L'équipe MAVERICS

Matériaux pour Accélérateurs Vide dynamiquE et Recherche Innovante pour Cavités Supraconductrices

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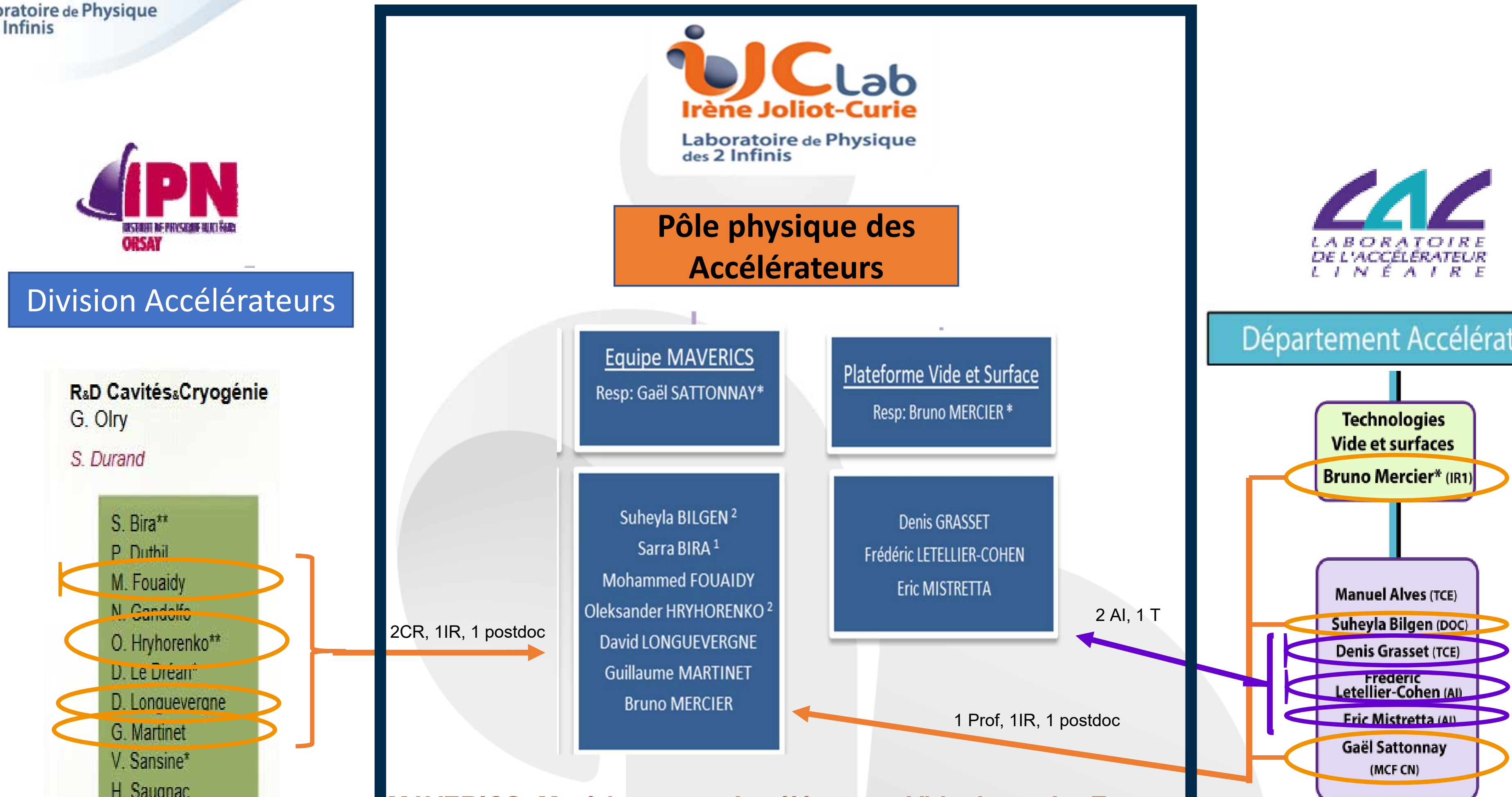
+

La plateforme vide et surfaces

Bruno Mercier

Pôle Physiques des accélérateurs

LE CONTEXTE



MAVERICS: Matériaux pour Accélérateurs Vide dynamiquE et Recherche Innovante pour Cavités Supraconductrices

Les Motivations

Formation d'une équipe de recherche et d'une plateforme autour des problématiques vide, surfaces et matériaux pour accélérateurs

➢ Motivations

Les performances fonctionnelles (gradients accélérateurs, pertes RF, qualité faisceau, Ultra Vide,...) des composants (structures accélératrices, lignes faisceaux..) sont étroitement **liées aux propriétés des matériaux**

→ limites intrinsèques des matériaux utilisés actuellement sont atteintes

➢ Objectifs:

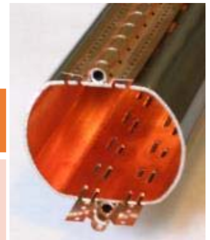
- **MAVERICS**
  - ✓ **Recherche :** améliorer notre compréhension des phénomènes physiques limitatifs liés aux matériaux et de leur surface
  - ✓ **Etudes/Développement :**
    - De procédés de traitement de surface ou de traitement thermique
    - De nouveaux matériaux / matériaux alternatifs (couches minces)
- **Plateforme Vide et surfaces**
  - ✓ **maintenir, acquérir et adapter les moyens d'analyse de surfaces pour répondre aux mieux aux problématiques des matériaux pour accélérateurs**
  - ✓ **maintenir et développer une expertise sur des projets ultravide (UHV)**

MAVERICS : Thématiques de recherche

amélioration des performances des accélérateurs de hautes énergies

Nouveaux matériaux supraconducteurs pour cavités RF

Vide dynamique
Interactions rayonnement-surfaces



	Cavités SRF	Lignes faisceaux / chambres à vide		
	Augmenter les gradients accélérateur Réduire les pertes RF	**Limiter le multipacting**	**Limiter les augmentations de pression**	
Traitements de surface	Niobium massif : thermique, dopage/ infusion N, polissage *(Projets HELOISE et PACCAS du MP SRF)*	Traitements thermiques Conditionnement des surfaces Nettoyage plasma, UV		**Traitements de surface**
Couches minces	Matériaux alternatifs : multicouches supraconductrices S-I-S *(Projet AXE SRF du MP SRF)*	TiN, Carbone amorphe, NEG *(Projet MULTIPAC du MP SRF + CNRS 80PRIME)*		**Couches minces**

- Participation in accelerator design / construction projects (PIP2)
- Participation in the Transverse Group FATI (metal additive manufacturing) / Project FABBAC

Nécessité de développer des moyens d'analyse de surfaces et d'ultravide

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

cnrs université PARIS-SACLAY FACULTÉ DES SCIENCES D'ORSAY Université de Paris

Plateforme Vide et surfaces (V&S)

Expertise en vide

Calculs et Simulations

Moyen d'analyses UHV

- Spectrométrie de masse
- Mesure de taux de dégazage
- **Mesure du taux d'émission électronique secondaire (SEY)…**

Mise en œuvre installations UHV / dépôts

- Traitements thermiques et chimique
- brasage fort
- Dépôt NEG / TIN

Enseignement / Formation

Moyens de caractérisation des surfaces

Informations: **Structurales** **topographique**: **Composition**:

- **Diffractomètre à rayons X rasant (DRX)**
- spectrométrie des ions secondaires (SIMS)
- microscope confocal

P2IO Physique des 2 Infinis et des Origines

nouveaux équipements

En 2021

- microscope électronique à balayage(MEB) + microsonde X (EDS) + **diffraction des électrons (EBSD)** **(Fin** îledeFrance
- Récupération d'un bâti multi techniques d'analyses (XPS, **RHEED**)

En 2022/23 (equipex PACIFICS)

- spectromètre de photoélectrons (XPS de routine)
- Bâti multi techniques d'analyses à froid (XPS, SEY)

Regroupement de tous les équipements dans les Halls D3 et D4 (420m^2) après leur réhabilitation (début 2022)

Bât. 209C
Hall D3 D4 de l'IGLEX (CPER)

MAVERICS Activities

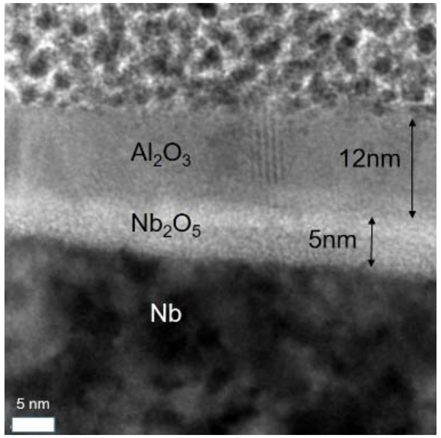
- **Dynamic vacuum**
  - ***In situ* measurements of pressure, ion and electron currents during the LHC run II operation (collab. CERN).**
  - **ISD (ion stimulated Desorption) yield measurement (collab. CERN)**
  - **Surface analysis of materials**
  - **Modeling and simulation of dynamic pressure**

