductivity) in order to find the optimum values of these parameters and get a tight specification for a reliable large scale production.

VIII. Fast Active Cold Tuning Systems

The development program of Fast Active Cold Tuning Systems (FACTS) is driven by the needs of ESS (pulsed machine), PIP II (high quality factor and high accelerating gradient?) and

MYRRHA (high reliability and availability). The main function of FACTS are : 1) slow tuning, after the cool down of the cavity from 300 K to Liquid Helium (LHe) temperature (T=2K-4.2 K), of the resonator fundamental frequency to the RF source frequency. The corresponding detuning (~+/- 50 kHz) is due to uncertainties of cavity preparation (chemical etching, furnace degassing) and the differential thermal contraction between materials (cavity: Niobium, LHe tank: titanium, supporting rods: epoxy-glass or titanium), 2) fast and dynamic compensation of Lorentz detuning due to small cavity wall deformation (1-10µm), when subjected to RF surface field, 3) reduction and damping of vibrations and micro-phonics induced by the environment (vacuum pumps, cryogenic system, external perturbations). IN2P3 in kid contribution to ESS includes the design, development and production of 13 cryomodules. Each cryomodule houses two double spoke cavities with their LHe tank and fully equipped with the RF power coupler, FACTS, magnetic shielding and cryogenic instrumentation. A FACTS dedicated to ESS Double-Spoke cavity cold tuning was studied, designed: two FACTS prototypes were produced in the industry, assembled and instrumented at IJCLab. These FACTS were attached to a ESS double-spoke cavity and successfully qualified (acceptance tests) at cryogenic temperatures in a vertical cryostat. These prototypes were thoroughly investigated to gain experience and develop the serial version of ESS FACTS. The main criteria and new requirements for the serial version are: 1) easy assembling, 2) reduced manufacturing costs, 3) increased reliability at cryogenic temperature under vacuum, 4) integration of safety and diagnostic system to ensure optimal operation and maintainability, 5) use of materials withstanding ionizing radiation up 500 kGy. Moreover, a test stand was developed and successfully used for the characterization, at cryogenic temperatures, of piezoelectric actuators from three suppliers. We measured the following parameters of these actuators as function of temperature: maximum stroke, dielectric properties (capacitance, loss tangent), dielectric losses when the actuator is subjected to sinusoidal voltage. Note that several years ago (framework: CARE), we performed radiation hardness tests with fast neutrons at 4.2 K with a neutron fluence of 10^{15} n/cm^2 : all the actuators tested sustained this radiation without any significant damage or performance reduction. We have also developed and successfully qualified an innovative thermal uncoupling system: it will be used for testing the fault tolerance strategy for which a fast detuning of MYRHHA cavity is needed. In order to increase the qualification and acceptance test rate of the FACTS at liquid nitrogen temperature, we have developed a dedicated test stand. This facility, which allow the test of four FACTS simultaneously, is routinely used for acceptance runs with high reliability and repeatability. The test stand was also used for reliability and lifetime studies of ESS FACTS. We have successfully produced and tested 26 FACTS for ESS spoke cryomodules. The FACTS qualification test stand will be used for other SRF projects (e.g. PIP II, MYRRHA) with requirements and performance higher than those of ESS. Finally, During the production phase, a quality assurance plan was implemented in order to guarantee a successful production of the FACT by industry.

IX. LLRF for MYRRHA

In the framework of MYRRHA ADS, IN2P3 developed for MINERVA (part of MYRRAHA consisting of a 100 MeV protons linac) a Superconducting RadioFrequency (SRF) Accelerating SYStem. This SRFACSYS includes: 1) a prototype cryomodule housing two spoke cavities fully equipped (Main Power coupler, Fast Active Cold Tuning System (FACTS), Magnetic Shielding, Cryogenic instrumentation), 2) the RF source, 3) The Low Level RF system (LLRF) allowing the operation and control of the cryomodule. For MYRRHA, the reliability, beam availability and quality are of a prime importance. The LLRF system, jointly with the FACTS will be used to operate the cryomodule at T=2K in order to tune and optimize the operation parameters and asses if the following important needed requirements are fulfilled: 1) Fault tolerance operation and machine protection so as to insure the system reliability, tuning flexibility and beam availability, 2) Lorentz detuning dynamic compensation and micro-phonics damping as well as regulation of the resonator frequency and the field (amplitude and phase) in order to obtain the needed beam quality and achieve a good acceleration efficiency. We have chosen the MTCA technology, which is compact and well suited for this application. In close collaboration with the industry, we developed various printed circuit board dedicated to fault operation detection and interlocks, RF front-end. A tight collaboration with industry is mandatory in order to guarantee the availability of the needed components/elements on shelf and to allow an easy upgrade and maintenance. The second R&D topics is devoted to modeling and numerical simulation of the following system: 1) the SRF cavity in operation with the beam and subjected to several perturbations (Lorentz detuning, micro-phonics), 2) LLRF feed-back part. The main objective is tune efficiently and optimize the regulation parameters.

