Thin films and surfaces treatments in accelerator technology

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On behalf of TE-VSC

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9/4/2015

Outline

- Surface treatment
- Thin film activities – general
- SRF Thin films
- Visit

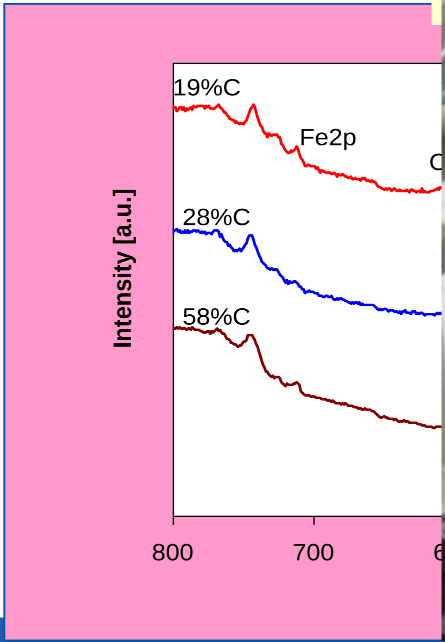
Surface Treatment

Cleaning UHV components and monitoring cleanliness :

Precision cleaning is important to reduce outgassing and achieve UHV (standard up to 7m length)

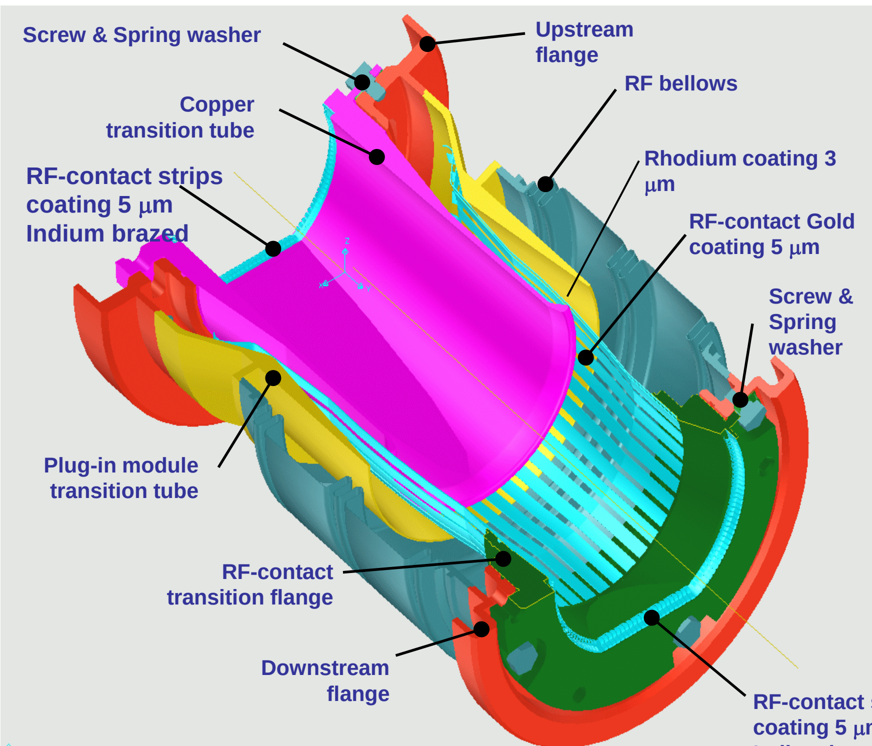
FTIR
Through elution with C_6H_{14}

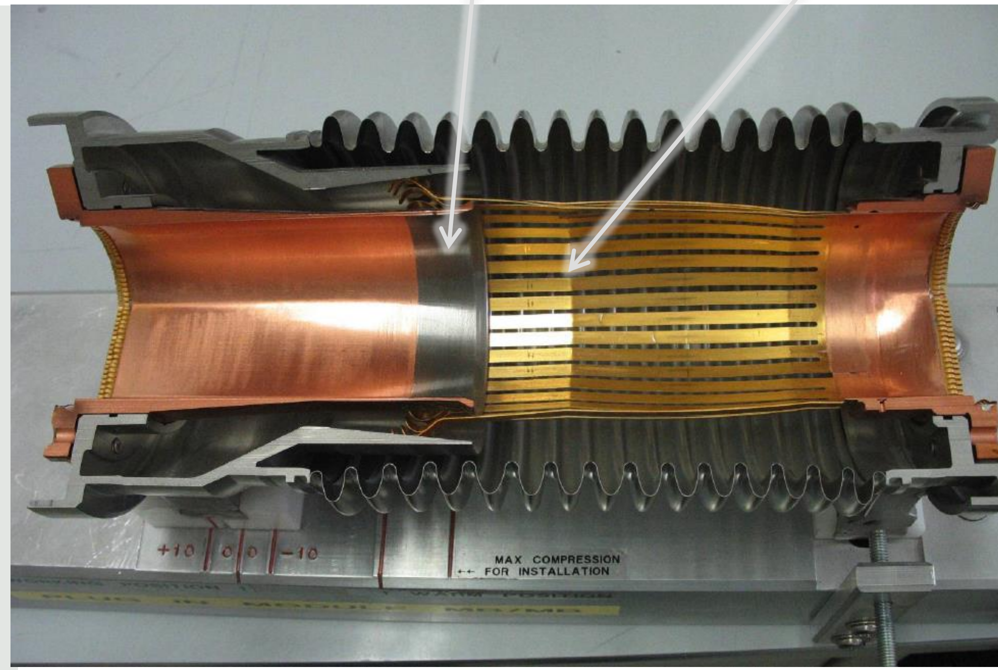
XPS



Plug-in Modules with RF Fingers

- RF bridge (fingers) to interconnect superconducting magnets (~ 1 700 PIM)
- Au/CuBe and Rh/Cu plating: different metals to avoid cold welding under vacuum and soft-on-hard contact to have sufficiently low resistivity (< 0.1 mOhm contact resistance)



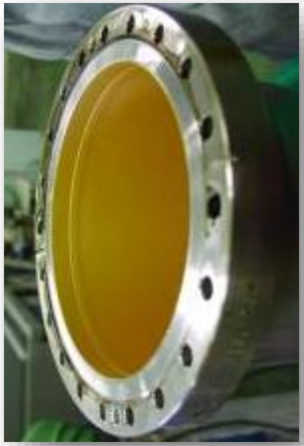


Courtesy R. Veness

Room temperature position → cooling → Working position at cryogenic temperature

Electrolytic deposition: on stainless steel, copper and aluminum

Gold

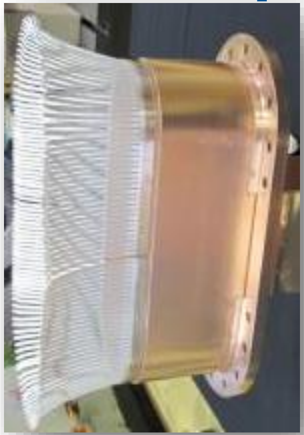


LINAC3 test chamber

Copper electroplating

Cover of DTL LINAC 4

Silver electroplating



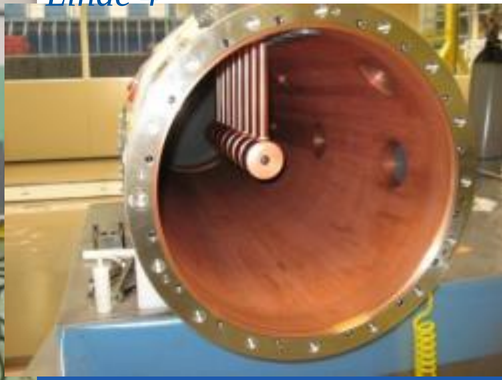
RF fingers TDI shield

Rhodium

RF transition LHCVSR

Ag plating on Al stripline contact AD

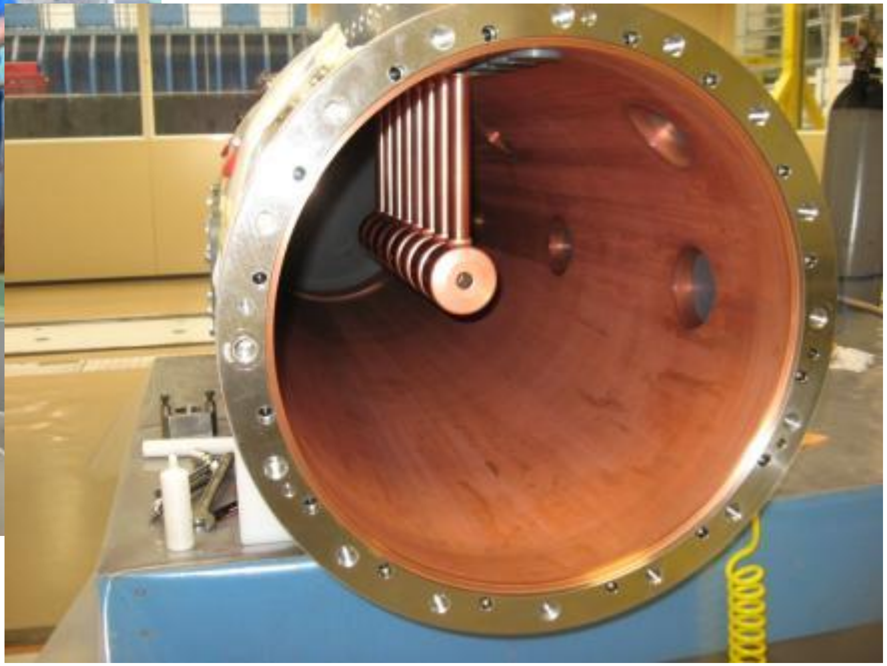
Cu plating on DTL tank of Linac 4



Wet surface treatments: Cu plating of DTL tank of LINAC4

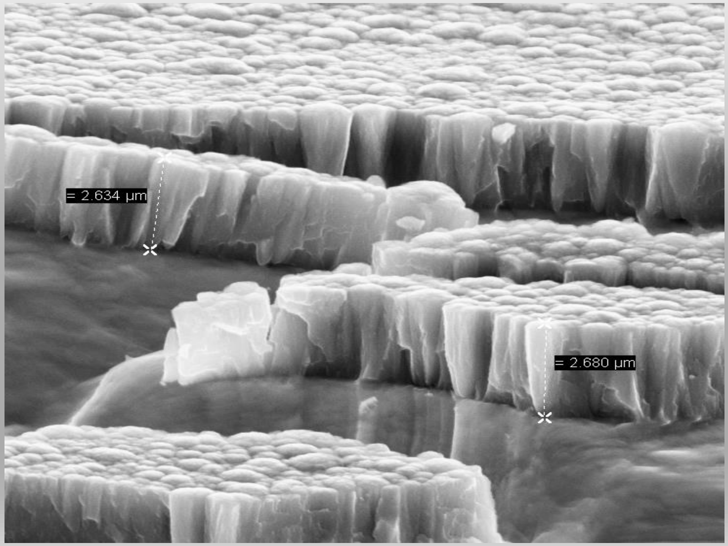
Difficult to obtain uniform plating and plating in the ports

Final assembly with the electrodes for the accelerator

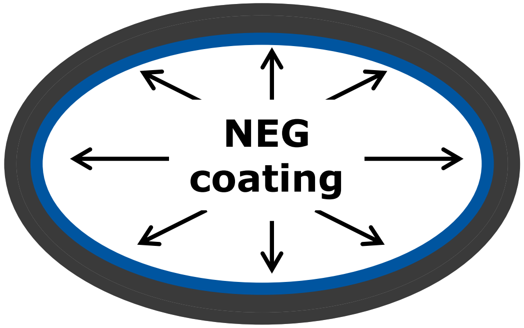


Thin Films for Accelerators

Thin film of Non-Evaporable-Getter as vacuum pump



➔ transform the entire vacuum chamber in a pump by coating it with a getter thin film: ~2µm of TiZrV deposited by DC magnetron; activated with a standard vacuum bake-out at 180°C-230°C (24h), operates at RT