- **SRF accelerating cavities**
  - **Heat treatment processes and N_2 infusion/doping of Nb surface**
  - **Alternative path for SRF cavity fabrication and surface processing**
  - **Thin films as alternative superconducting materials**
  - **Thin films for multipacting mitigation**

Multipacting mitigation for SRF cavities and beam lines

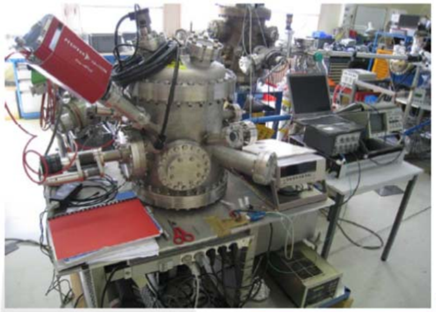
→ Study of multipacting and how to mitigate this phenomenon *(Master Project SRF + EPISAMA)*

- **Collaboration for thin films elaboration by ALD (Atomic Layer Deposition):**
  - -CEA/IRFU (couches supra)
  - -SIMAP Grenoble (projet EPISAMA/AP CNRS 80prime : IJCLAB-SIMAP-LPSC – PhD thesis + funding) *« Exploration of Surface Engineering Processes Anti-Multipacting effect for Particle Accelerators. »*



MET – coupe transverse (A. Gentils/S. Jublot-Leclerc)

- **SEY measurements (@RT / @cryo T) / Surface analysis (IJCLAB)**

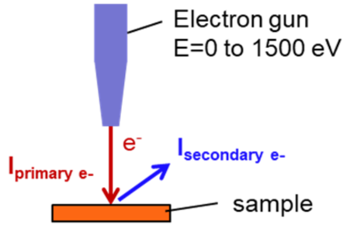


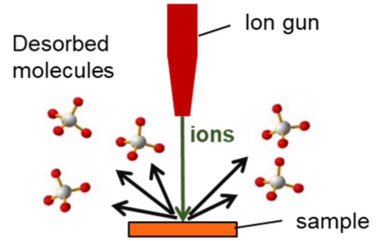
Sey IJCLAB

- **Multipacting test (LPSC- Y. Gomez Martinez)**

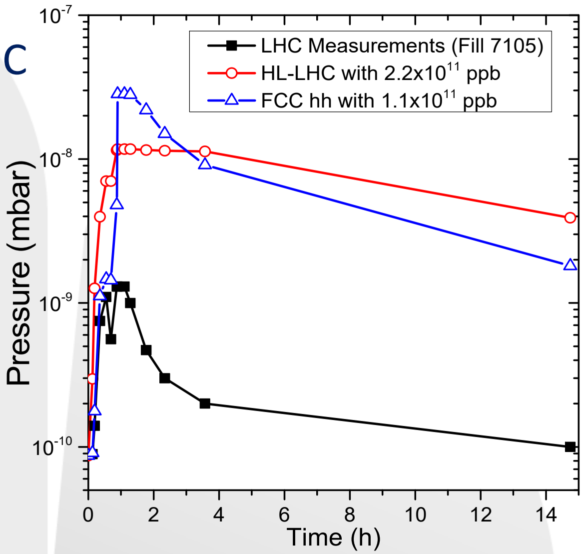
Objectifs prioritaires (à 5 ans)

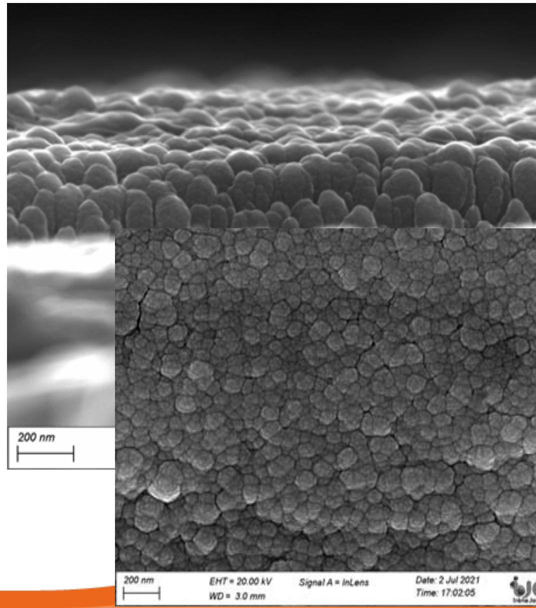
Etudier le vide dynamique dans les collisionneurs (Master Projet New Particle Colliders – Projet Vacuum : vide dynamique dans FCC-ee)





- Emission électronique secondaire des dépôts NEG (rôle de l'épaisseur)
- Mesures des rendements de désorption ionique
- Nouvelle série de mesures lors du prochain run du LHC
- Améliorer/optimiser le code DYVACS :
outil prédictif du vide dynamique dans FCC-ee



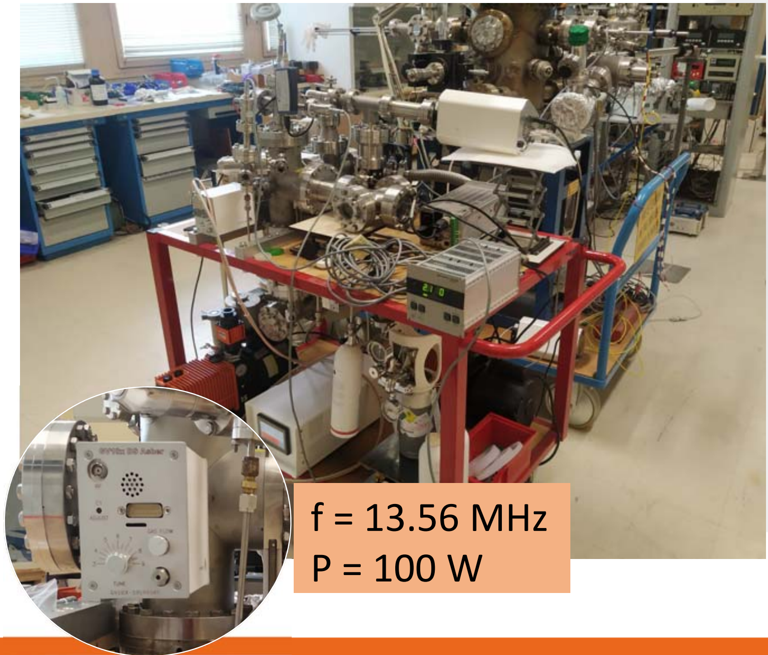


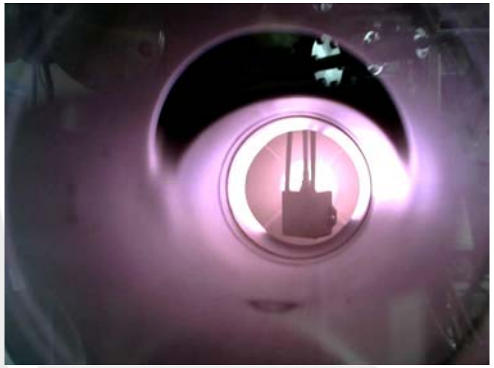
Objectifs prioritaires (à 5 ans)

Innovative surface treatments for SRF cavities

→ Contribute to improving the performance of RF superconducting cavities through the use of innovative surface treatments (*Master Projet SRF*)

- ➢ Surface preparation by mechanical polishing (PACCAS)
- ➢ Nitrogen infusion / doping of Nb (HELOISE)
- ➢ Multilayer deposition (Supra-Insulators-Supra) on Nb (IRFU-Axis SRF collab)
- ➢ **Plasma cleaning (SPIRAL2 cavities, collab. GANIL)**





C-coating removal versus time

Plasma cleaning set-up with the SPIRAL2 cavity

Conclusion

AXES	activités	2021	2022	2023	2024	2025
Materiaux en couches minces	Coating production (NEG, a-C, TiN…)					
	Structural characterization					
	Measurements of electron emission properties (multipacting/electron cloud)					
Traitements de surfaces innovants pour des cavités en Nb	nitrogen infusion experiment					
	Superconducting multilayers (S-I-S)					
	Polishing					
	Surface cleaning (plasma, UV)					
Vide dynamique	Measurements of the ion and electron stimulated desorption					
	Study of changes in surface properties induced by irradiation (conditioning)					
	Development of the simulation code DYVACS					
	Measurements at CERN-LHC (run 3)					
Développement de la Plateforme « Vide et Surfaces »	Mise en service des bâtis de dépôt					
	Installation MEB					
	Formation ISIS Set-up (ICMMO)					
	Développement du bâti SEY (coupe Faraday)					
	Intégration des équipements dans D3-D4					
	Installation XPS+ bâti-multitechnic (PACIFICS)					

➢ + Participation à la conception / construction des projects (PIP2, THOMX, + PERLE, +Einstein télescope ?)