X. Fundamental Power Coupler

The main function of the Fundamental Power Coupler (FPC) is the efficient transfer, in matched condition, of the RF power from the source through the waveguide network to a beam-loaded cavity operating under UHV conditions. This impedance matching network operates in stringent conditions:

a) Handle and transmit a high RF power (10 kW-500 kW) through a ceramic window,
b) It is a low thermal conductance interface between warm (T = 300 K) and cold parts (T = 2–4.2 K) of the cryomodule
c) It is a RF transparent vacuum barrier between atmospheric pressure in the wave guide operating at room temperature and ultrahigh vacuum (<10^{-8} mbar) in the SRF cavity at T= 2 K.

The FPC should satisfy other important requirements:1) to be multipactor-free or equipped with component allowing to cure multipacting (e.g bias voltage, magnet), 2) Easy assembling and suitable to clean cryomodule assembly procedures to minimize the risk of particle contamination of the superconducting cavity, 3) minimize heat load to the cavity at the coupling port so as to not impact the RF performance (quality factor and accelerating field), 4) minimize cavity field perturbations which could impact the beam quality or cavity performance.In some applications, the reliability of the RF power coupler could be very demanding: for example, in the case of the ADS (Accelerator Driven System) SRF based linac MYRRHA, less than five beam trips in excess of 1 s duration per year are tolerated. The key technologies pertaining to FPC development are mainly: 1) material properties of alumina window, 2) vacuum brazing, 3) surface treatment (copper plating of inner and outer conductors), 4) heat intercept at cryogenic temperature or cryogenic heat exchanger for FPC handling RF power in excess of 50 kw in CW mode operation.

A complete study on the multipacting is done on spiral2 couplers.

The SPIRAL 2 coupler was designed according to the aforementionned criteria and constraint. Multipacting simulations performed with MUSICC3D leading to the following results: 1) no resonant electron trajectories on the coupler window is observed, 2) very low level of multipacting activity at a forward RF power P_{RF} ~100 W RF power. These numerical simulation results were confirmed by experimental runs data: 1) on the test bench low multipacting activity (<0.2 mA at power lower than 200 W) is measured, 2) on the cryomodules RF power conditioning of the fundamental power coupler multipacting barriers are found for RF power in the range 30-600 W and in particular at P_{RF} ~100 W with a maximum electron current lower than 0.6 mA.
As an anti-multipacting coating on the ceramic window is generally agreed upon by the community SPIRAL 2 choose to test the TIN coating. For this, SPIRAL 2 order 4 couplers with TiN coating with thickness of 30± 5 nm, 10±2 nm and 1 nm. The TiN coatings are made by

sputtering process, before window brazing, as the design of the coupler did not allow a post-brazing coating. The Rutherford Back-scattering Spectrometry measurement has validated the thickness control of the coating and show that the baking changes the feature of the coating, for example, it increases the proportion of oxygen up to 10% and so its conductivity. The couplers tested in RF in a push – pull configuration up to 40 kW 100 % duty cycle in travelling wave mode shows minor differences in multipacting measures between couplers with and without TiN as already low multipacting (<0.2 mA at power lower than 200 W) is measured in uncoated couplers. But it is observed that the TiN coating led to temperature increase with RF power, which show that it is very important the choice of the TiN thickness and its stoichiometry.

Annex1 Supratech IJCLab facility

Context:

The facility includes equipment and technical area for the development, the preparation, assembling and testing SRF cavity, accelerating cryomodules equipped with the cryogenic cold box and housing SRF cavities fully dressed with their ancillaries (e.g. power coupler, magnetic shielding, cold tuning system, pumping systems, instrumentation).The cold tests are performed at liquid helium temperature in the range 1.7 K- 4.2K. The RF instrumentation and RF power sources allow to perform both low (up to 200 W) and high RF power (from 80 kW to MW peak power) tests at two main frequencies: 352 MHz and 704 MHz.