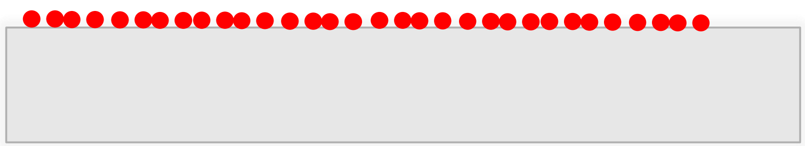


Pumps (chemisorption) H_2, CO, CO_2, …..
Does not pump CHx and noble gases

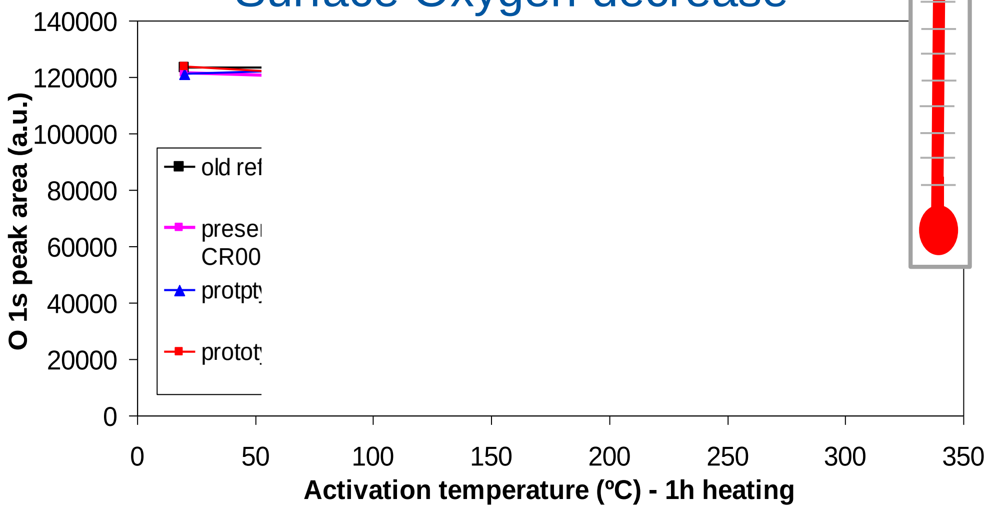
Characterised by XRD, EDX, SEM, XPS…

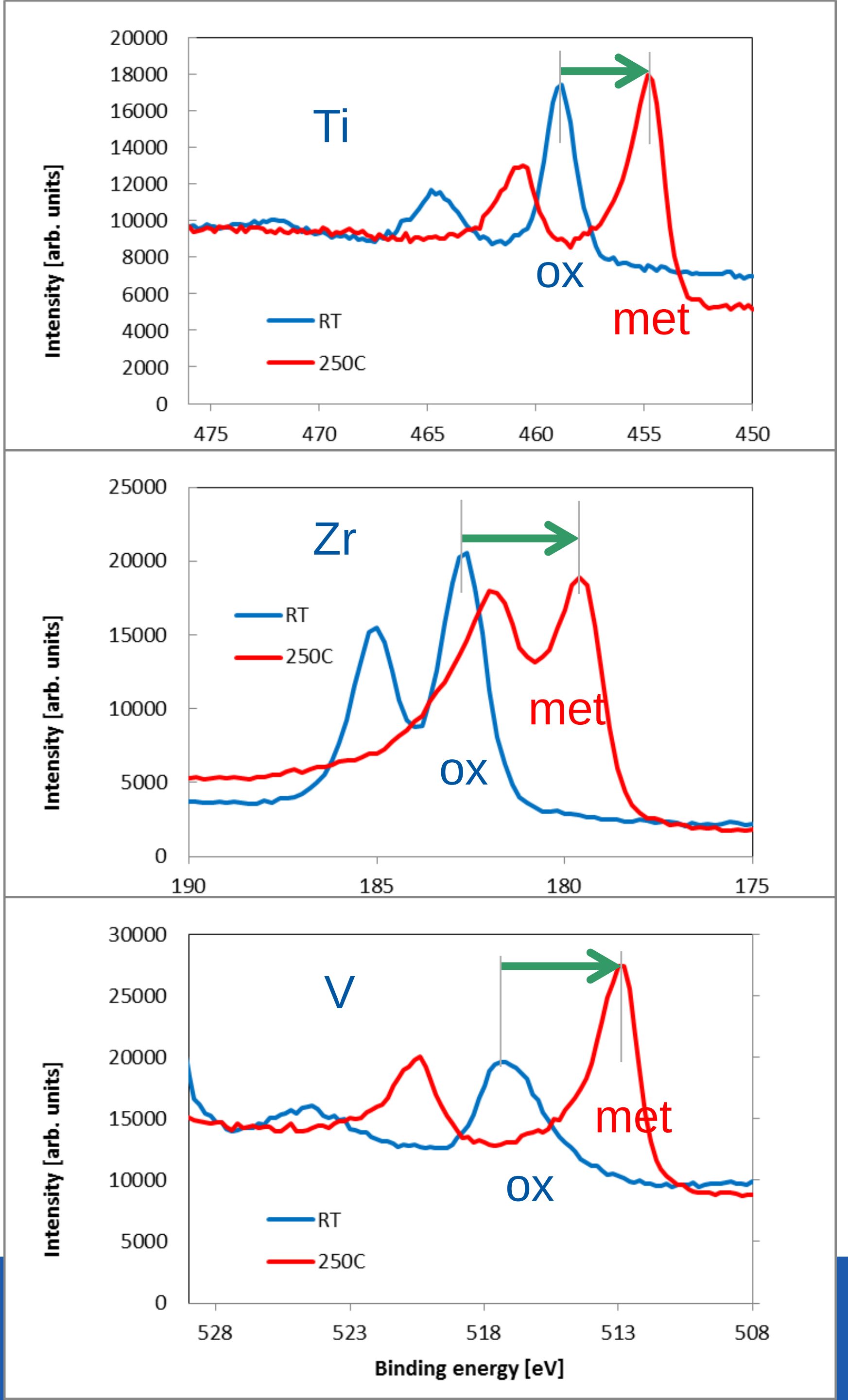
Activation process: Monitoring by surface analysis (XPS)

- ❑ Heating stepwise for 1h at each T
- ❑ Diffusion of O into the bulk
- ❑ Reduction of the surface oxides of all the metals: the surface is metallic and reactive

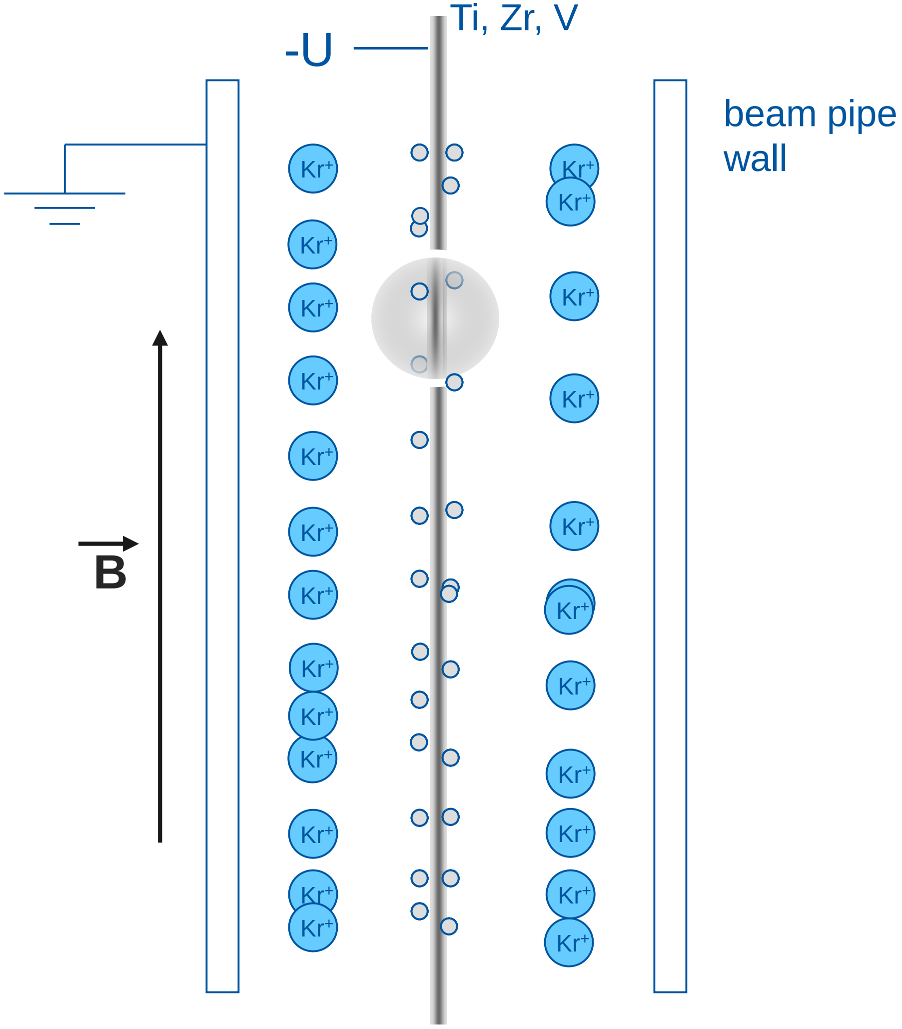


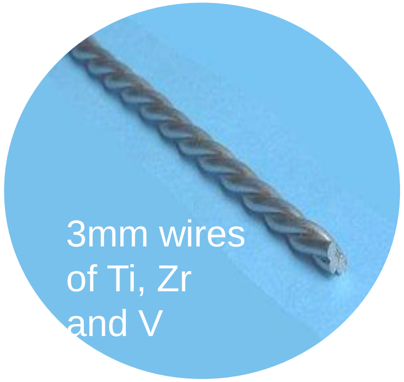
Surface Oxygen decrease

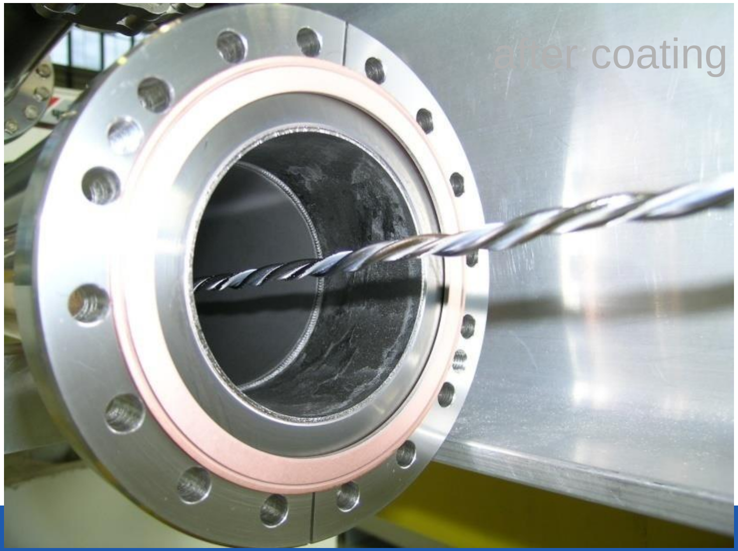




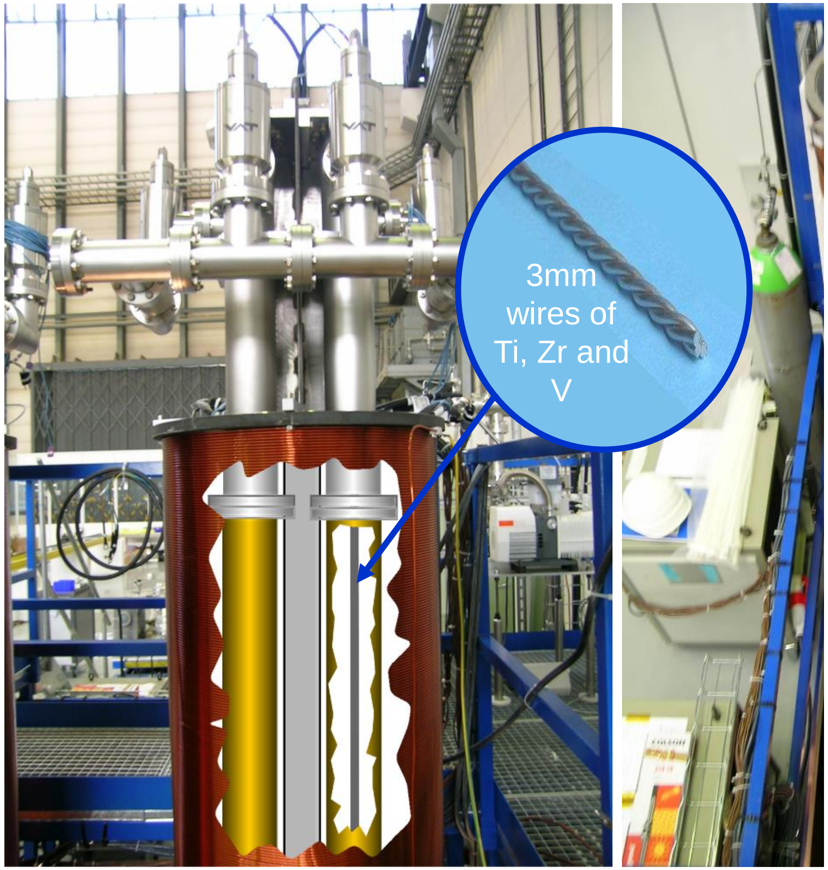
The NEG thin film is obtained by ion bombarding a target made of inter twisted wires of titanium, zirconium and vanadium. The atoms of the target are then sputtered and deposited on the beam pipe walls.