➢ Evolution des Ressources Humaines

Equipe MAVERICS en 2020

- **D. Longuevergne**, **CR**
- **G. Sattonnay, Pr**
- **G. Martinet, CR**
- **M. Fouaidy**, **IR**
- **B. Mercier, IR**
- **O. Hryhorenko**, **doc**
- **S. Bilgen, doc**
- **S. Bira, doc**

Equipe MAVERICS en 2022

- **D. Longuevergne**, **CR**
- **G. Sattonnay, Pr**
- **G. Martinet, CR**
- **M. Fouaidy**, **IR (départ à la retraite ~2ans)**
- **B. Mercier, IR**
- **S. Bilgen, IR (2021)**
- **O. Hryhorenko**, **Post doc (fin oct 2022)**
- **Y. Pisi, doc (début oct2021)**

plateforme vide & surfaces en 2020

- **E. Mistretta**, AI
- **F. Letellier**, AI **(départ NOEMIE en nov2021)**
- **D. Grasset**, TCE **(retraite début 2022)**
- **M. Alves**, TCE **(retraité juillet 2020)**

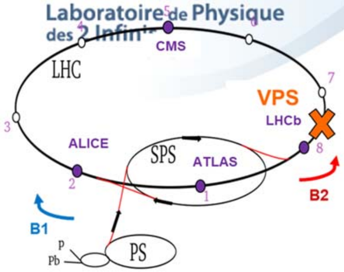
Plateforme Vide & Surfaces en début 2022

- **E. Mistretta**, AI
- **Poste AI Noemie 2022**
- **poste IE CDD 2022 IN2P3**

Renforcement nécessaire pour maintenir notre expertise/opérer les nouveaux équipements

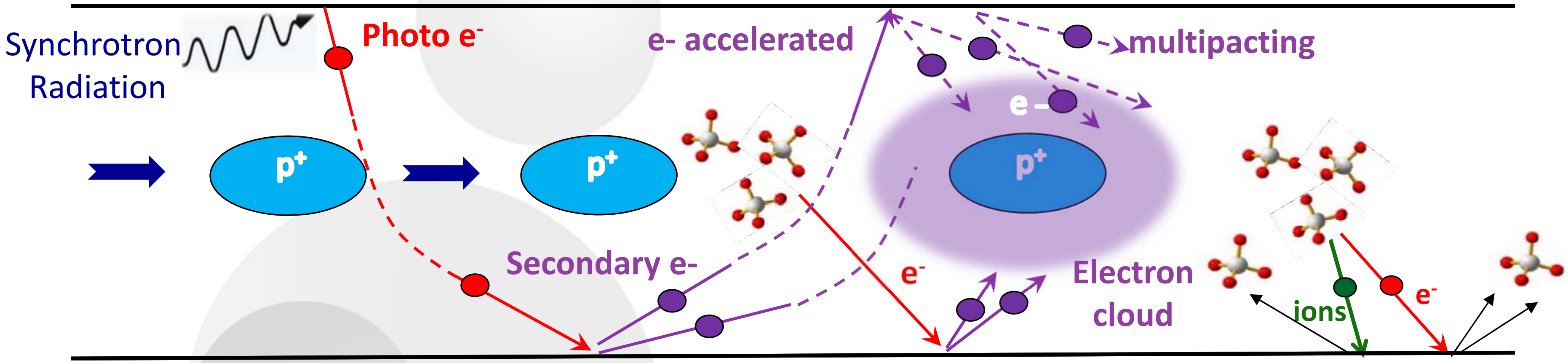
BACK UP

Dynamic pressure in particle accelerators : the LHC as an example



Stimulated desorption and secondary particle creation

All of these phenomena affect the LHC beam



2018 LHC
26.7 km, 7.74 T
13 TeV, 2556 b, 1.1x10^{11} ppb
RUN 2

LHC
27 km, 8.33 T
14 TeV, 2808 b, 1.2x10^{11} ppb
NOMINAL PARAMETERS

HL-LHC (2026)
26,7 km, 8.33 T
14 TeV, 2808 b, 2.2x10^{11} ppb

FCC-hh
100 km, 16 T
100 TeV, 10600 b

FCC-ee
100 km
45 GeV, 16640 b

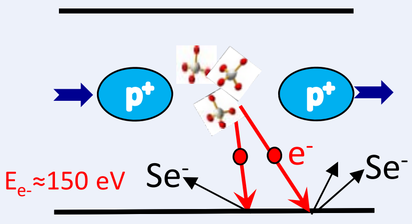
To stay operational during 2018, the LHC was limited to fewer than the nominal number of bunches due to dynamic pressure phenomena

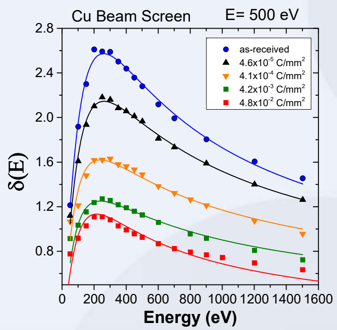
Can these nominal parameters be reached for future colliders ?

Dynamic pressure (S. Bilgen Thesis 2020)