Technical means:

1. Chemical etching facility

Goal: Chemical etching of the RF surface of the cavity for removal damaged layer and/or possible surface contamination

Features:

- Operational since 2009
- Acid mixture for Buffered Chemical Polishing (BCP): Phosphoric, Nitric and Hydrofluoric (2.4:1:1)
- Volume of acid: 180 L
- Average etching rate: 0.5 µm/minute
- Chiller to maintain cavity temperature between 15 and 20°C
- Typical etching depth: between 10 and 250 µm
- Maximal Niobium concentration in acid 50 g/l
- On average 10 cavity processing per year

Characterization and quality control:

- Ultrasonic probe (local depth measurement)
- Roughness meter
- Optical microscope (×1000)
- Bright Field, Dark Field, Polarized light

Weighing of a cavity

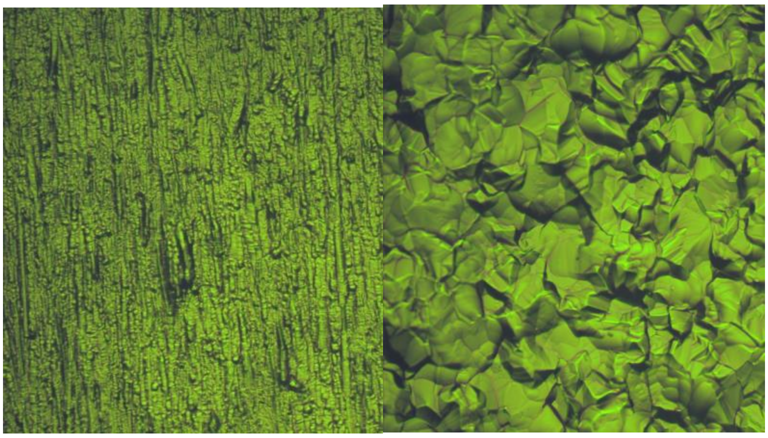
Ultrasonic cleanin: 200L Ultrasonic bath operating at a power of 10 kW/l (dimensions 100x50x50)

Cavity preparation

BCP etching

Rinsing with ultra-pure water

Etching of Spiral2 QWR



Left: surface morphology prior to BCP etching (×200)

Right: surface morphology state after 100 µm BCP etching (×200)

2. Clean room dedicated to SRF cavity preparation and cryomodules assembling

Goal: Final SRF cavity preparation and assembling

Features:

- Total area: 85 m^2, class 10 (ISO 4) area: 45 m^2
- Controlled ambient temperature and humidity.
- Filtered N2 and He gases (for leak tests and particle counting)
- Versatile handling carts for cavities of various shapes and dimensions (elliptical, Spoke, QWR)
- Particles Counter (Range : 0.3 µm-25 µm)
- Deionized water tank: 1500L (about 4h00 of HPWR process)
- Leak detectors (Helium spectroscopy)

Clean room in operation since 2007

Particle counting

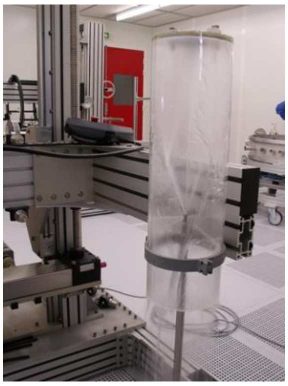
3. High Pressure Water Rinsing (HPWR) System

Goal: Reduce field emission and increase accelerating fields

High pressure water rinsing is currently a standard process for SRF cavities preparation prior to cold tests. It allows efficient removal of potential metallic and dielectric dust particles (field emitters) from the cavity RF surface

Features:

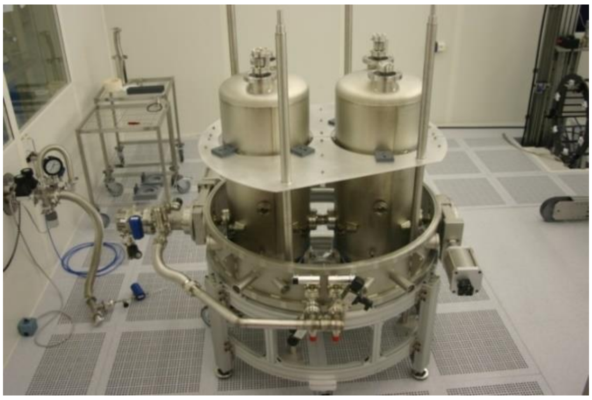
Ultra-pure water (18.2 MΩ·cm) flow rate: 100 l/h
HPWR system: Pressure: 100 Bar, Flow rate: 400l/h