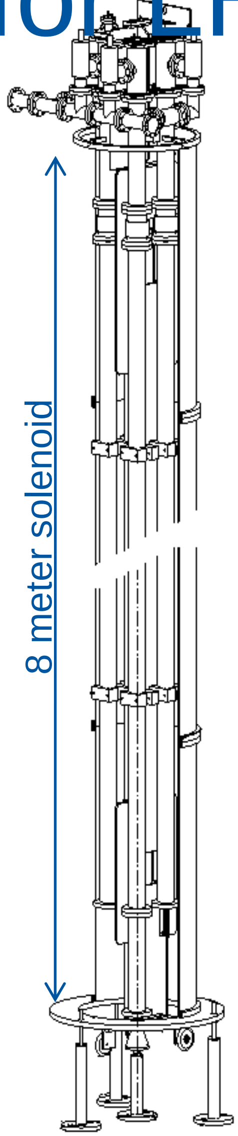


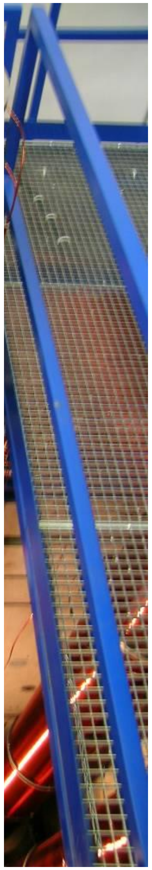




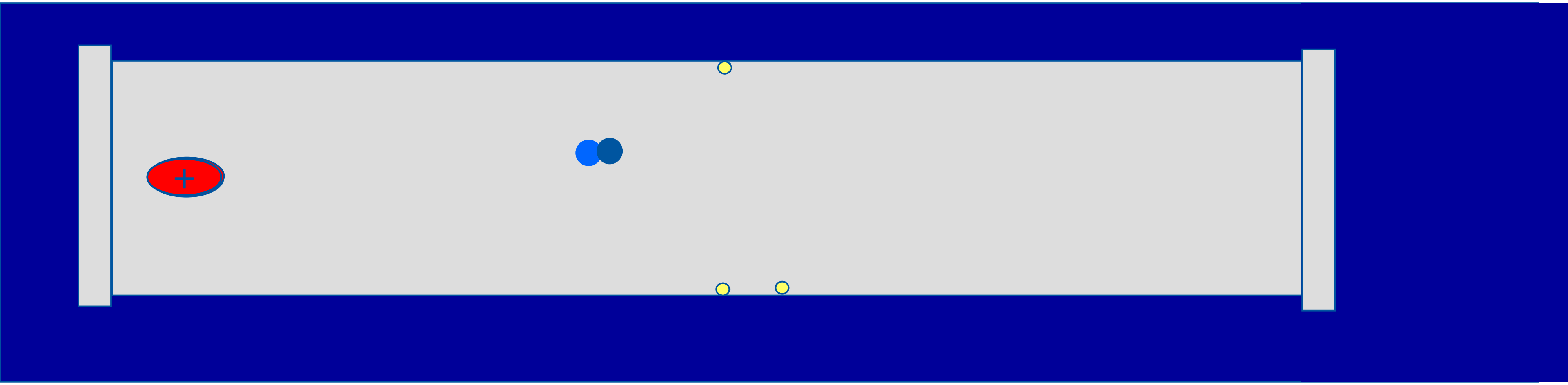
NEG coatings for LHC LSS & experiments







Electron cloud and SEY



Proton bunch (charge +)

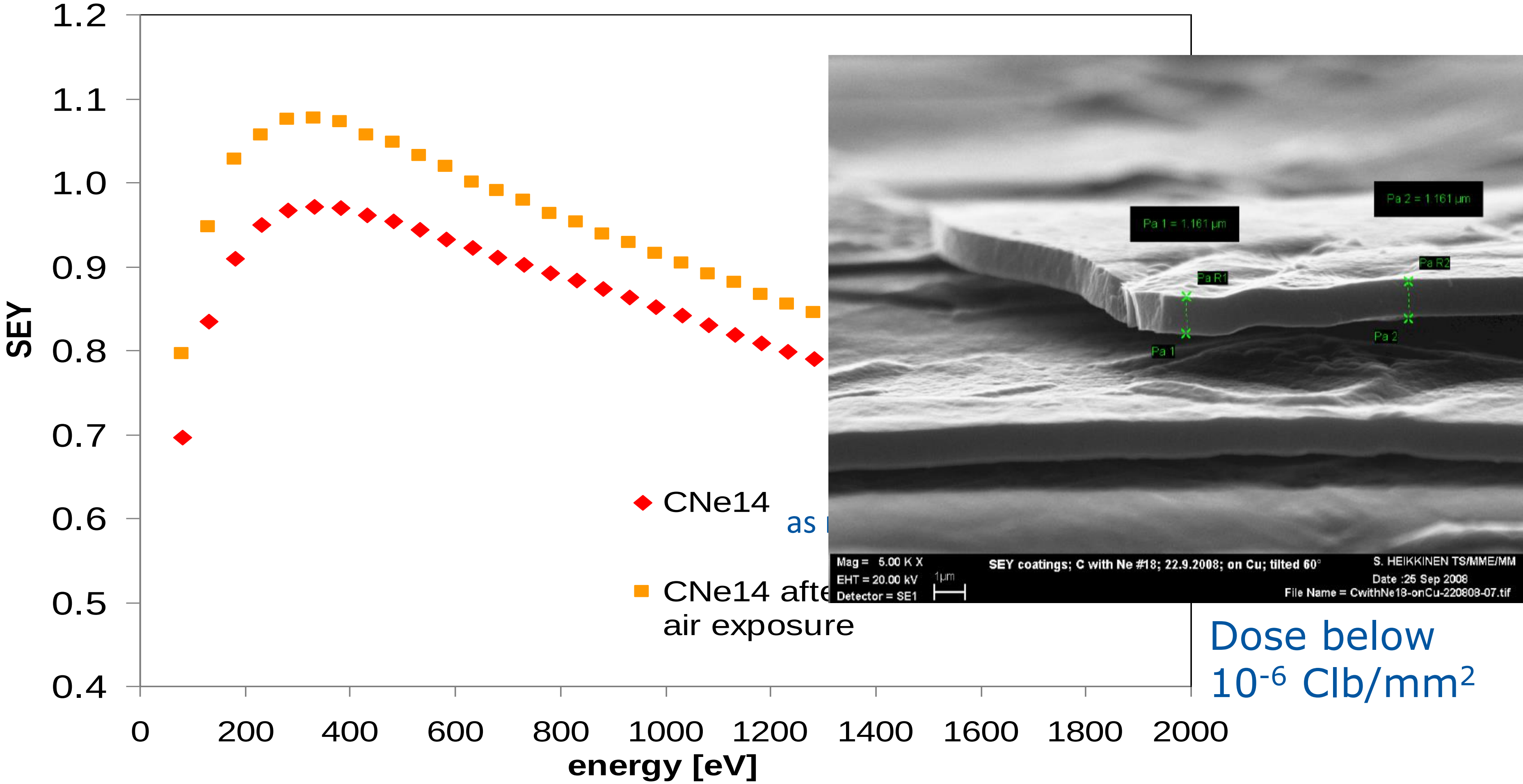
Gas molecule

Electron (charge -)

→ Perturbation of the beam (emittance growth), thermal load on cryogenics, noise on beam instrumentation; the problem is more important for high beam currents (beam potential) and short bunch spacing

To reduce the effect one must reduce the secondary electron yield (SEY) of the walls or attract the generated electrons by other means

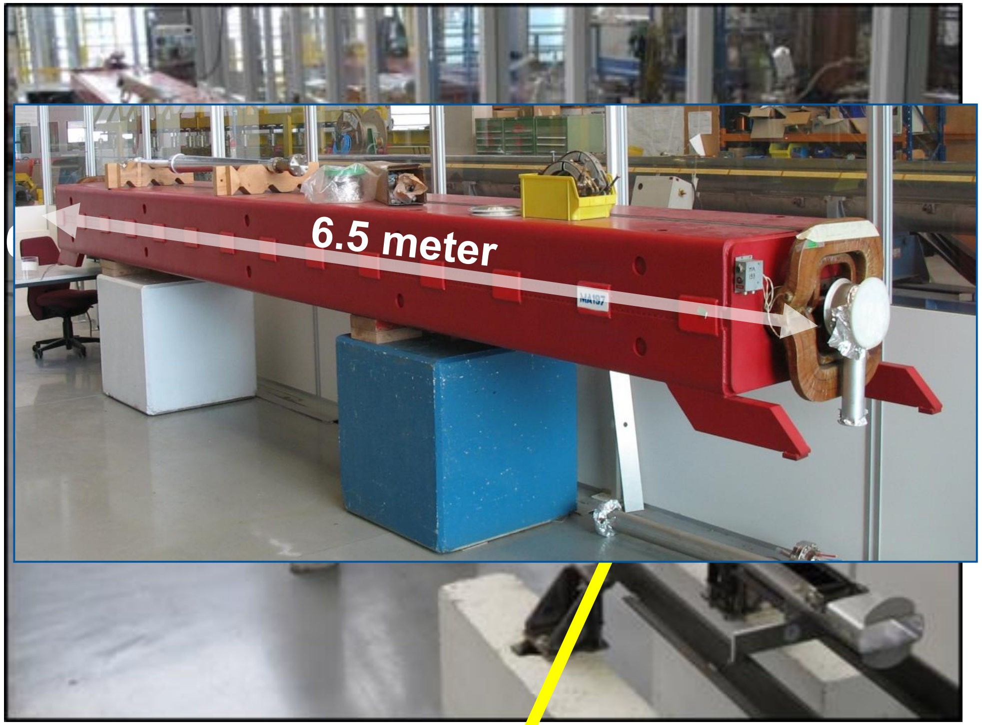
The possible solution : carbon a-C coatings



Dose below 10^{-6} Clb/mm²

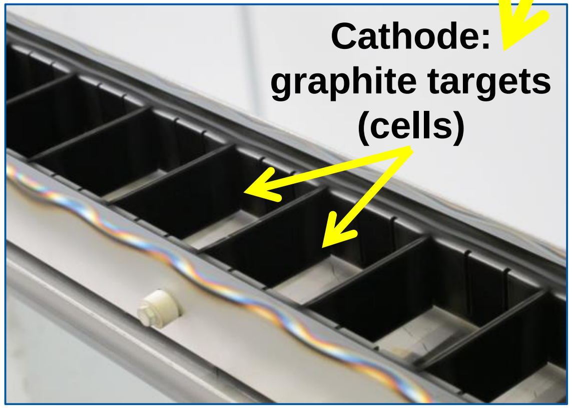
-Carbon (graphitic) coating on copper deposited by magnetron sputtering
-SEY does not change for thicknesses above 50 nm
-development started in 2008 for an upgrade of SPS

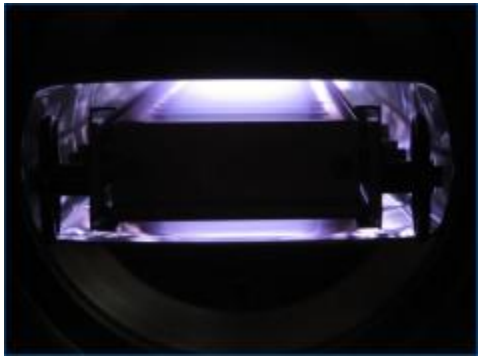
LIU-SPS: Carbon coating of the SPS vacuum chambers



Project of coating of the Super Proton Synchrotron dipoles with carbon to mitigate electron cloud (744 dipoles x 6.5 m each, 18 t)

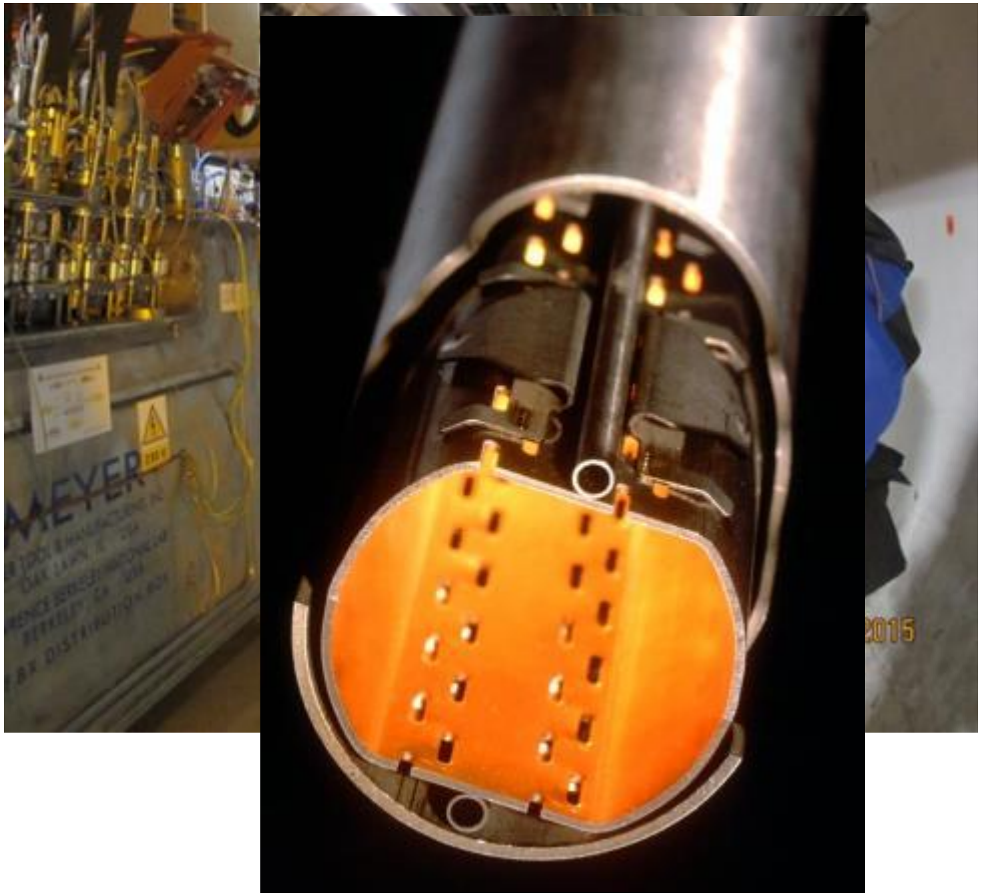
- hollow cathode coating (cannot apply axial B-field for magnetron in the yokes)
- successful on short section, tested with beam in SPS (section ~200 m)
- development ongoing to do the coating in the tunnel in 2018