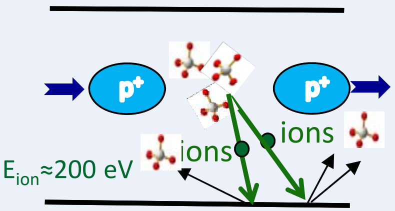
Experimental measurements in lab

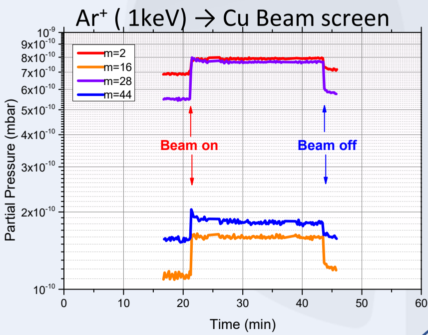
SEY *Secondary Electron Yield (IJCLab)*



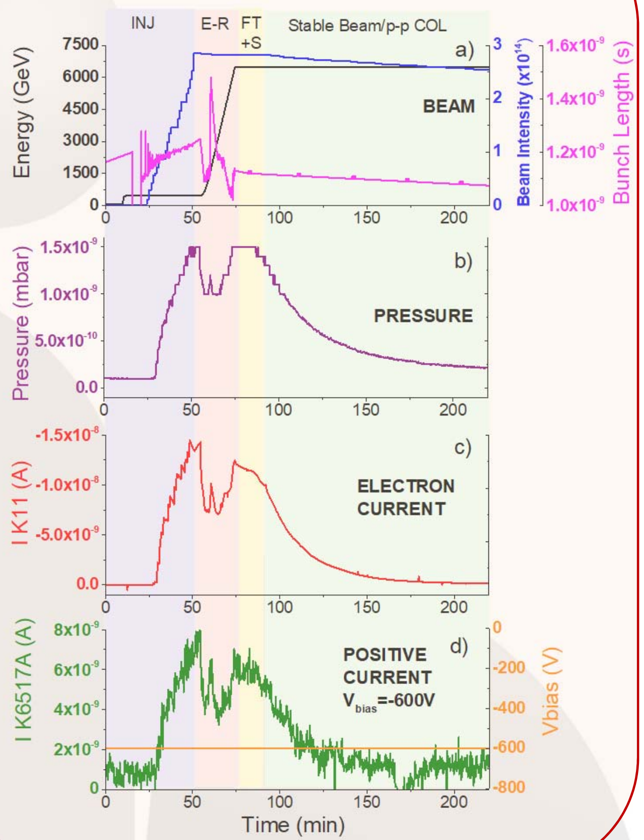


ISD *Ion Stimulated Desorption (CERN)*



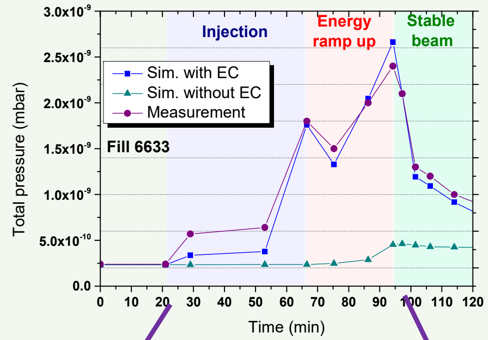


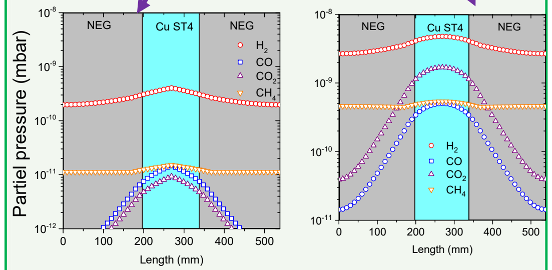
In situ measurements in the LHC

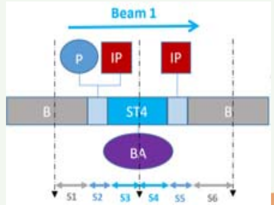


Simulations

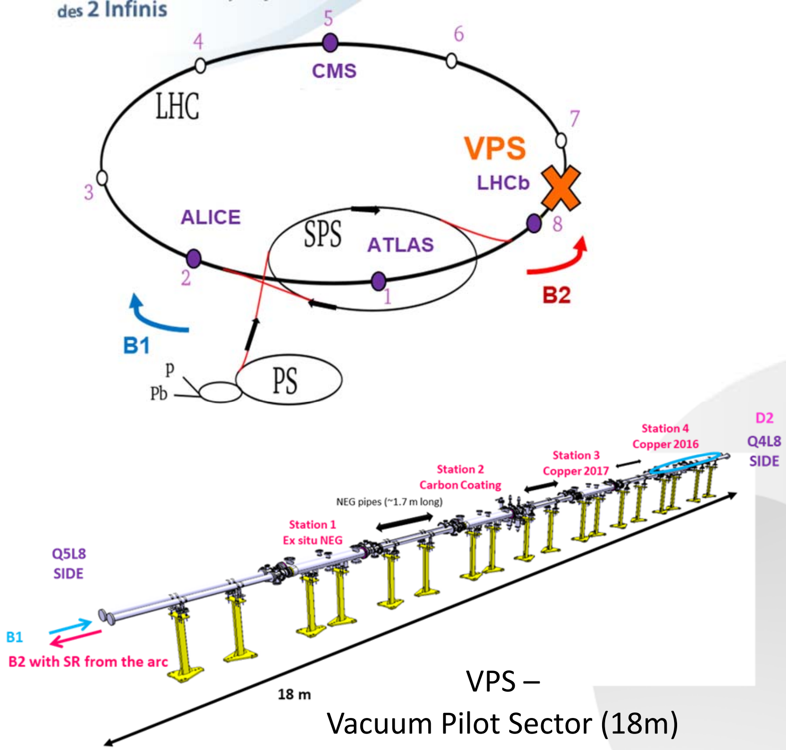
DYVACS simulation





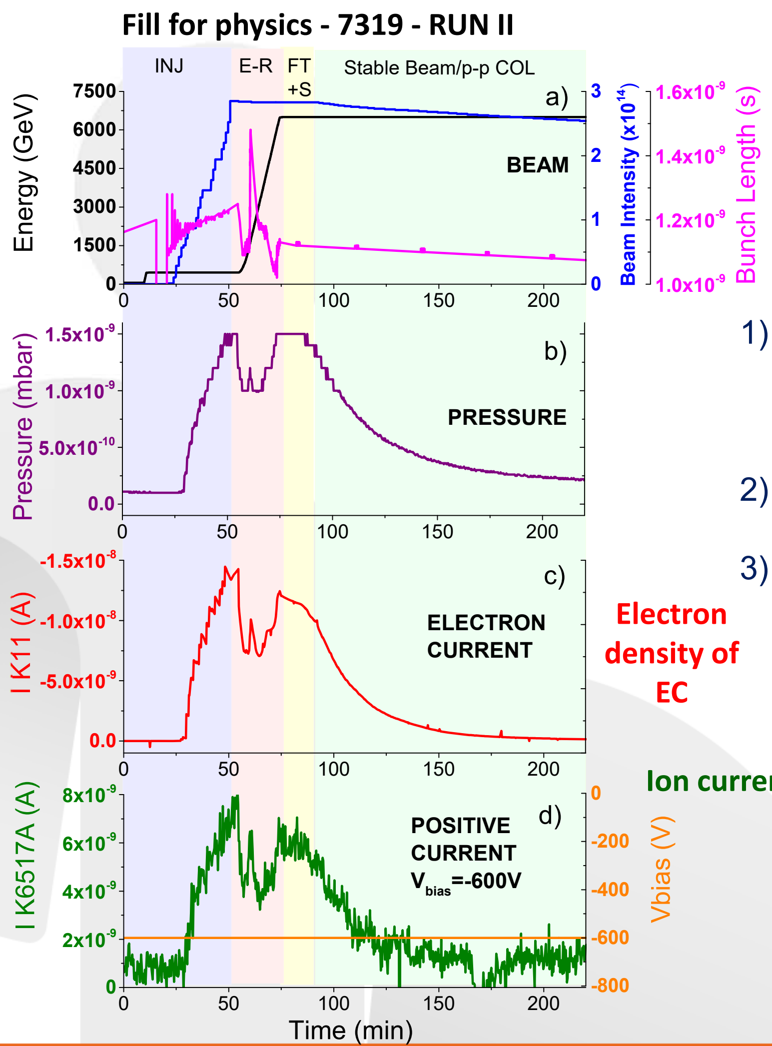


Dynamic pressure : *In situ* measurements in the LHC (S. Bilgen Thesis 2020)



VPS –
Vacuum Pilot Sector (18m)

CERN collab



Electron density of EC

Ion current

1) Ions are detected: The positive ion current could correspond to 2.5% of the electron current.

2) SEY was estimated between 1.6 and 1.7.

3) Our measurements validate the electron energy spectrum recorded in the VPS.

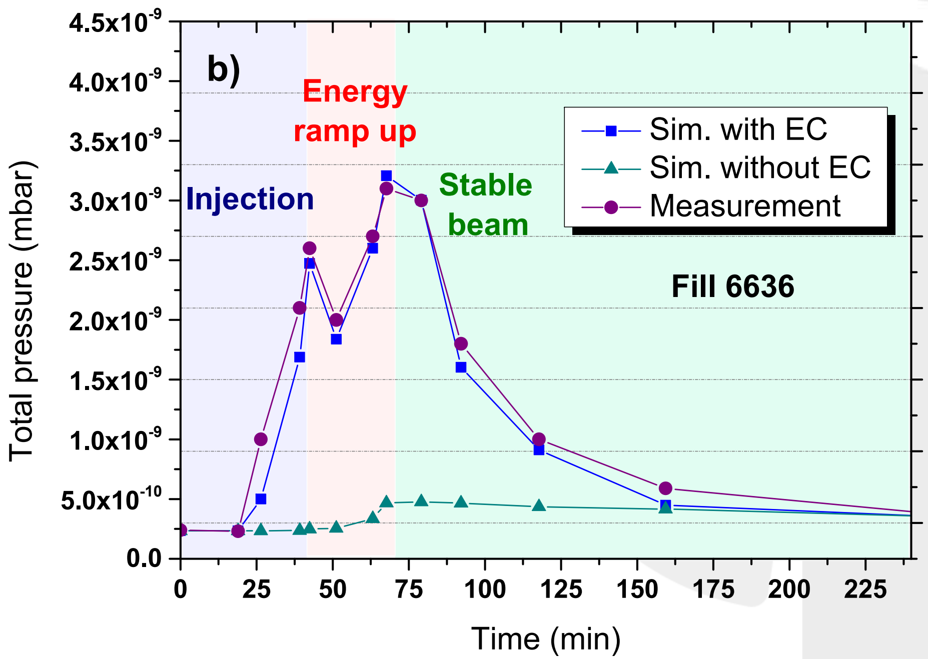
DYVACS – Simulation of Gas density profiles

Analytical model of the dynamic pressure – DYVACS – DYnamic VACuum Simulation code

$$\underbrace{C_j \frac{\partial^2 n_j}{\partial x^2}}_{\text{diffusion}} + \underbrace{D_{ion-j} + D_{e-j} + D_{ph-j}}_{\text{Stimulated desoprtion}} + \underbrace{D_{th-j}}_{\text{outgassing}} - \underbrace{S \cdot n_j}_{\text{Distributed pumping}} = 0$$

DYVACS is based on the gas balance differential equation (VASCO)
It is used to compute the gas density n_j