High Pressure Water Rinsing (HPWR) System

Assembling of Spiral2 Quarter Wave Resonator (QWR) in clean room

Assembling of Spiral2 cryomodulein clean room



Assembling of cavity for power coupler conditioning

Assembling of 700 MHz protons cavity (R&D for MYRRHA)

4. Cryogenic infrastructure

The cryogenic infrastructure, which includes two tests areas respectively located in the buildings 103 and 106, consist of the following equipment's:

1. An helium liquifier (Linde L70)
2. Helium pumping systems for tests in superfluid helium
3. Gaseous helium recovery for recycling after use
4. A cryogenic test facility #1located in building 103
5. A cryogenic test facility #2 located in building 106
6. Three test stands with vertical cryostats (ID: 800 mm, 350 mm and 125 mm)
7. Several cryogenic inserts for cavity testing, material and component characterization at low temperature
8. A facilty for calibration of cryogenic thermometers in the range 1.6 K -300 K

• Production of liquid helium and recycling of gaseous helium

Production of liquid helium

Liquid helium is produced at IJCLab using a commercial helium liquefier Linde L70: the liquefier is in operation since 2009 with a liquefaction rate of 70 l/h. More than100 000 l of liquid helium (LHe) were produced since 2009, including 50 000 l of LHe used for Spiral2 project.

Linde L70 helium liquefier

Recovery, compression and recycling of gaseous helium

Due to heat load, during the cryogenic tests the liquid helium is evaporated. The resulting gaseous helium is then recycled after use. Helium gas is recovered, compressed then stored prior to be purified and re-liquefied. The Gaseous helium storage capacity corresponds to 3000 liters of liquid helium

Gaseous helium inflatable balloon

Three stages room temperature helium gas compressor

Pressurized (200 bars) gaseous helium storage

- Helium pumping systems

The two cryogenic test facilities of building 103 and 106 allow experimental test with saturated liquid bath at subatmospheric pressures. Rotary vane pump and roots pumps are used for reducing vapor pressure of liquid helium down to mbar corresponding to a bath temperature

of 1.6 K.

Helium pumping systems

The available refrigeration power (temperature T= 2K) for the two cryogenic tests facilities (Bldg 103 and Bldg # 106) is given in the following table

Test area #	Site#1	Site#2	Site#3
1	10W@2K	20W@2K	40W@2K
2	40W@2K	80W@2K	

5. Cryogenic test facilities and test stands

Cryogenic test area #1- Bldg 103

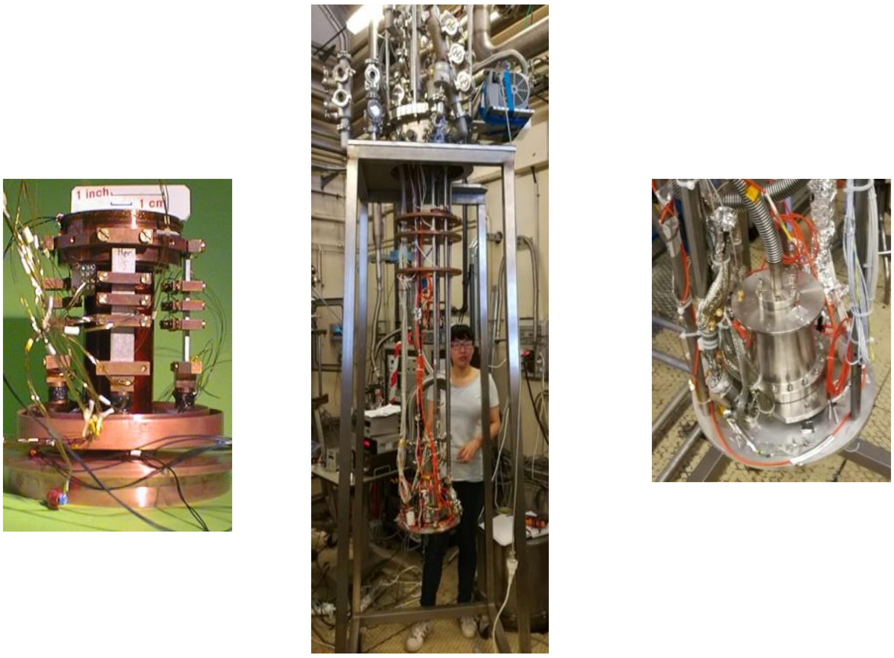
This area consists of 4 tests stand where cryogenic tests are performed in vertical cryostats (ID: 800 mm, 350 mm and 125 mm) from 300 K down to 1.6 K. The fourth test stand is dedicated to precise automatic calibration of temperature sensors in the range 1.6 K- 300 K.