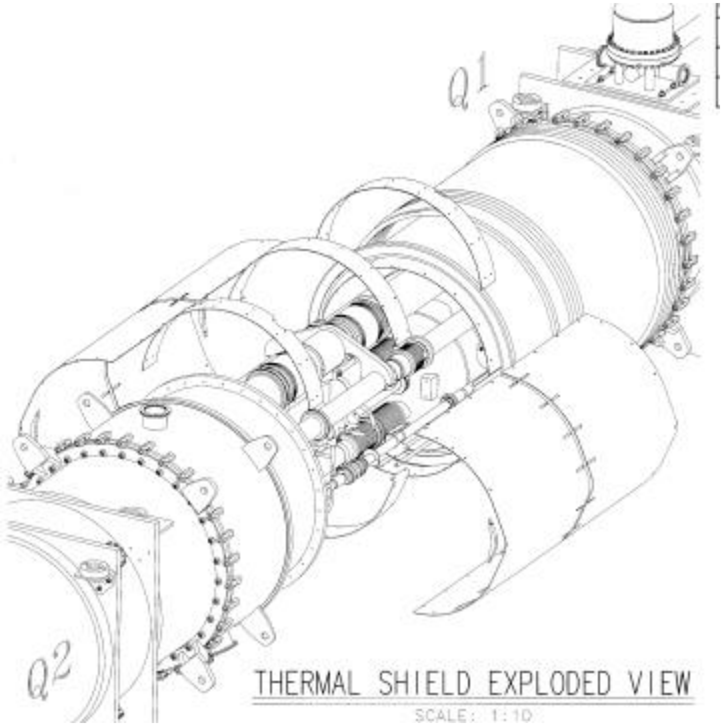


Carbon coating of triplet magnets of LHC in situ during LS2

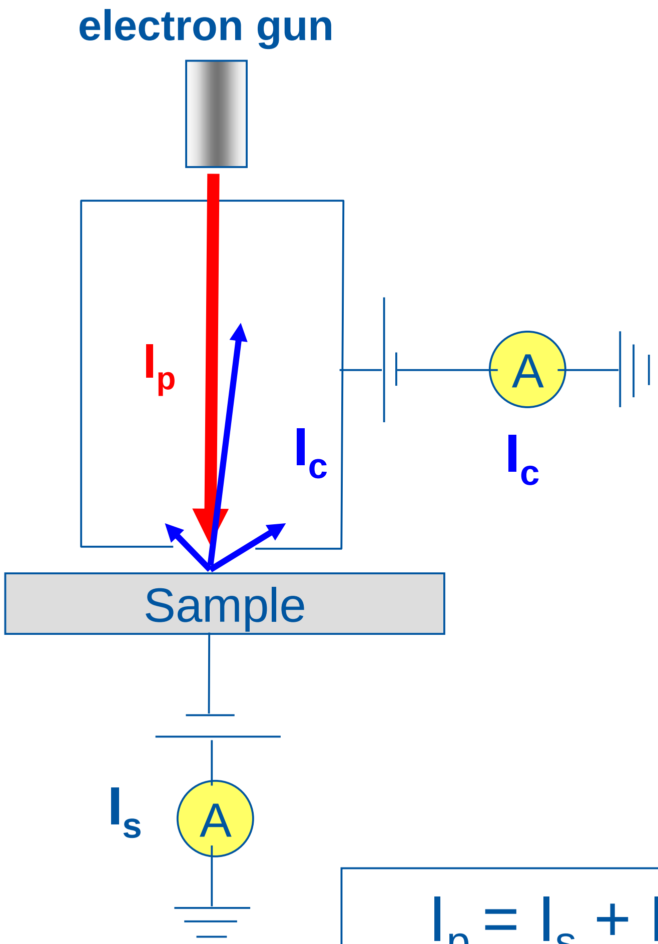
In order to cope with the thermal load on cryogenics provoked by e-cloud
Close to interaction points
Coating 35 m of beamscreen without dismounting the cryogenic magnets

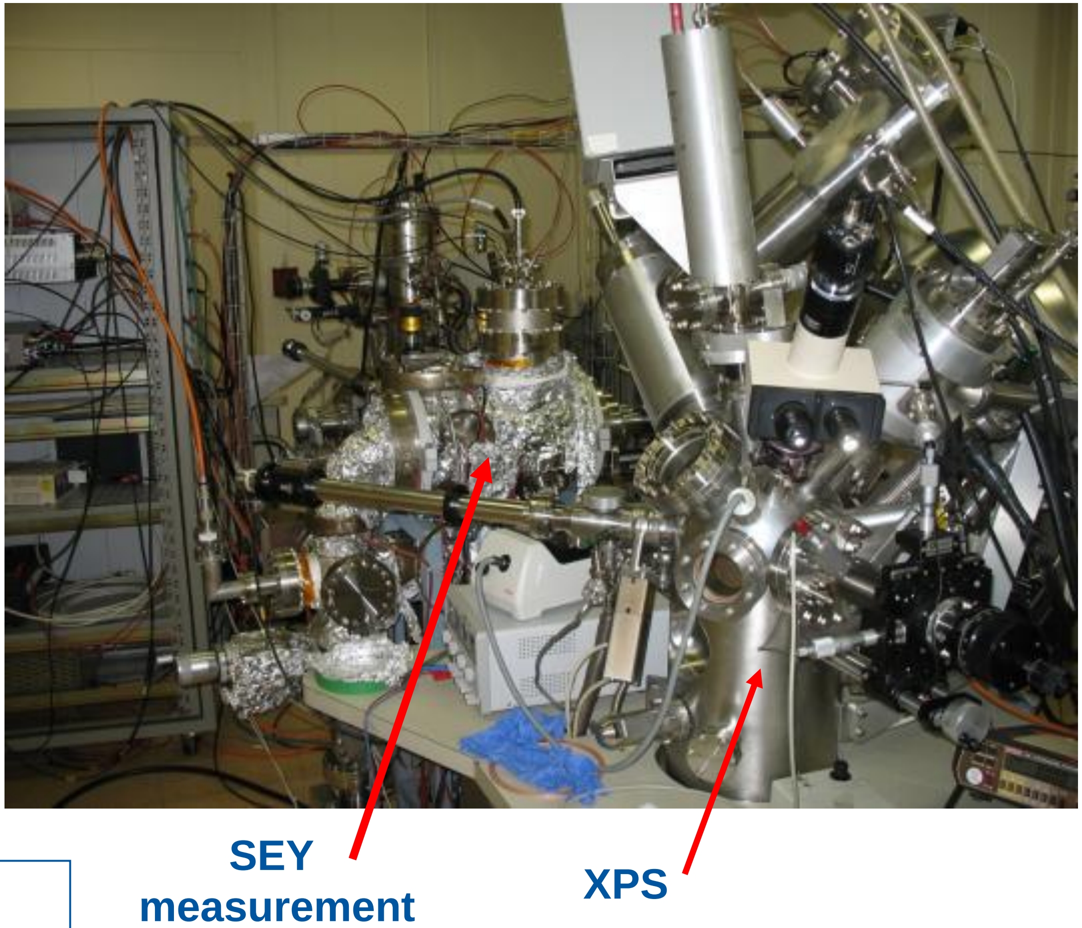


- ARC types, ≥Q7 (c.bore inner diam. 50 mm)
- LSS types, Q1–Q6 (cold bore inner diameters 50, 53, 63, 69 and 74 mm)



Measurement of SEY

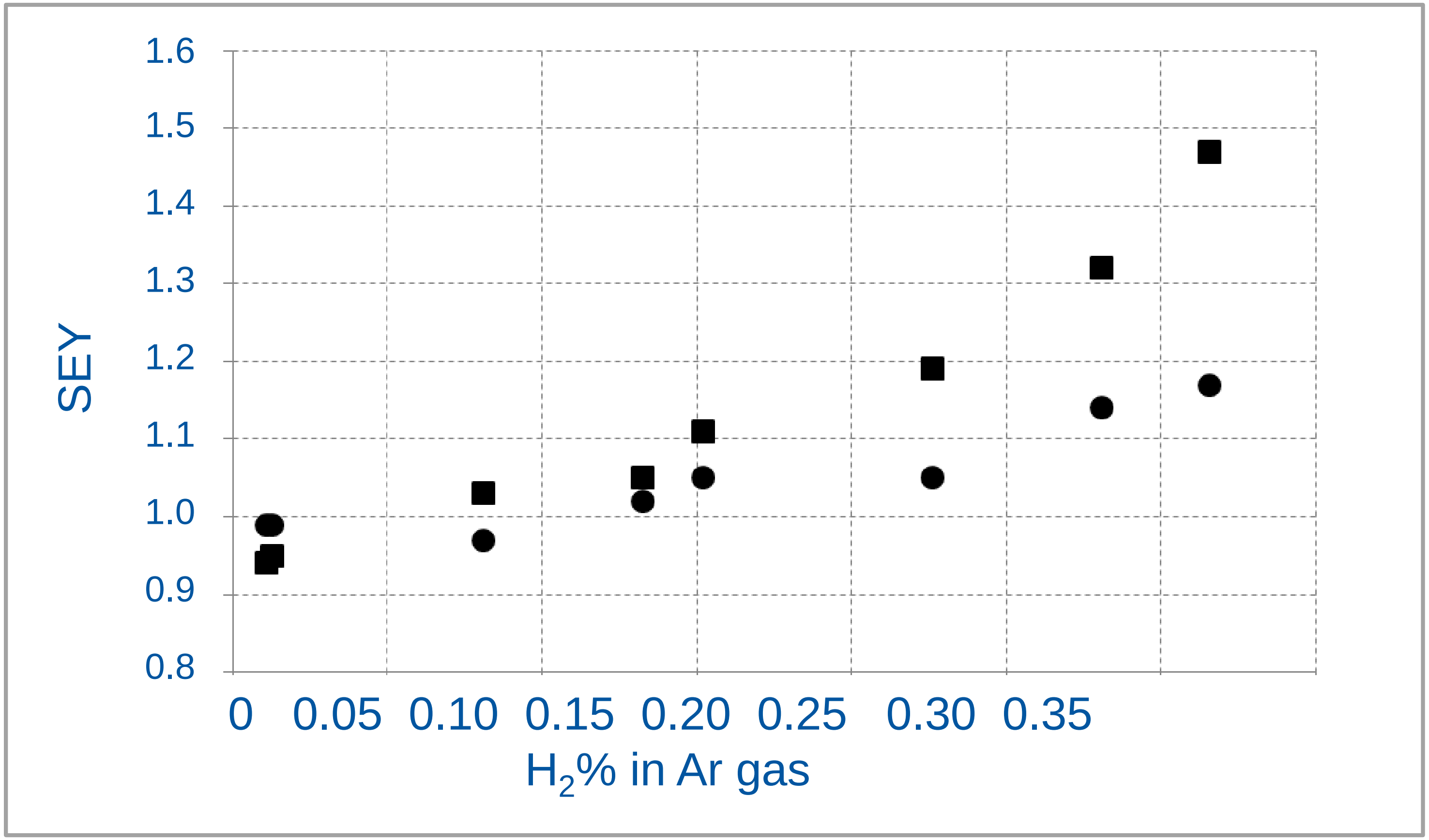




$$I_p = I_s + I_c$$

$$\delta = I_c / (I_s + I_c)$$

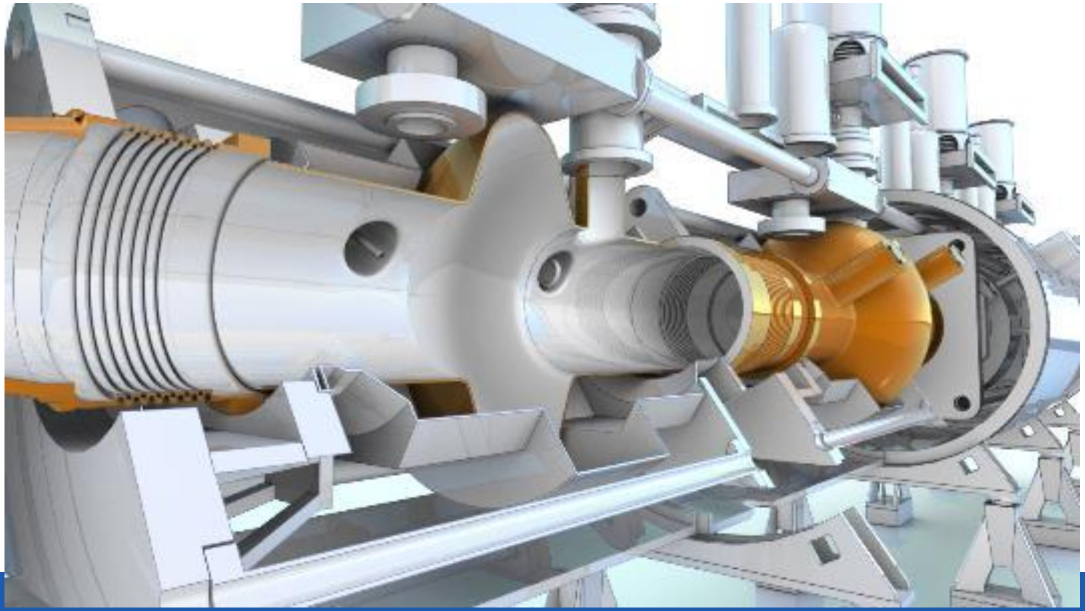
Effect of hydrogen content in the sputtering gas



Hydrogen is the most important residual gas in a baked vacuum system (outgassing), therefore a special care must be taken to have a «clean» coating system

Remark: it is very difficult to measure the H content in a carbon coating.