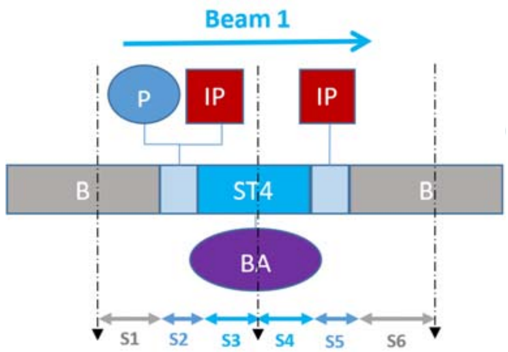
for j= H_2, CH_4, CO, CO_2

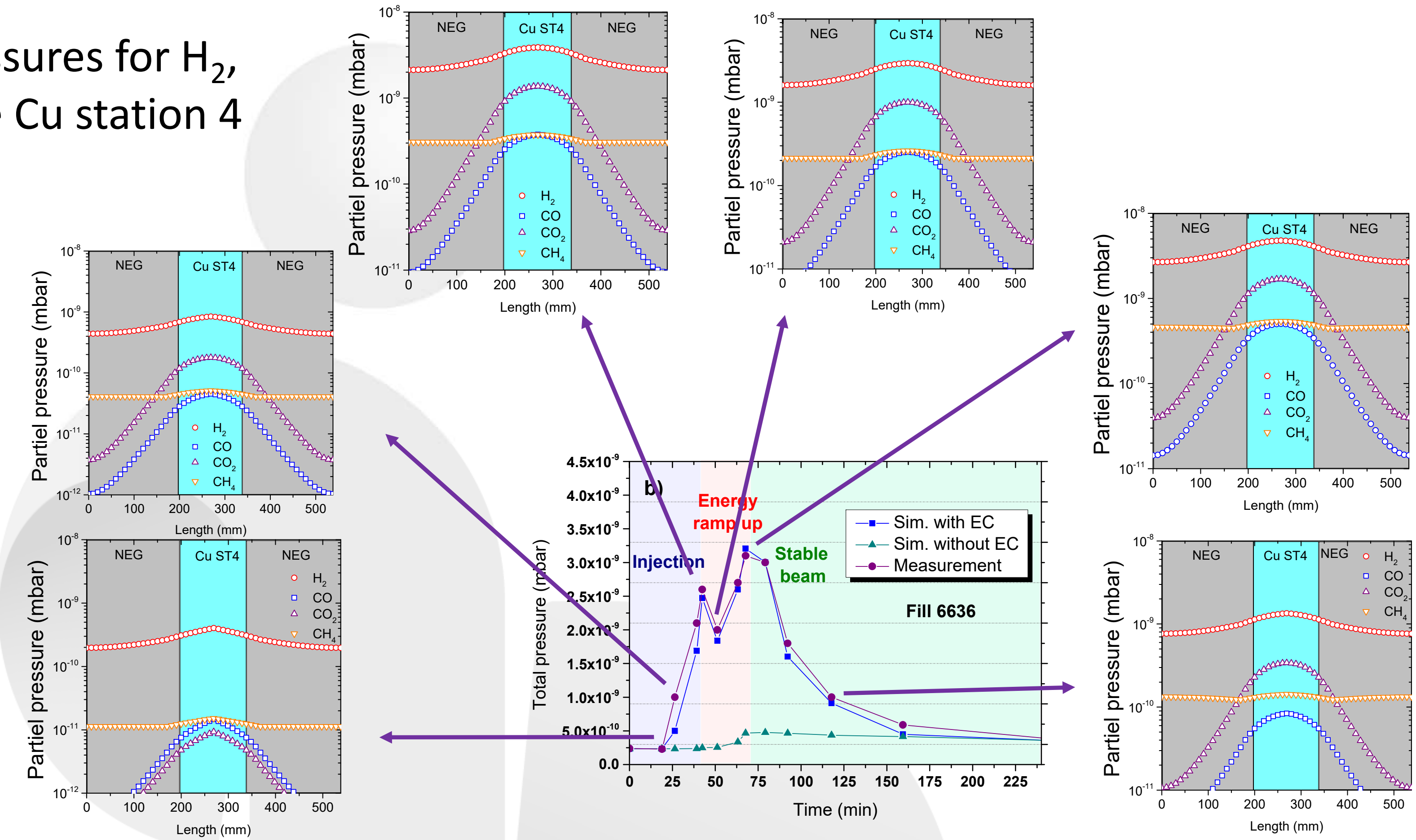


A **good agreement** was observed in a short computation time, between the *in situ* pressure measurements and DYVACS simulation

DYVACS – Simulation of Gas density profiles

Distribution of partial pressures for H_2, CO_2, CO and CH_4 along the Cu station 4

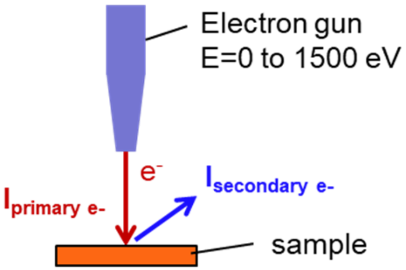


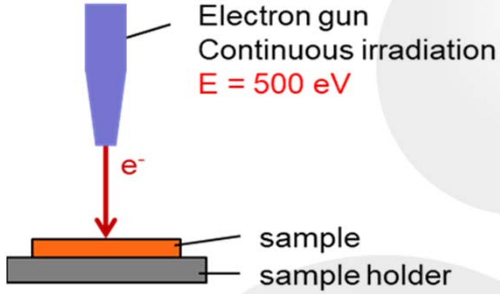


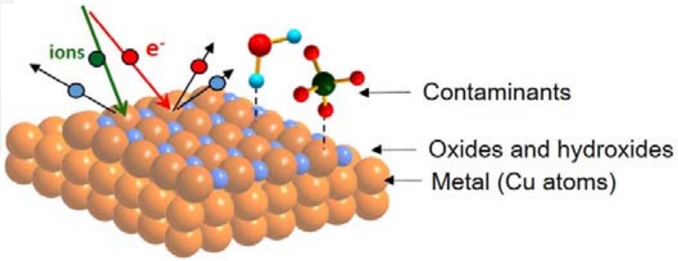
DYVACS reproduces the evolution of the partial pressures for H_2, CO_2, CO and CH_4 during beam operation

Surface conditioning induced by electron bombardment

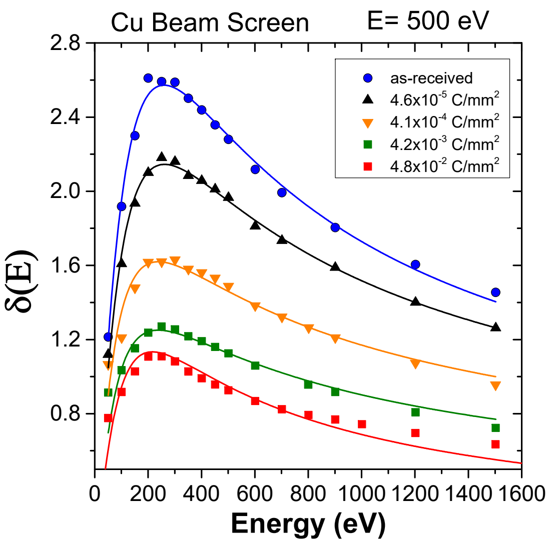
Gaphitization phenomenon of copper surfaces of the LHC beam screen induced by an electron bombardment (S. Bilgen PhD thesis 2020 – collab ANDROMEDE)



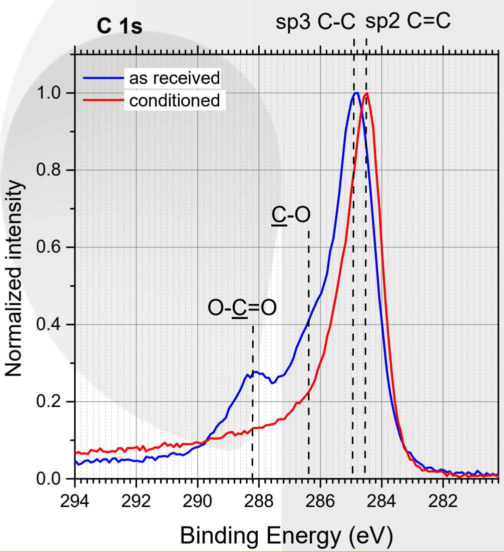




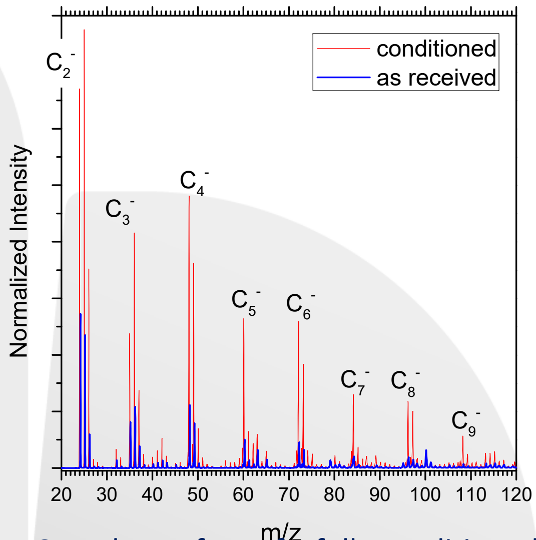
Secondary Emission Yield (SEY)