These experimental facilities allow low power RF test of SRF cavities resonating at the following frequencies: 88 MHz, 352 MHz, 704 MHz, 1.5 GHz, 3 GHz, 3.8 GHz and 5.6 GHz.

Vertical test of cavities of a ESS double spoke cavity (f=352 MHz)

Low temperature characterization of material used for the fabrication of srf cavities and ancilaries

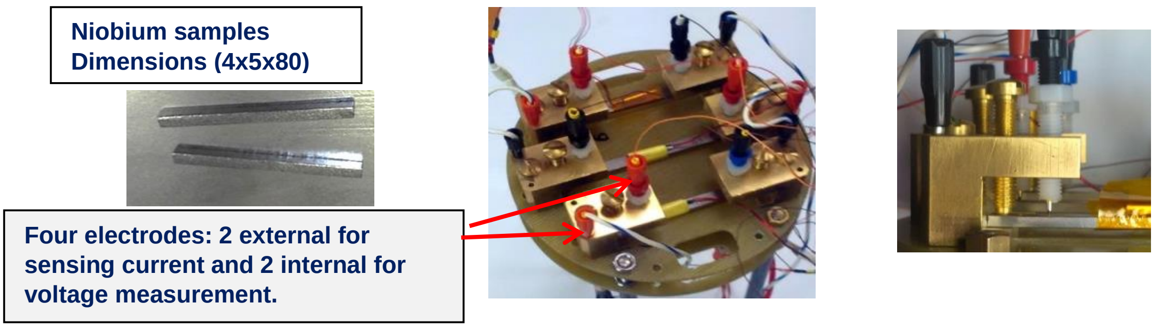
Two tests apparatus with several cryogenic insert are used for material and components characterization at low temperatures. They allow the measurements of electrical, superconducting, electromechanical and thermal properties at low temperatures. One insert is dedicated to R&D on special sensors and electronics for investigation of anomalous RF losses and phenomena limiting the performance of SRF cavities (e.g quench detection via second sound events, surface thermometry, field emission probes).



Thermal conductivity test cell and its cryogenic insert

- **Electrical resistivity and RRR measurement**

The RRR is defined as the ratio between electrical resistivity of the material at the ice point (T=273K) and the residual electrical resistivity ρ_R measured at the liquid helium normal boiling point (T=4.22 K). This measurements is performed using the standard DC four probes method with reversing the sensing current to eliminate parasitic thermoelectric voltages.The electrodes are clamped to the flat test sample by means of copper-beryllium springs (contact pressure: ~12 Bars). The test sample (length: 80 mm), is equipped with a calibrated Cernox thermometer (T=1.6K– 300 K) and immersed in a saturated liquid helium bath at T= 4.2K. The sensing current of 1 A, is delivered by a precise standard DC voltage supply, is on-line measured via the voltage drop across a precision resistor.



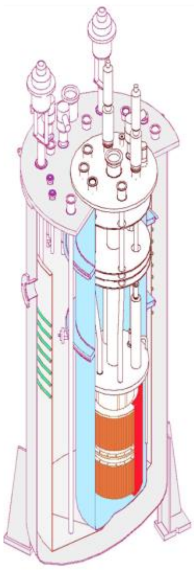
Electrical resistivity test-cell, close view to electrodes and niobium samples