Superconducting Radio Frequency (SRF) Thin Films activities at CERN

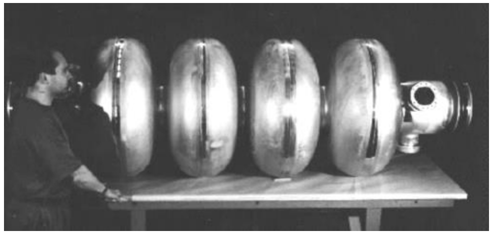


Thin Film SRF at CERN

Thin Film SRF projects at CERN

Past:

- **x288** Nb/Cu 350 MHz 4-cells cavities for LEP2 (90's)
- **x16** Nb/Cu 400 MHz single cell cavities for LHC (2008)



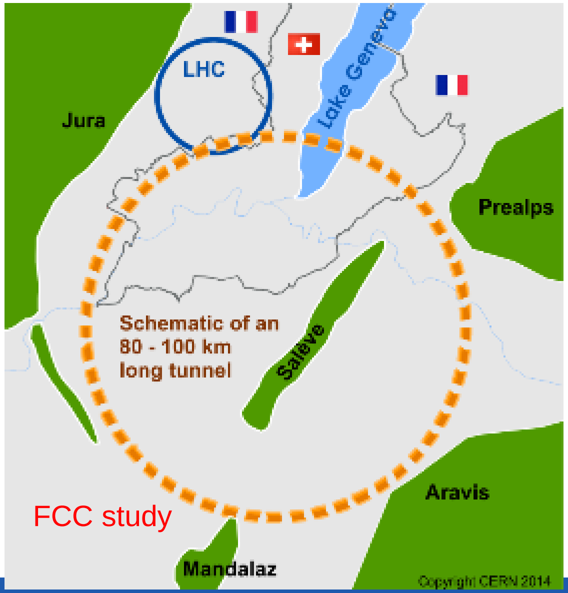
LEP2 4-cells cavity

Current:

- **x25** Nb/Cu 100 MHz cavities for HIE-ISOLDE
- **x8** Nb/Cu **spare** 400 MHz cavities for LHC

HIE-ISOLDE cavity

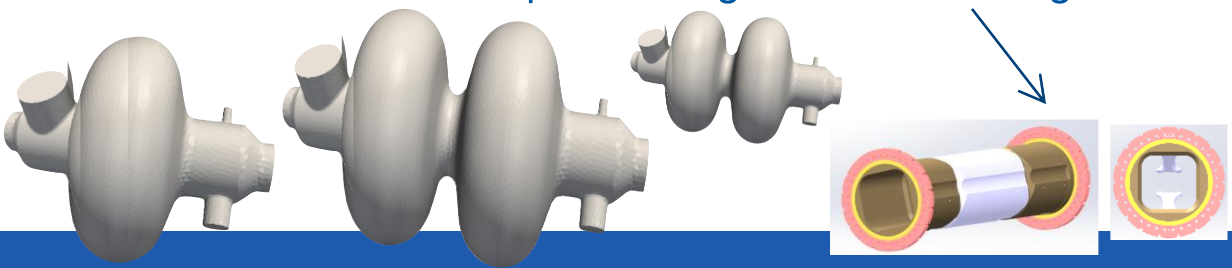
LHC cavity



FCC study

Future: **FCC** (Future Circular Collider) study

- 400 MHz elliptical single cell, **quantities ~ 300**
- 400/800 MHz elliptical multi-cells, **quantities > 1000**
- 400 MHz Wide Open Waveguide for "crabbing"



SRF Cavities production

1. HIE-ISOLDE QWR Nb/Cu cavities

Superconducting booster for ISOLDE radioactive ion beam facility at CERN

39 MV needed to reach 10 MeV/u

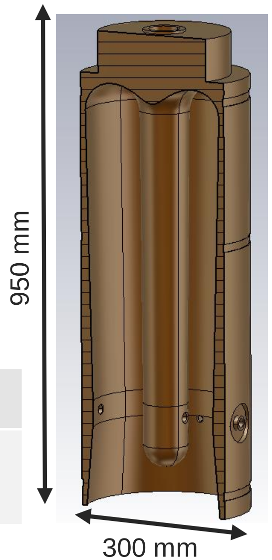
for A/q = 4.5 (highest possible at ISOLDE)

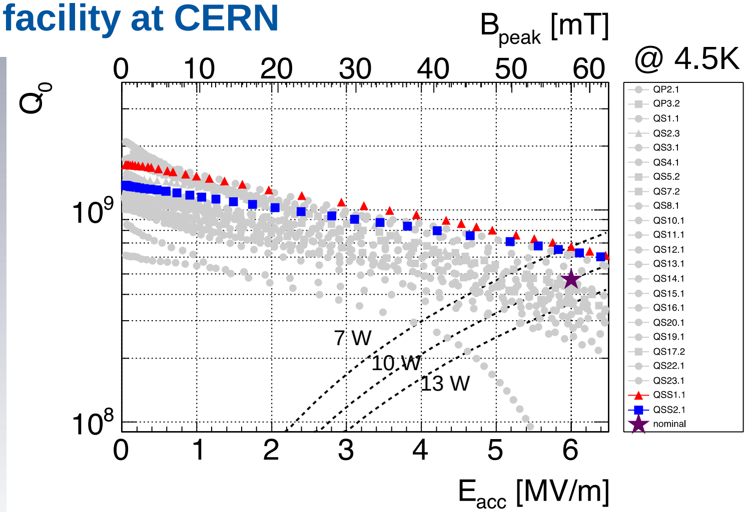
25 Quarter Wave Resonators cavities

→ cavities production for phase 2 completed,

→ 4th cryomodule under commissioning,

→ + 3 spare cavities produced out of 5

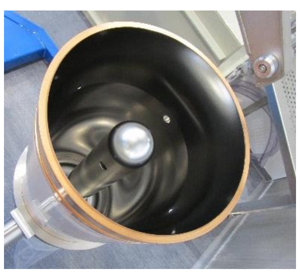




Frequency	**101.28 MHz**
Specification	**6 MV/m @ Q_0 = 4.7x10^8**

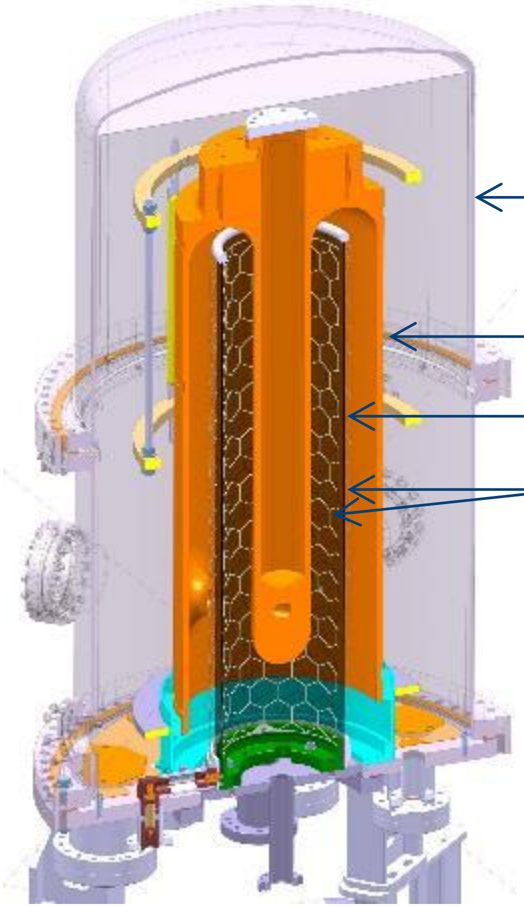
First 2 seamless (no weld) cavity coated

→ Best RF performance of all the production!



SRF Cavities production

1. HIE-ISOLDE QWR cavities – Nb coating hardware and process



- **Cavity in UHV chamber** (10^{-8} mbar base vacuum)
- Cu cavity substrate, biased at -80 V
- Nb cylindrical cathode **used on both sides**, not cooled
- Anode grids on both sides of cathode, grounded

→ DC-bias diode sputtering, 8 kW, 0.2 mbar Ar

→ Cavity bake-out to 650°C (IR lamps) prior to coating

→ Coating at high temperature (300 → 620°C)

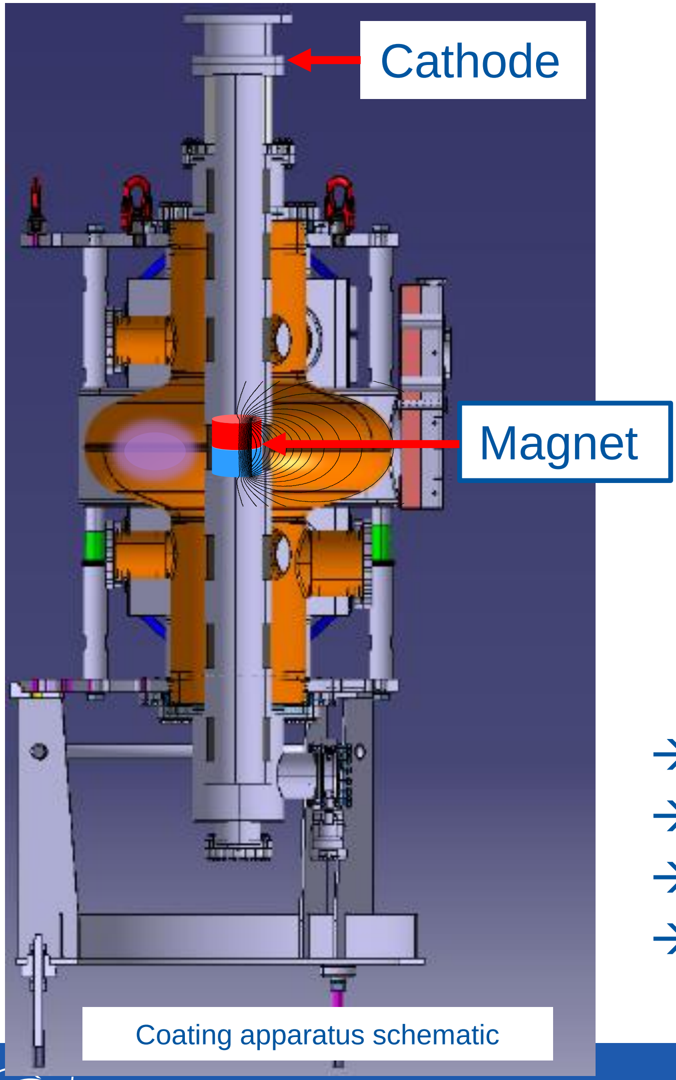
→ 15 runs of 25’ each, net coating duration = 6h

→ Multi-layers due to coating run/cool-down cycles

→ Nb layer thickness ranging from 1.5 μm to 12 μm

SRF Cavities production

2. LHC spare cavities – Nb coating hardware and process



Coating apparatus schematic

- **Cavity as UHV chamber**
  (10^{-8} mbar base vacuum)
- Cavity = anode, grounded
- Nb cylindrical cathodes tubes
- **movable electromagnet inside**, liquid cooled

→ **DC-magnetron sputtering, 6.4 kW, 6.10^{-4} mbar Kr**

→ Cavity bake-out (bake-out tent) to 180°C
→ Coating 7 steps for the 7 different electromagnet positions
→ Duration = 1h 20’ at low temperature (150°C)
→ Nb layer thickness ~ 2 μm