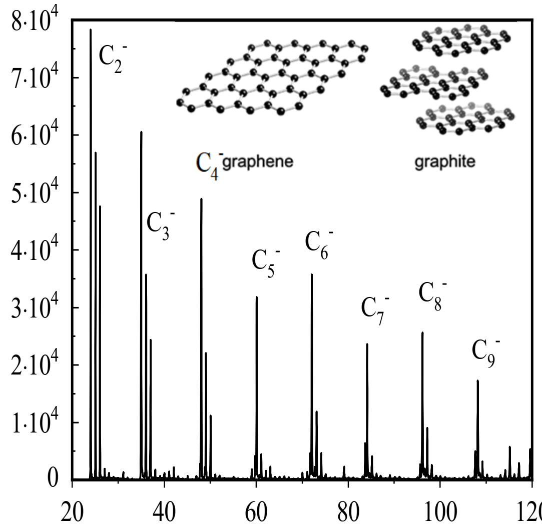
XPS



MeV-TOF-SIMS



C on the surface of a fully conditioned Cu



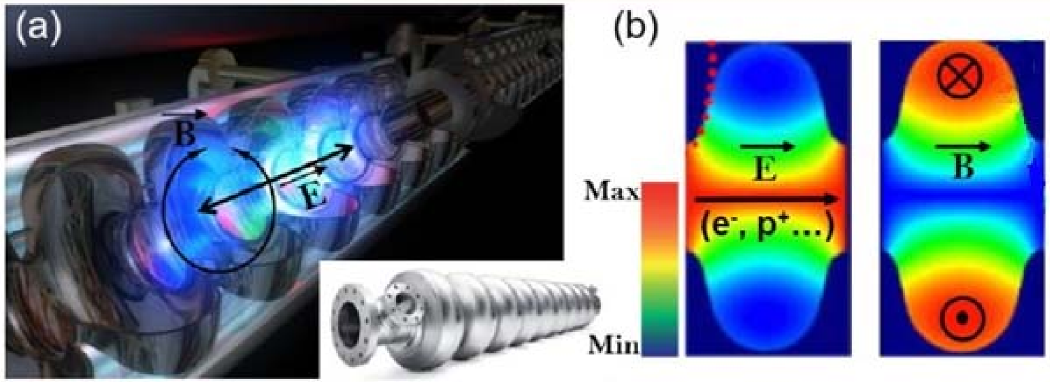
Graphene reference sample

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Outlines

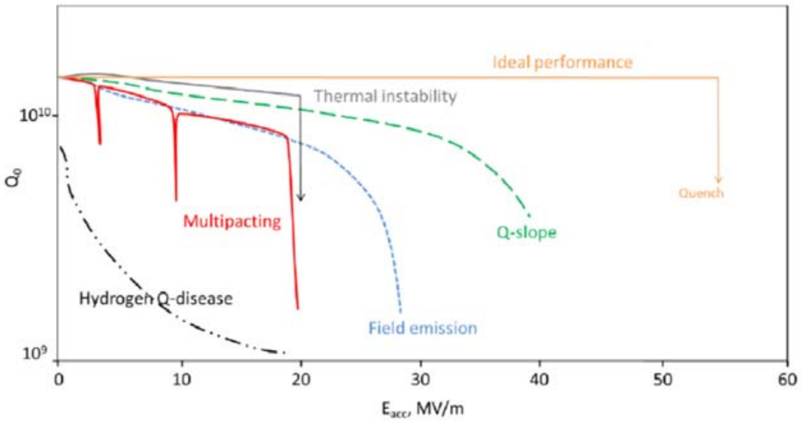
- Genesis of the MAVERICS research team
- Research topics
- MAVERICS Activities
  - Dynamic vacuum
    - *In situ* measurements of pressure, ion and electron currents during the LHC run II operation (collab. CERN).
    - ISD yield measurement (collab. CERN)
    - Surface analysis of materials
    - Modeling and simulation of dynamic pressure
  - SRF accelerating cavities
    - **Heat treatment processes and N_2 infusion/doping of Nb surface**
    - **Alternative path for SRF cavity fabrication and surface processing**
    - **Thin films as alternative superconducting materials**
    - **Thin films for multipacting mitigation**
- Equipment : Vacuum&Surfaces platform
- Scientific production
- Top priorities (at 5 years)
    - Research for solutions to mitigate multipacting for SRF cavities and beam lines *(EPISAMA project)*
    - Dynamic vacuum in colliders *(Master Project :Future Circular Collider - Project: Vacuum : dynamic vacuum in FCC-ee)*
    - Contribute to improving the performance of RF superconducting cavities through the use of innovative surface treatments *(Master Project : SRF)*
    - Develop the "Vacuum and Surfaces" platform (EQUIPEX+ PACIFICS)

Increase accelerator gradient



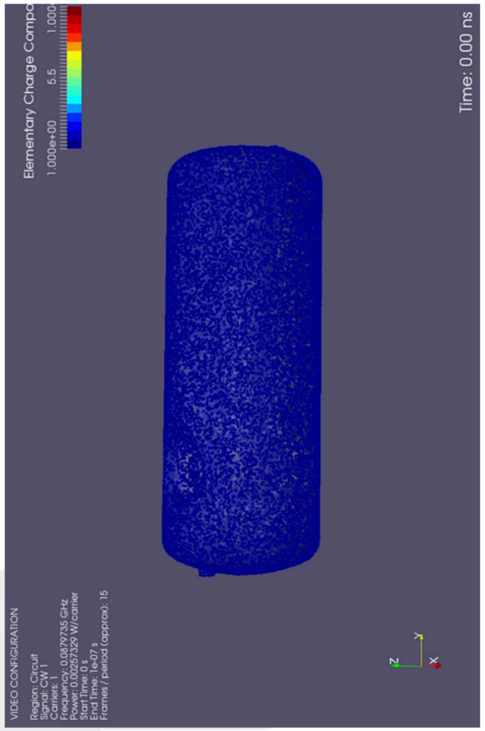
If you want to increase Eacc, watch out for Bc on the surface!
(destruction of the supra state, penetration of the magnetic vortex)

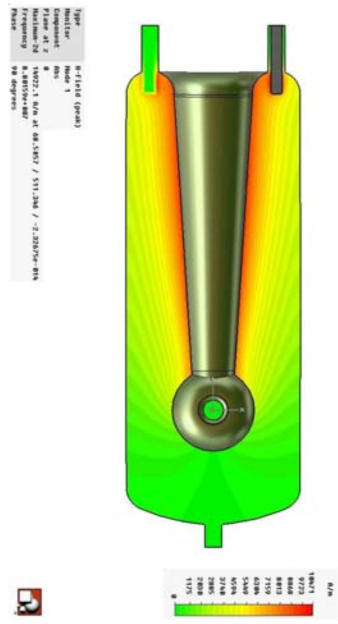
Quality factor Q_0



Multipacting effect in cavities

SPIRAL2





Simulation Spark 3D (CST)
Ningyuan Hu (Service RF/IJCLab)

- ✓ Processing of surface is mandatory to ensure good RF performance
- ✓ Surface and Heat Treatment of SRF cavities : a key technological process to be mastered for a good reliability and high yield rate for large scale projects

Innovative heat treatment for Niobium (HELOISE, AXE SRF, FJPPL)

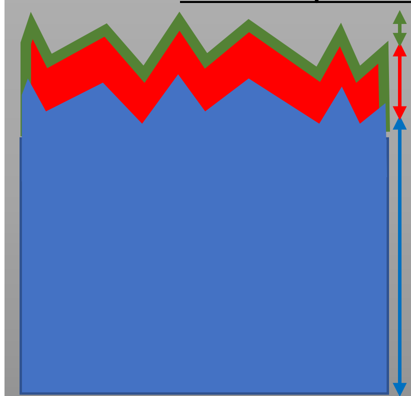
Motivations

- Increase operational gradient of Low Frequency Cavities (Q-slope mitigation)
- Reduce RF losses by minimizing residual and BCS resistances
- Develop diagnostic tools (second sound, magnetic and X-rays mapping)
- Measure material properties (Tc, conductivity)

ON-GOING COLLABORATIONS & ROLES

- **IJCLab** : Furnace operation & Material characterization
- **IRFU** : Surface cleaning and RF testing of 1.3 GHz cavities
- **KEK** (FJPPL) : Lessons learned
- **DESY** : Surface cleaning and RF testing of 1.3 GHz cavities

Tune and optimize Niobium surface and bulk



~ 5 nm = oxide layer

~100 nm = superconducting properties (tuned purity, low cristalline defects)

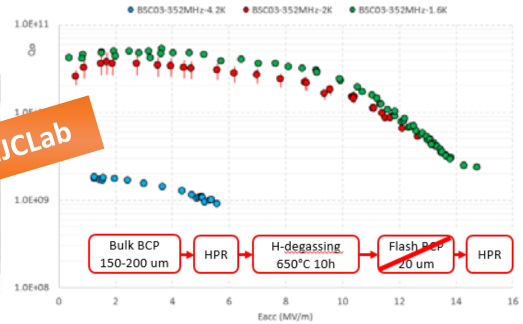
=> High Q, High gradient

Bulk ~ 3mm = thermal properties (high purity, low cristalline defects)

=> High gradient

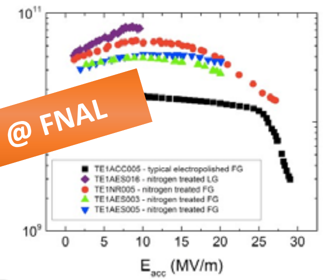
AXIS 1 : Heat treatment under vacuum

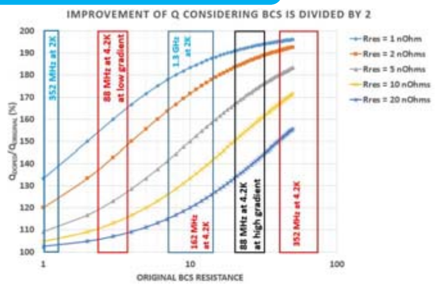
- Furnace dedicated to Niobium cavities
- Qo ~ 4E10 reached at 2K without flash BCP at 650°C
- Investigation of Mid-T baking (T~ 300-400°C) as alternative to N-doping



AXIS 2 : Heat treatment with low partial pressure of pure gas (doping)