Cryogenic thermometers calibration facility

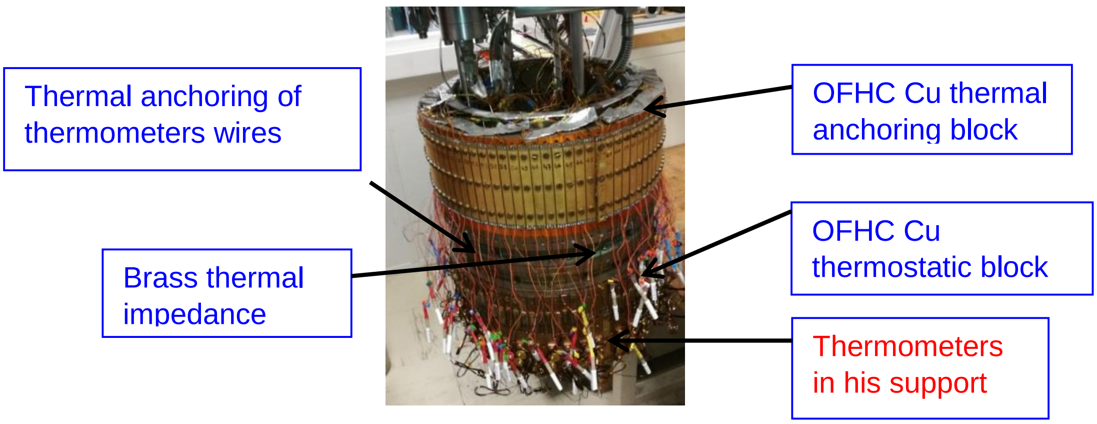
The cryogenic thermometers calibration facility was designed and constructed in the frame of the Large Hadron Collider (LHC). More than 5000 thermometers were calibrated with this facility. These sensors (1800 sensors for the magnets and the 3200 for the cryogenic lines and equipment) are used for cryogenics and operation process of the LHC.

Features:

- Calibration is performed by comparison to reference sensors: the thermometers to be calibrated are mounted on the same thermostatic copper block as the 4 reference thermometers (4 RhFe working temperature references)
- Temperature range: 1.6 K-300 K
- Absolute accuracy of ± 5 mK from 1.6 K to 4.2 K
- Relative accuracy: 1 % of temperature T in the range 4.2 K -300K.
- Capability: up to 90 thermometers
- Temperature of the thermostatic OFHC copper block is regulated (PID) by means of a heater attached to the block and helium cooling loop.
- Automatic data acquisition and analysis (fit of experimental data)
- Calibration data saving in a dedicated database
- A vapor pressure bulb soldered on the calibration block and connected to a pressure sensor is used as a primary temperature reference for in-situ control of the working standard thermometer calibration