SRF Cavities production

2. LHC spare Nb/Cu cavities

→ **8 Spare cavities to be manufactured, Nb coated and dressed with He-tank**

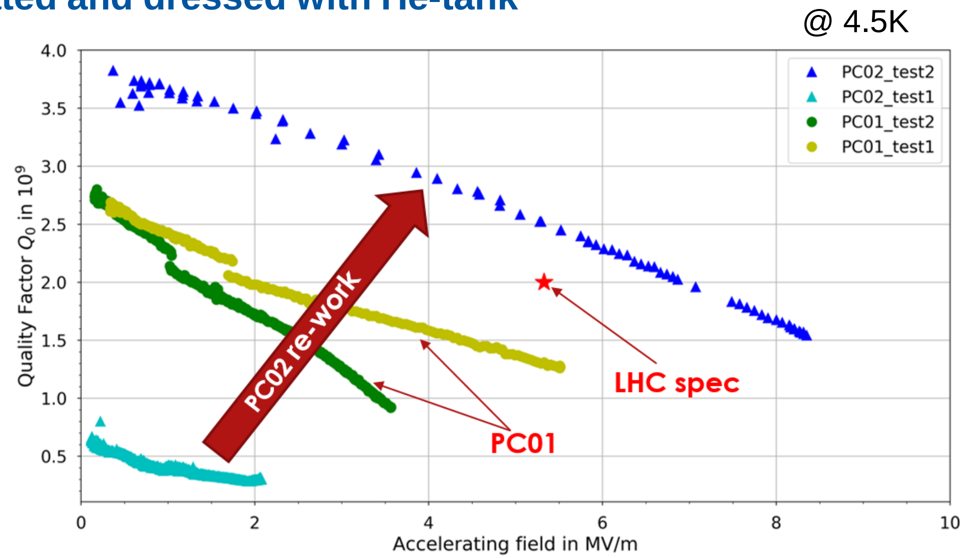
Practice cavities (PC): 3 coatings

PC01 recoated: substrate structural defect

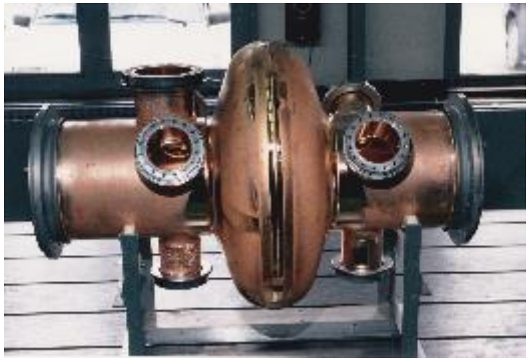
PC05: coated, RF test pending

PC02 recoated:

- **Cavity at specs ($Q_0 = 2.2.10^9$ at 6 MV/m)**
- **Coating recipe and assembly flow validated**
- **Ability to recover a heavily damaged cavity by surface machining**



Frequency	400.8 MHz
Specification	5 MV/m @ $Q_0 = 2x10^9$



R&D: HiPIMS coatings for SRF cavities

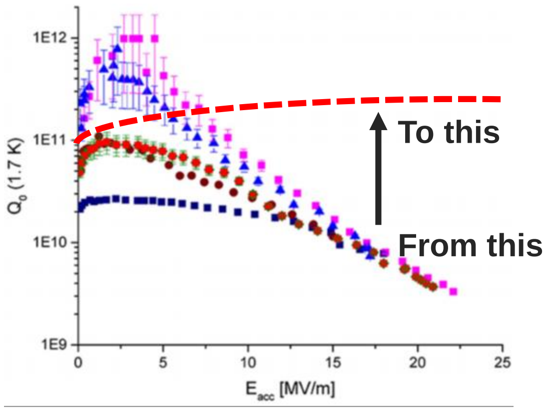
GOALS AND MOTIVATION

Mitigate the high field Q-slope in Nb/Cu cavity

Low surface resistance (<10 nΩ, 1.3 GHz, 2K) with Nb layer

High Power Impulse Magnetron Sputtering

Layer densification



GOALS AND MOTIVATION

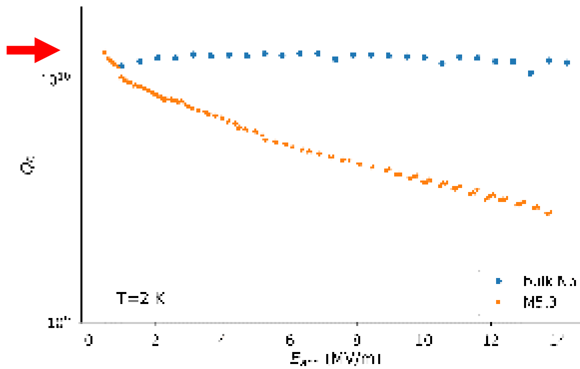
Very encouraging results on 1.3 GHz cavities: **20 nΩ residual resistance** →
Target: **5 nΩ.**
Q-slope among the best for sputtered cavities

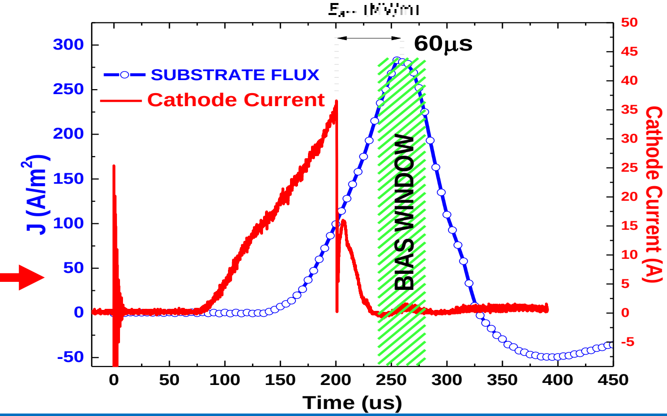
Bias effect: lower values induce lower surface resistance

Substrates affected by surface defects → collaboration with Jlab for surface finishing (centrifugal barrel polishing)

Coating on β = 0.65 704 MHz cavities enabled by tuning magnetic configuration : Best candidate to evaluate the Q-slope dependence to layer density

Ions Energy Analysis → bias delayed to mitigate working gas incorporation





R&D: A15 Materials for SRF cavities

GOALS AND MOTIVATION

Switch from Nb/Cu to A15/Cu

Higher Tc ,Higher efficiency

Low surface resistance R_{BCS} ~ 0.25 nΩ @ 4.2K / 400MHz (Nb ~ 60 nΩ)

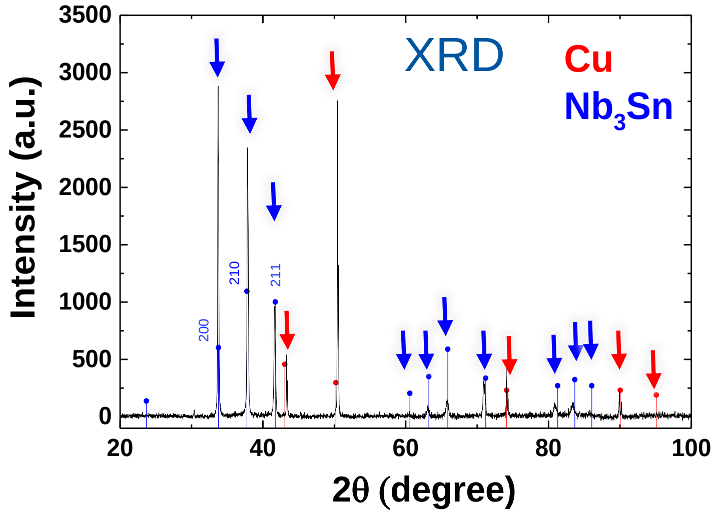
Toward leptonic machine compatible thin film on copper

CHALLENGES

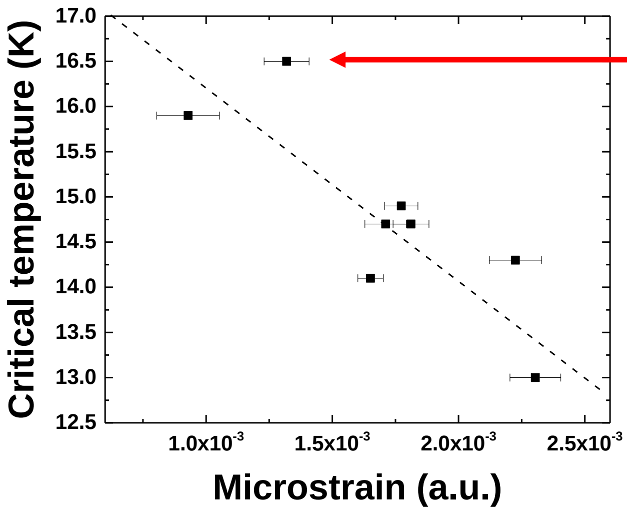
- Synthesize A15 crystalline phase
- Obtain theoretical Tc (18.3K for Nb_3Sn) on copper substrate
- Manage stress in the film

RESULTS

Substrate plays a major role in the layer final properties



FCC cubic phase synthesized on Cu

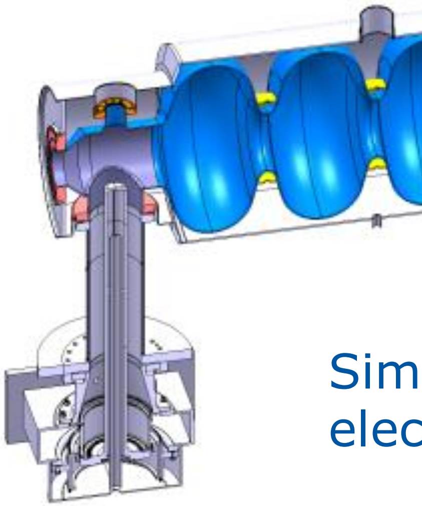


Impact of layer microstrain on superconducting properties

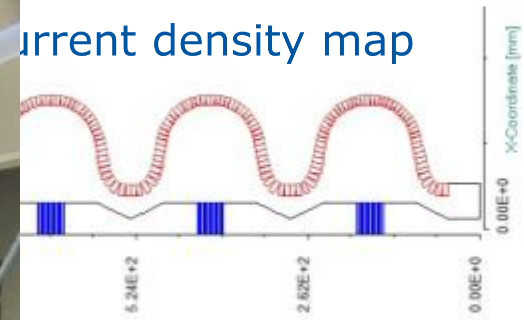
SRF properties to be characterized in 2018