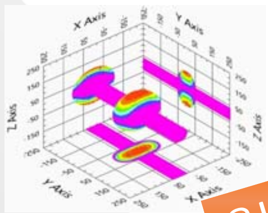
- Furnace upgraded with high purity injection line
- Reproduce state of the art (N2 infusion on 1.3 GHz elliptical cavity)
- Improvement of Qo to allow 4K operation of Spoke resonators





AXIS 3 : Deploy diagnostics for cavity RF tests and cryogenic physical properties

- **Second sound transducers** and electronics developped & operational
- Magnetic sensitivity : predictive model and measurement with **cryogenic probe**
- X-rays mapping with pin diodes
- Development of set-up to measure Tc and conductivity between 1.6K and 300K



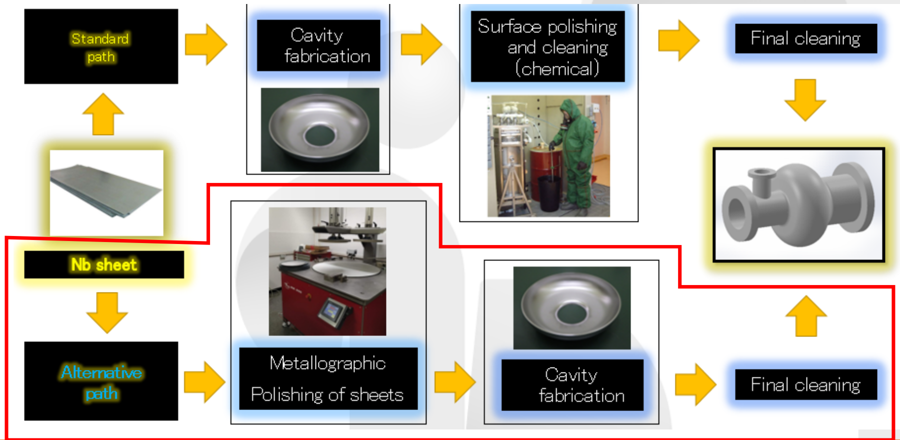
Alternative path for SRF cavity fabrication and surface processing (PICASU, PACCAS, AXE SRF)

Motivations

- **Possible cost reduction of cavity fabrication & surface processing (ILC, FCC…)**
- **Achieve better surface roughness than standard chemical cleaning & study impact on SRF properties**
- **Substrate preparation for thin films deposition (prepare for future technology)**
- **Improve enviromental footprint and worker safety (reduce usage of acids)**

ON-GOING COLLABORATIONS & ROLES

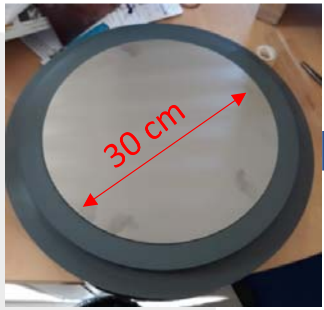
- **IJCLab**: Niobium polishing & material characterization
- **IRFU** (H2020, Axe SRF): Expertise in metallurgy
- **KEK** (FJPPL): Niobium forming & welding. Cavity fabrication
- **LAMPLAN**: company specialized in lapping & polishing

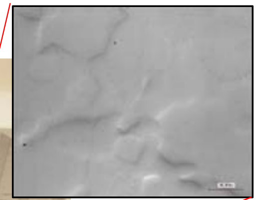


PHASE 1 : PICASU : Optimization of Polishing on small samples (2016-2019)

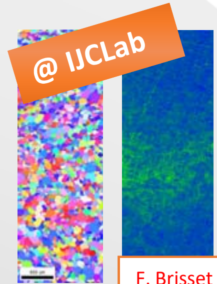
- Supported by IN2P3, H2020 (Ensar2)
- 1 PhD : Oleksandr Hryhorenko

PHASE 2 : PACCAS : Large disks polishing (2020 – 2021)





PHASE 3 : PACCAS : Optimized forming of pre-polished sheets (2020 – 2022)



F. Brisset (ICMMO)

Alternative SRF materials (ECOMI, AXE SRF)

Irène Joliot-Curie

Motivations

- Go beyond bulk Niobium technology.
- Improvement of accelerator gradient (Eacc) and quality factor (Qo)
- Dope Niobium surface (remove deleterious oxide layer) to improve superconducting properties
- Study several pathways : thick films (Nb3Sn) or multilayers (S-I-S structures)

Multilayer path (SIS)

- 2 layers of superconductor separated by a thin layer of isolator (S-I-S)
- Suggested by Gurevich in 2007
- Shielding by multilayer still not fully demonstrated under intense RF fields
- ALD (Atomic Layer Deposition) very promising as very uniform nanometric layers required
- TODAY investigated at IN2P3

Thick films (A15 compounds)

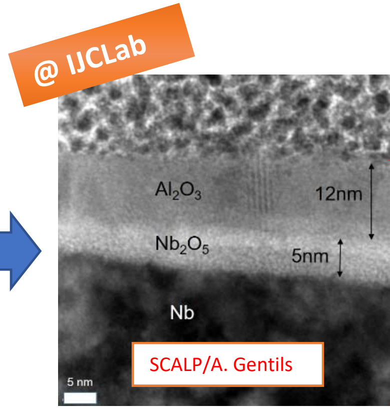
- A15 : Nb3Sn, V3Si
- Operation at 4.2K (Tc > 15K)
- Accelerating gradient doubled
- But limitation today at B~80 mT because of granular superconductivity
- Several paths : Sn diffusion on Nb (USA), Nb/Sn deposition on copper (CERN), « bronze route » (China).
- NOT investigated at IN2P3

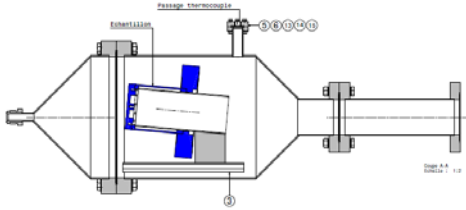
ON-GOING COLLABORATIONS & ROLES

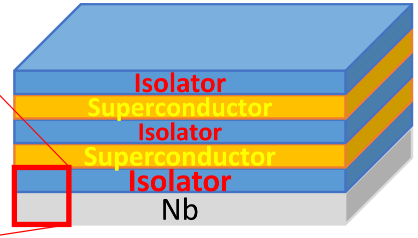
- **IJCLab** : Material characterization & metallographic polishing
- **IRFU** (Axe SRF, I-FAST): Expertise in ALD & SRF testing (1.3 GHz elliptical cavities)
- **HZB** (TTC): SRF testing in Quadrupole Resonator (QPR)

AXIS 1 : AXE SRF : Production of thin films by ALD at IRFU (2018-2022)

- Supported by IN2P3, IRFU, Ile de France Region
- 2 PhDs : Sarra (IJCLab), Yasmine (IRFU),

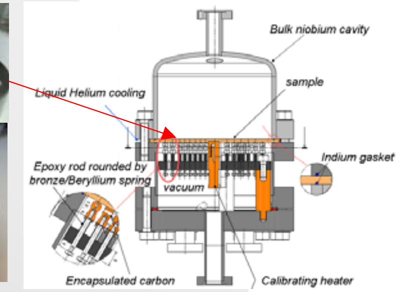


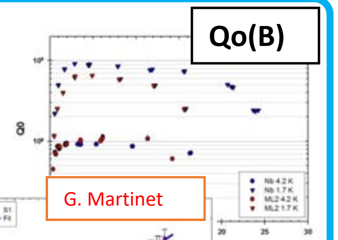


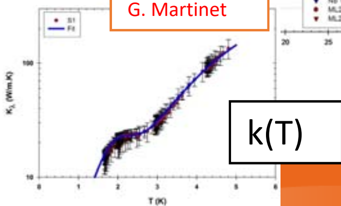


AXIS 2 : ECOMI : SRF testing of flat disks (2012 – 2020)

- TE011 resonator (RF and calorimetric measurement)







Mitigation of multipacting phenomenon in accelerators (MULTIPAC, EPISAMA)

Irène Joliot-Curie

Motivations

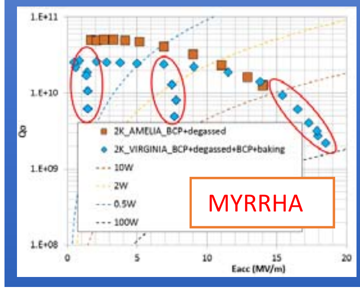
- Multipacting is a general problem/limitation in SRF structures (cavity and couplers)
- Causes vacuum degradation (e- clouds) in synchrotrons (limitation of luminosity in LHC)
- Mitigation of multipacting helps mitigating risks of failure and improvement of reliability in accelerators

ON-GOING COLLABORATIONS & ROLES

- **IJCLab** : Material characterization & Simulations
- **LPSC** : Simulation & Dedicated multipacting test bench
- **IRFU** : TiN coating by ALD & Plasma processing
- **SIMAP** : Expertise in thin film deposition (ALD, PVD, …)