Cryostat and calibration cryogenic insert



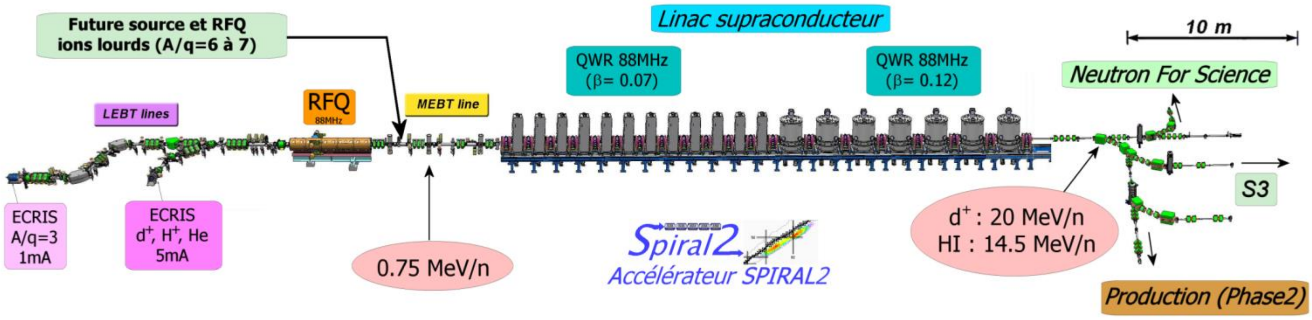
Cryogenic thermometers calibrati

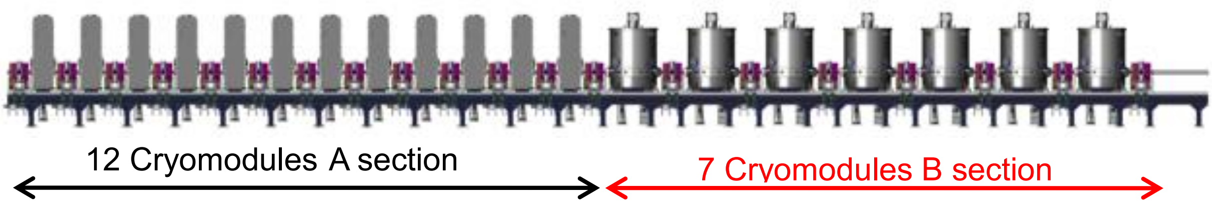
Some recent developments

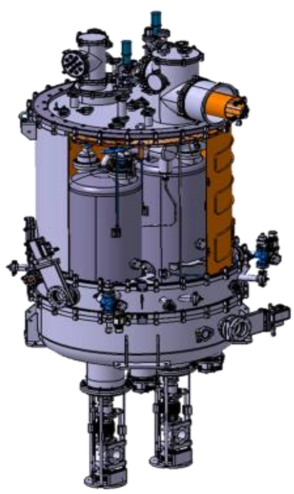
High energy section of the SPIRAL2 superconducting LINAC

Main achievements:

- Fourteen 88MHz QWR, β=0.12 SRF cavities successfully tested
- High energy section β=0.12 superconducting linac consisting of seven cryomodules CMB1 to CMB7. The 7 crymodules housing each, two QWR fully equipped (power coupler, cold tuning system, magnetic shielding, and cryogenic instrumentation) were assembled, completed, successfully tested, shipped to GANIL and installed.
- Cryogenics for sipral2 (helium refrigerator, 19 cold boxes, cryogenic lines and cryogenic instrumentation for the whole linac).



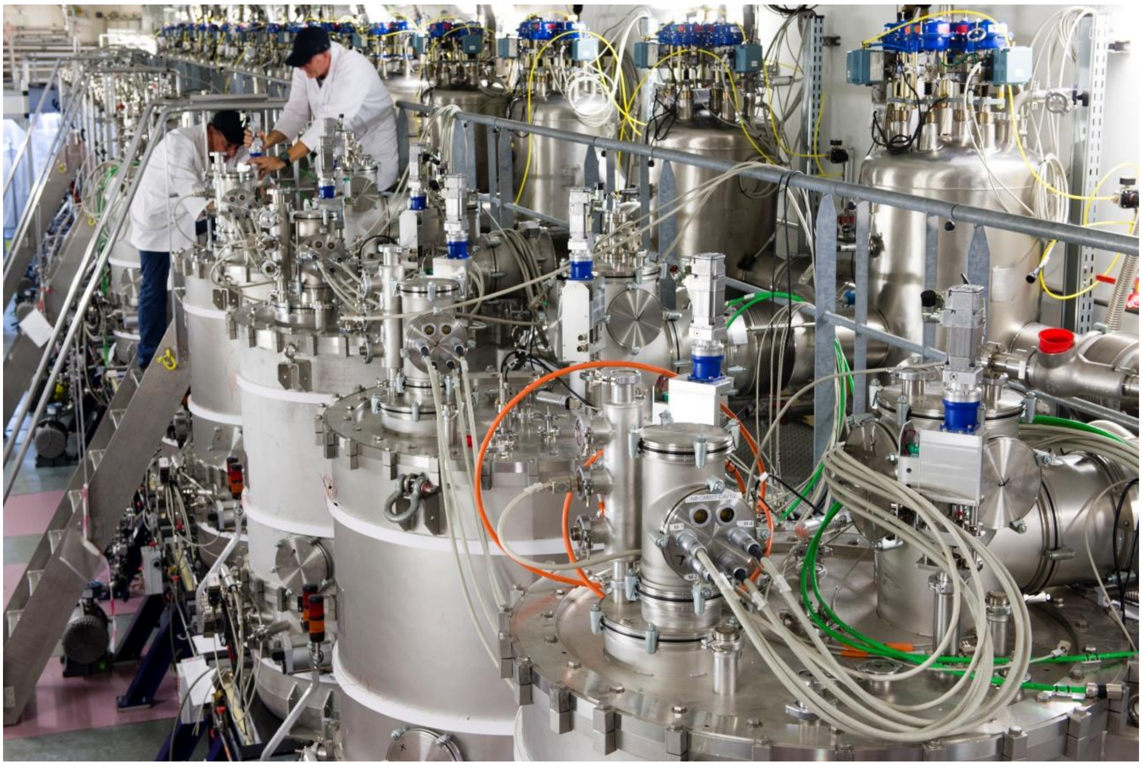




Spiral2 cryomodule B

Cold boxes of spiral2 superconducting linac

Helium refrigerator and one cold box of spiral2 superconducting linac



Spiral2 superconducting linac during installation at GANIL

Annex2 IJCLab Power coupler Infrastructure

Context:

Clean rooms are available for cleaning, assembling, preparing and RF conditioning of power couplers. The existent infrastructures and equipment are adapted for mass production at a rate up to 8-10 couplers per week.