Bulk Nb superconducting cavities: Optimization of the Electropolishing

5-cell cav



urrent density map



Sim
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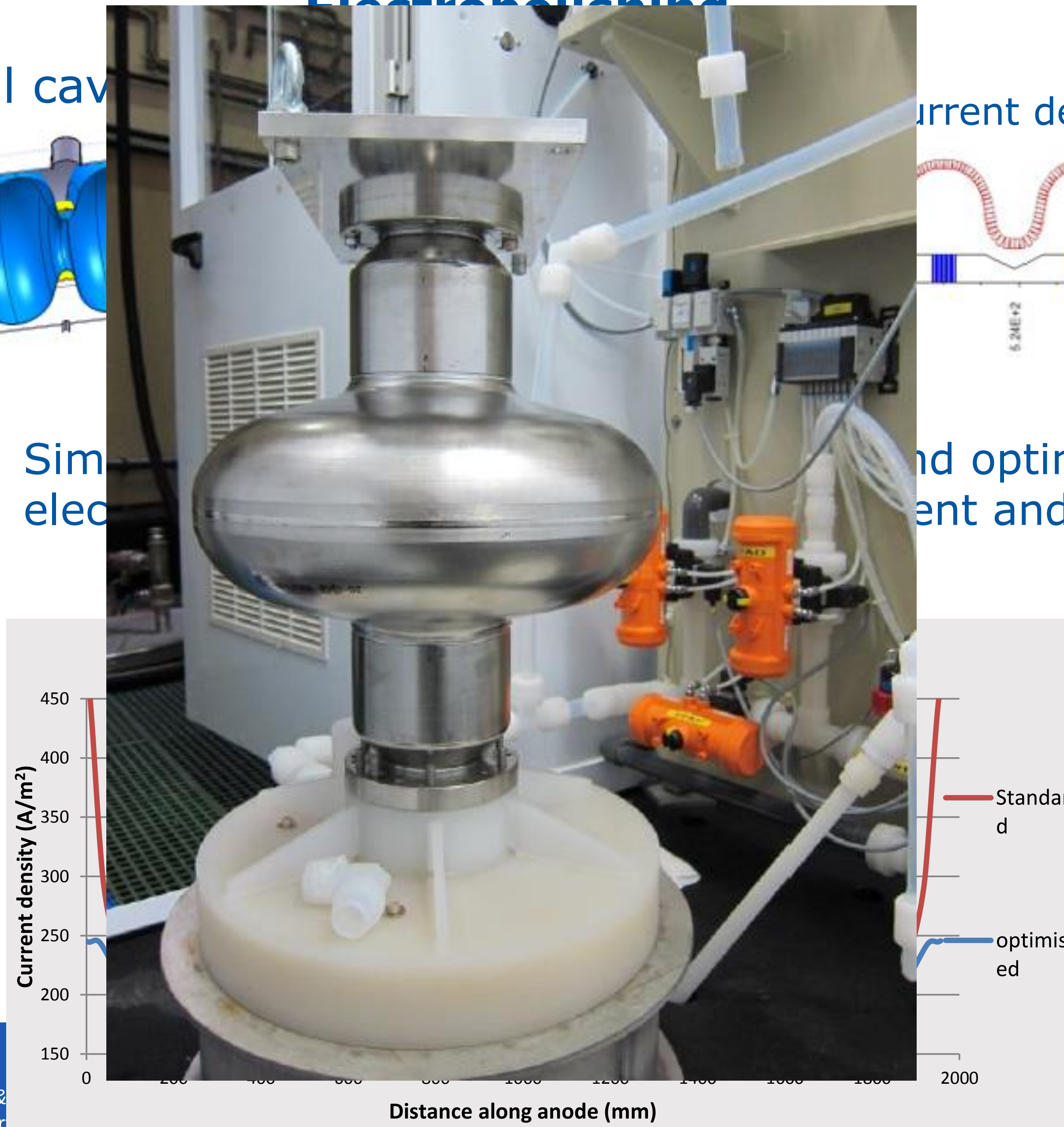
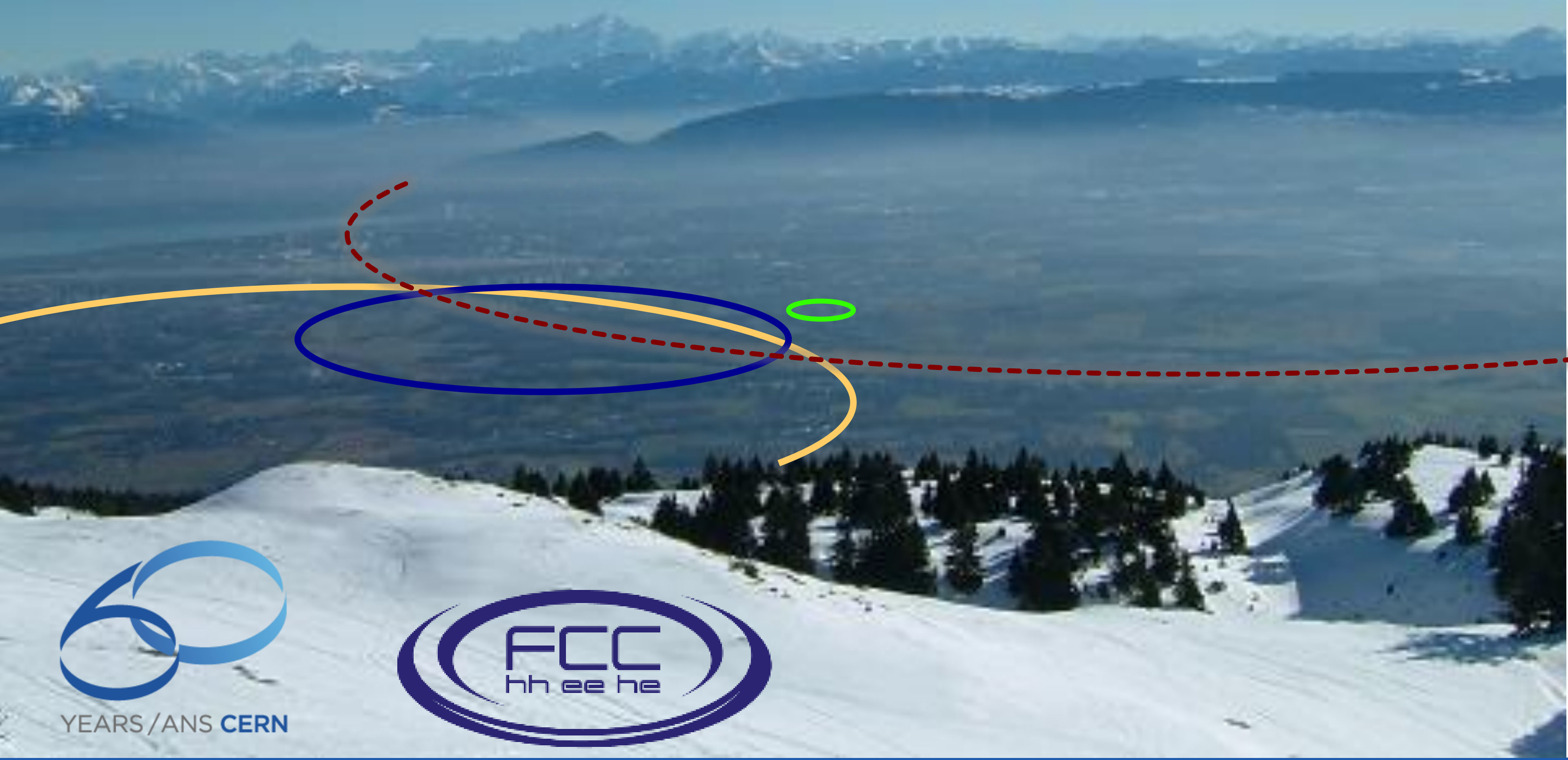


COMSOL software

Future Circular Collider Study
Beam Screen Impedance



FCC-hh: pushing the energy frontier

The name of the game of a hadron collider is energy reach

$$E \propto B_{dipole} \times \rho_{bending}$$

Compared to the LHC:

Factor ~6 in energy → E_{cms} 100 TeV pp

Factor ~3 in radius → $\rho_{bending}$ 100 km

Factor ~2 in field → B_{dipole} 16 T

Factor ~144 in synchrotron radiation power → $E^4\rho^{-2}$

Synchrotron radiation/beam screen

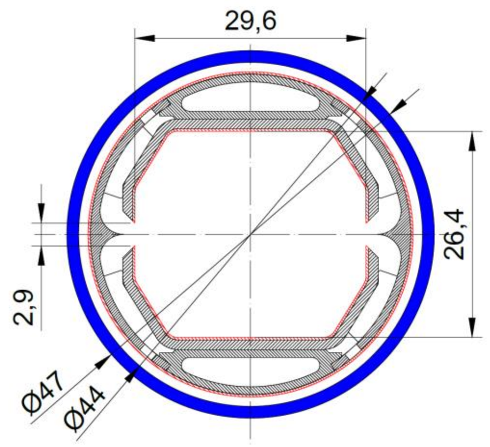
High synchrotron radiation load (SR) of protons @ 50 TeV:

~30 W/m/beam (@16 T)

→ 5 MW total in arcs (LHC <0.2W/m)

New type of ante-chamber

- absorption of synchrotron radiation
- avoids photo-electrons, helps vacuum



Taking into account vacuum requirements, overall cryogenic efficiency and power consumption of the accelerator, the synchrotron radiation has to be absorbed at 50 K

Copper coating for impedance as in the LHC…
…might not be good enough for the FCC-hh

Impedance basics

Image charges flow on the surface of the beampipe and produce wakefields
The wakefields potential is proportional to surface impedance $Z_{surf} = V/I_b$

Power dissipation from wakes is $P_{loss} = MI_b^2 \,\mathrm{Re}(Z_{surf}^{eff})$ where Z_{surf}^{eff} is a summation of $(2\pi R/2\pi b)\, Z_{surf}$ over the bunch frequency spectrum

Wakefields have an effect on beam stability, in particular the transverse plane: the Transverse Coupled-Bunch Instability (TCBI)

Risetime of resistive-wall instability depends on the surface impedance

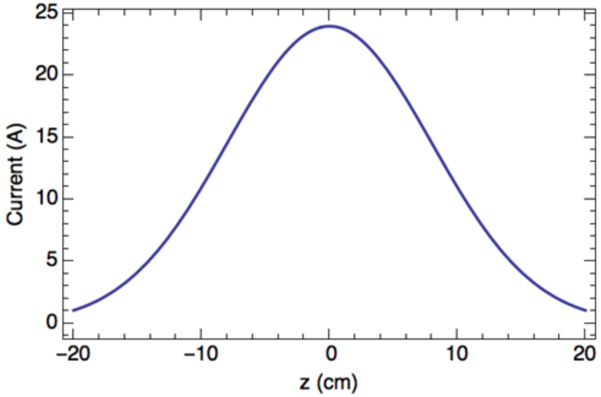
$\frac{1}{\tau} \propto \frac{I_b M}{EL} \mathrm{Re}(Z_T^{eff})$ with $Z_T = \frac{2\pi R\, c}{\pi b^3\, \omega} Z_{surf}$ at the frequency of the unstable mode

Transverse mode-coupled impedance (TMCI) $I_\mathrm{b} \propto \frac{E}{\mathrm{Im}(Z_\mathrm{T}^{\mathrm{eff}})}$ limits the maximum bunch intensity, also linked to the surface impedance

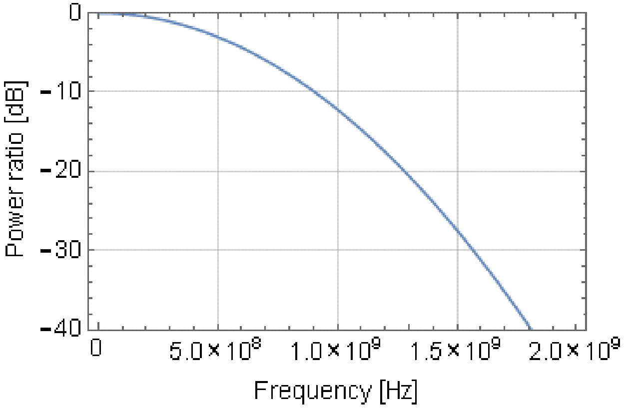
HTS films requirements for beam screen

Bunches of 10^{11} protons, 8 cm long

Beam instantaneous image current



Frequency spectrum for various bunch shapes

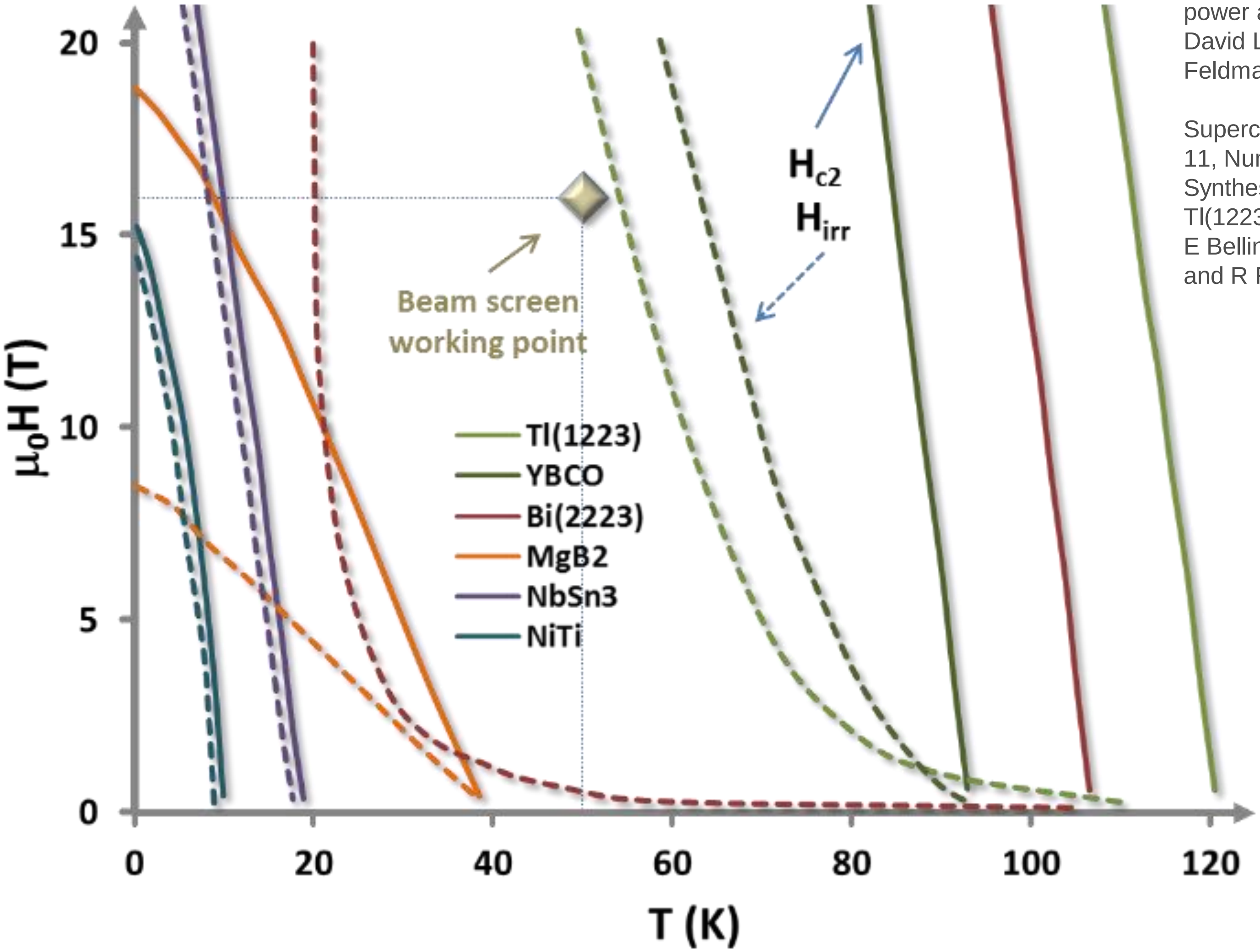


Beam screen of ~30mm diameter.