Multipacting in cavity

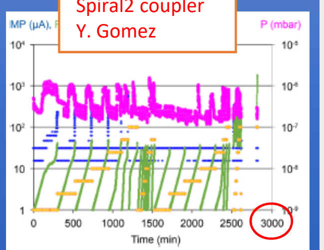
Qo degradation and field limitation



MYRRHA

Multipacting in coupler

Surface damages and long conditionning time

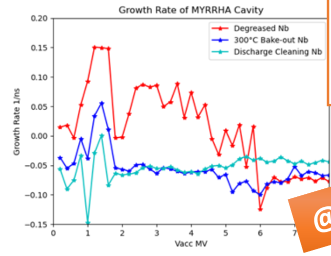


Spiral2 coupler
Y. Gomez

LHC coupler
E. Montesinos

AXIS 1 : SIMULATION : Identification & localization of multipacting)

- Several 3D codes available (CST PIC & SPARK3D)
- Code developed @ IJCLab (MUSICC3D). 1 PhD (2015).
- Integrated in design phase of cavities and couplers
- Essential for new accelerator projects : risk mitigations



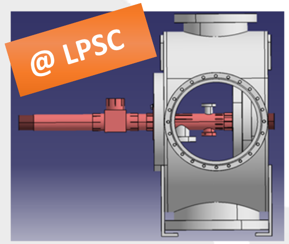
Spark 3D
(CST)
N. Hu

@ IJCLab

SPIRAL2

AXIS 2 : TESTING : dedicated test bench

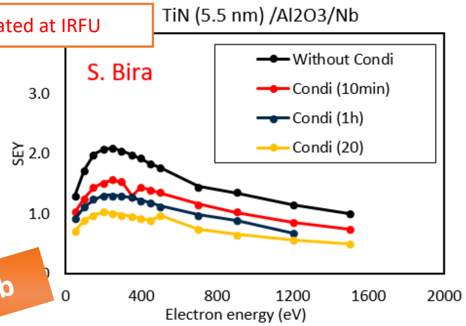
- Test in nominal conditions
- Measure SEY



@ LPSC

@ IJCLab

Coated at IRFU



AXIS 3 : MITIGATION : Improve TiN coating & surface processing (plasma, UV, …)

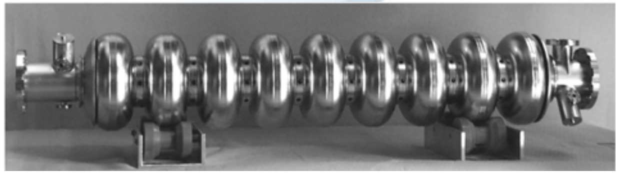
- Thin film deposition (TiN) on ceramics (Al2O3)
- Companies (HEF, PMB, Thalès-RI)
- IRFU (ALD)
- Investigate several coating techniques, thicknesses, …
- Investigate new materials (SIMAP)

SIMS @ IJCLab

- Specific surface processing as plasma and UV (Activity to be initiated)

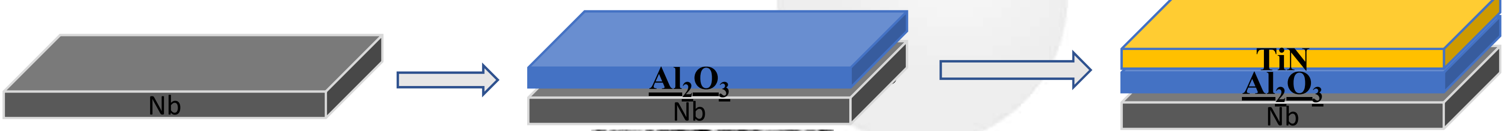
Influence of the nature of ALD deposits on the SEY of “Nb”

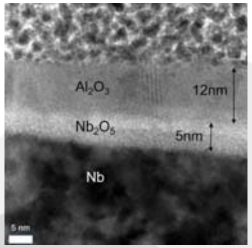
Sarra Bira PhD thesis (IJCLab)
Collab. ALD coating Thomas Proslier / Yasmine Kalboussi



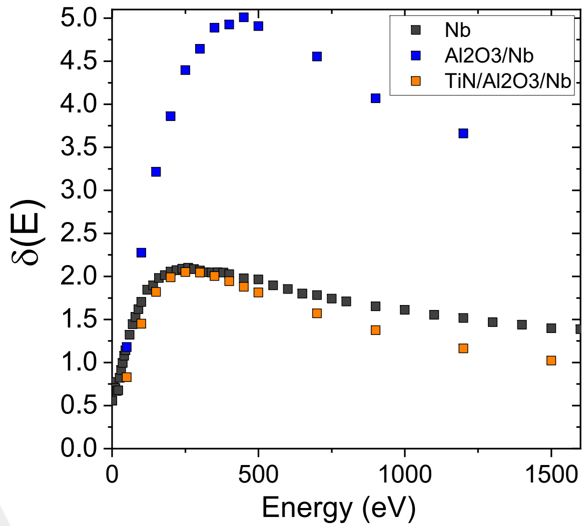
Al_2O_3 (10 nm) /Nb

TiN (5.5 nm)/Al_2O_3 (10 nm) /Nb

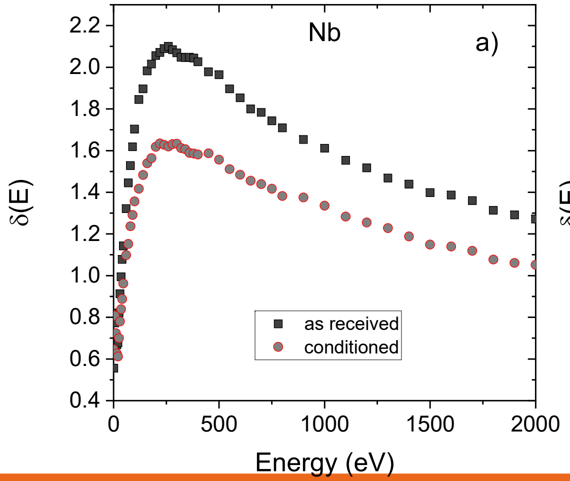


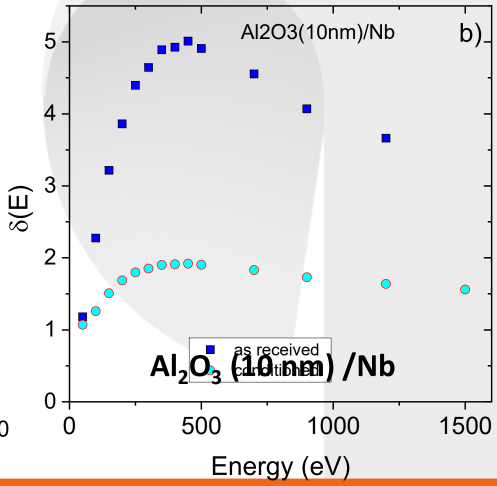


Comparison



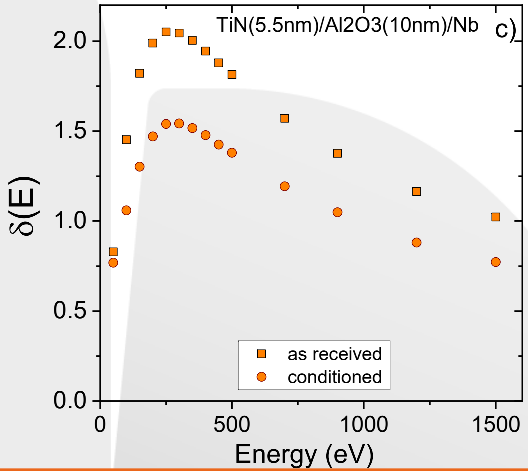
Nb





Al_2O_3 (10 nm) /Nb

TiN (5.5 nm)/Al_2O_3 (10 nm) /Nb



Cooperations/main collaborations

Projects

ESS
MYRRHA
PIP II
PERLE
FCC-hh/ee

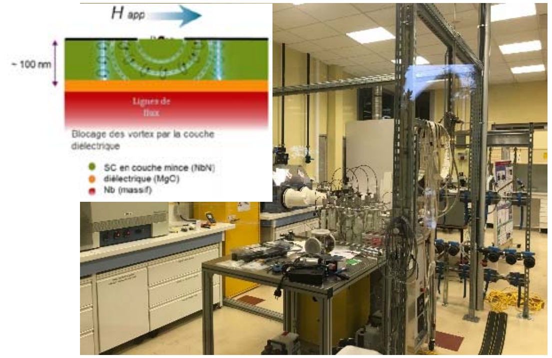
Thermal treatments: doping/infusion

IRFU
Desy (TTC)
CERN (via PERLE)
FNAL (PIP II)



Alternative SRF materials, multilayers

IRFU

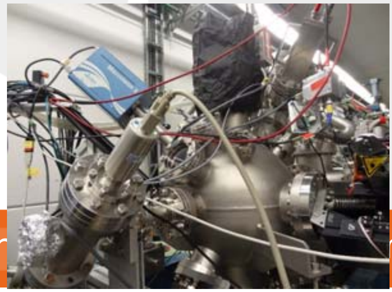


Dynamic vacuum

CERN


Stimulated desorption

CERN
GANIL
GSI



Multipacting Thin films

SIMaP
LPSC

Surface analysis

ICMMO
ANDROMEDE
SCALP