Technical means:

First clean room (ISO4 and ISO6):

- 200L Ultrasonic bath functioning at a power of 10 kW/l (dimensions 100x50x50)
- 1 Leak detectors,
- 1 particle counter,
- 1 vacuum furnace reaching up to 400°C,
- 25m^2 ISO6 area for cleaning and assembly.

- $12m^2$ ISO4 area for clean assembly,

Second clean room (ISO5) :

- 3 baking ovens equipped with in-situ pumping systems hosting 2 coupler pairs each, reaching up to 220°C and totally automatized with possibility of thermal cycle and vacuum level recording.
- 2 leak detectors,
- 4 RF test benches equipped with all the required diagnostics for coupler pairs conditioning (Arc detectors, electron pickups, vacuum monitoring, temperature sensors, power measurements...),
- $40m^2$ ISO5 area for assembly-disassembly and clean storage.

RF Power sources

- 1 RF power source 1.3 GHz, 2MW with variable repetition rate (2-4Hz) with the required waveguides, circulators, spreaders, loads…
- 1 RF power source 1.3 GHz, 5MW with variable repetition rate (1-10 Hz) with the required waveguides, circulators, spreaders, loads...

Achievements, related projects:

- About 60 TTF3 power couplers cleaned, assembled and RF processed before installation on FLASH (DESY),
- Mass production (preparation and RF processing) of 850 power couplers for the European XFEL.

Technical steps, expertise:

- Ultra sonic cleaning of power couplers,
- Clean room assembly,
- Leak detection,
- In-situ baking (up to 220°C) and vacuum monitoring during the process,
- RF Tuning,
- Residual gas analyser recording,
- Couplers automatic RF conditioning procedure (8 couplers in the same time),

Annex 3 Field of Expertise and Relevant Infrastructure or equipment at IJCLab

Field of Expertise	Relevant Infrastructure or equipment
• Design, fabrication and operation of Accelerating cryomodules including low level RF, and high power RF components	• Design softwares and numerical simulation codes (RF, Mechanical, thermal design) • 3D code for multipacting simulation
• Treatment and preparation of SRF cavities	• BCP facility • Clean Room with HPWR • Low temperature baking facilities
• Cleaning and preparation of power couplers	• ISO 5 clean room equipped with ovens for in-situ baking, adapted to mass production • ISO 4 clean room for clean assembly equipped with particle counter, leak detector • ISO 6 clean room for coupler cleaning equipped with 200l ultra-sonic bath, vacuum furnace
• High vacuum, High temperature (500 °C-1400°C) heat treatment of SRF cavities • Nitrogen infusion an Nitrogen doping	• Vacuum furnace
• Material and surface Characterization	• Optical microscope • Profilometer (contact) • SEM (Scanning Electron Microscopy) • Confocal microscope • Compact SIMS (Secondary Ion Mass Spectrometer) • Grazing X-Ray Diffractometer
• Cryogenic tests	• Helium liquefier: *Liquefaction rate: 70 l.h^{-1}* • Pumping system for sub-atmospheric operation of cryomodules and vertical cryostat
• Vertical acceptance Tests of SRF Cavities at cryogenic temperatures	• Low Temperature Vertical Tests Stands of SRF Cavities at low and high RF power and operating at different frequencies (88 MHz, 352 MHz, 704 MHz, 1300 MHz, 3-6 GHz) with a dedicated
• High power RF Tests of cryomodules (e.g. horizontal cryostat housing fully equipped cavity, with LHe Tank, Magnetic Shielding, Power Coupler, Cold Tuning System and cryogenic instrumentation)	• High RF power test stand at 352 MHz • High RF power test facility for coupler conditioning at 352 MHz • 2 High RF power test facility for coupler conditioning at 1.3 GHz
• Cryogenic instrumentation	• Calibration facility for cryogenic thermometers
• Test stands for RF and DC characterization of samples	Electrical resistivity, thermal conductivity, Kapitza resistance, heat transfer TE011 cavity (RF properties of materials), SEY measurement