Assuming a film thickness / skin depth of 1 µm the HTS material should have a critical current density

Jc of about 25 kA/cm² (2.5x10⁸ A/m²) at 50 K and 16T

Material choices



Data from:

Nature 414, 368-377 (15 November 2001)
High-Tc superconducting materials for electric power applications
David Larbalestier, Alex Gurevich, D. Matthew Feldmann & Anatoly Polyanskii

Superconductor Science and Technology, Volume 11, Number 8
Synthesis and properties of fluorine-doped Tl(1223): bulk materials and Ag-sheathed tapes
E Bellingeri, R E Gladyshevskii, F Marti, M Dhallé and R Flükiger

Courtesy: E. Bellingeri

Challenges for HTS coatings

- YBCO and Tl-based HTS are the only possible candidates

- How to obtain good quality HTS inside tube geometry
  - Considerable experience exists in coated tape production for YBCO, scalability to tubes is extremely challenging: develop forming techniques.

  - Tl-based HTS has characteristics similar to YBCO, and should allow full scalability to tubes thanks to electrodeposition on silver (coated) substrates: develop this (old) new material

Surface impedance basics

The surface impedance depends strongly on the depinning frequency

$$\nu_o(B_o) = \frac{k}{\eta\, 2\pi} = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n \sqrt{B_o}\, J_c(B_o)}{\sqrt{\phi_o}\, B_{c2}}$$

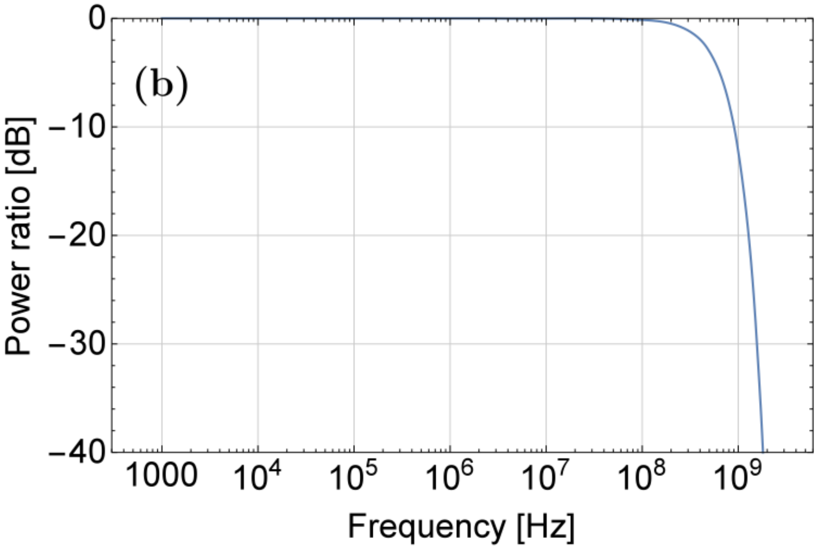
$$Z_{\mathrm{sf}} \equiv Z_{\mathrm{f}} = Z_{\mathrm{n}} \sqrt{\frac{B_o}{B_{\mathrm{c2}}}} \qquad \nu >> \nu_o$$

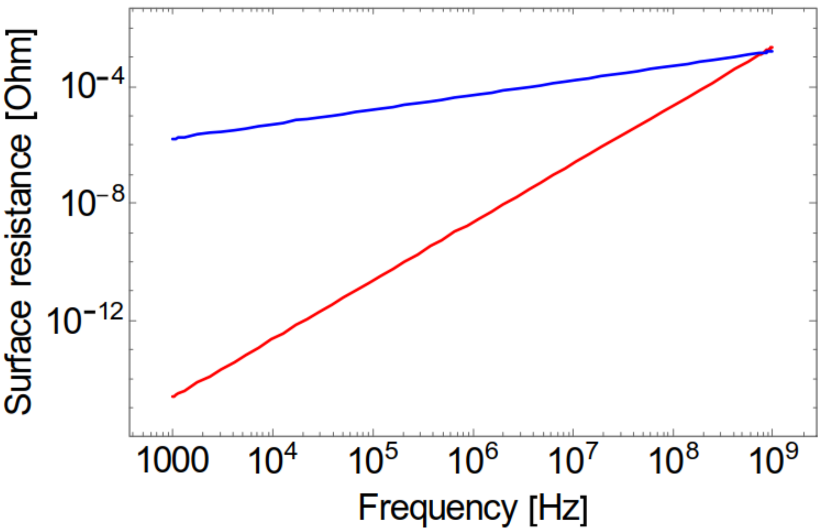
$$R_{\mathrm{sf}} \equiv R_{\mathrm{f}} = \frac{R_{\mathrm{n}}}{\sqrt{2}} \sqrt{\frac{B_o}{B_{\mathrm{c2}}}} \left(\frac{\nu}{\nu_0}\right)^{3/2}$$

$$\nu << \nu_o$$

$$X_{\mathrm{sf}} \equiv X_{\mathrm{f}} = R_{\mathrm{n}} \sqrt{2} \sqrt{\frac{B_o}{B_{\mathrm{c2}}}} \left(\frac{\nu}{\nu_0}\right)^{1/2}$$

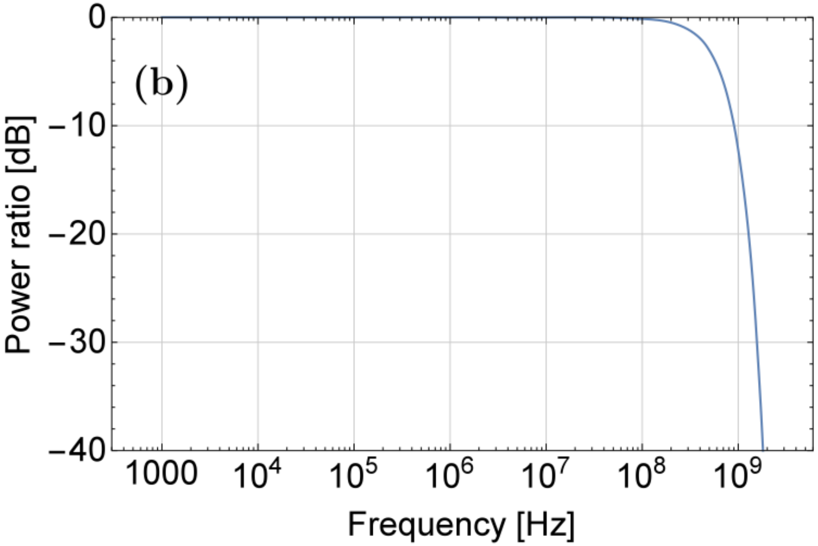
performance: YBCO relative to Cu at 50 K

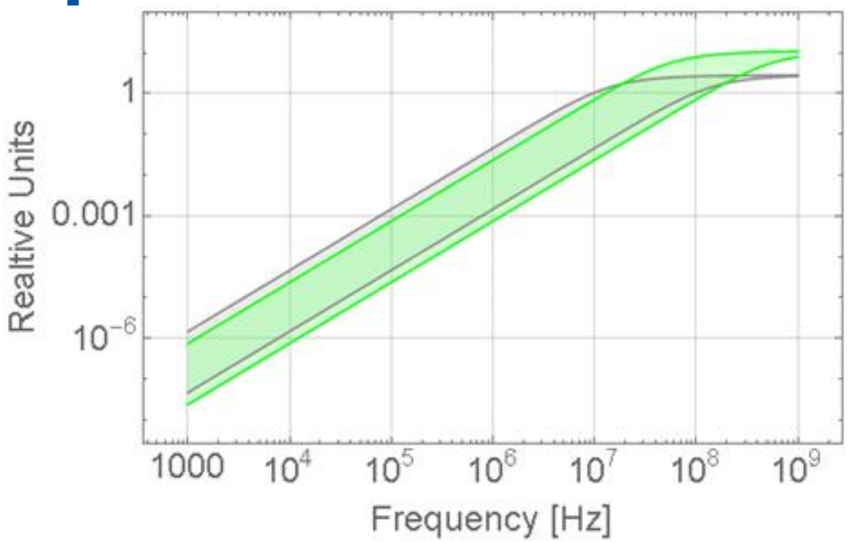




Surface resistance of superconductors in the presence of a dc magnetic field: frequency and field intensity limits,
S. Calatroni and R. Vaglio
IEEE Trans. Appl. Supercond. 27-5 (2017) 3500506

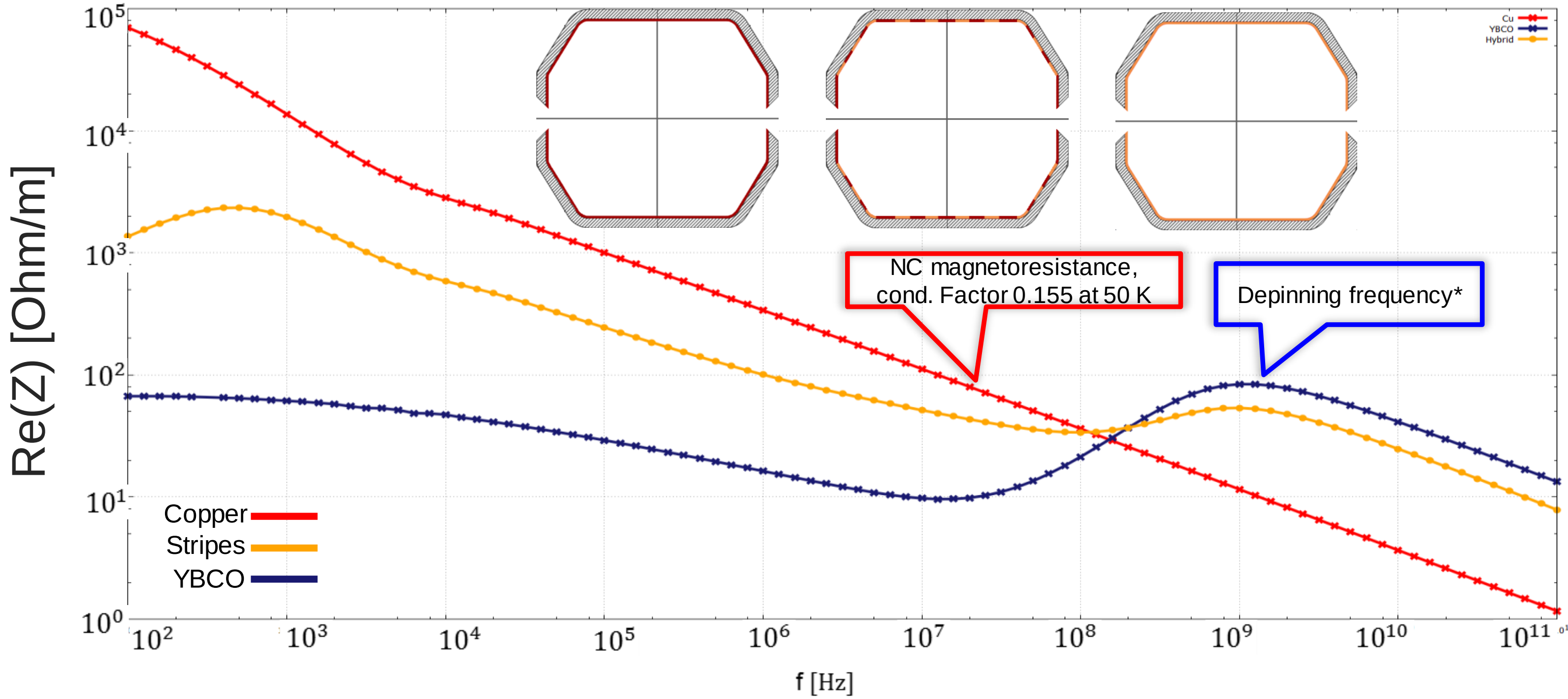
performance:
Tl-1223 relative to Cu at 50 K





Thallium-based high-temperature superconductors for beam impedance mitigation in the Future Circular Collider, Calatroni, S.; Bellingeri, E.; Ferdeghini, C.; Putti, M.; Vaglio, R.; Baumgartner, T.; Eisterer, M., **Superconductor Science and Technology, Volume 30, Issue 7, article id. 075002 (2017)**.

Impedance for 1m beam pipe @ 16T



Note that the SC impedance is always a surface impedance!
(the skin depth can never exceed the London depth)

Steel beam screen:	YBCO coating:	Copper coating:
κ = 180 MS/m	κ_n = 1.37 MS/m	κ = 6 GS/m
Thickness: 1 mm	Thickness: 1 µm	Thickness: 300 µm

[*]
B_{C2} = 45 T
$f_{dep} = 4\ GHz$

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Imaginary 16T

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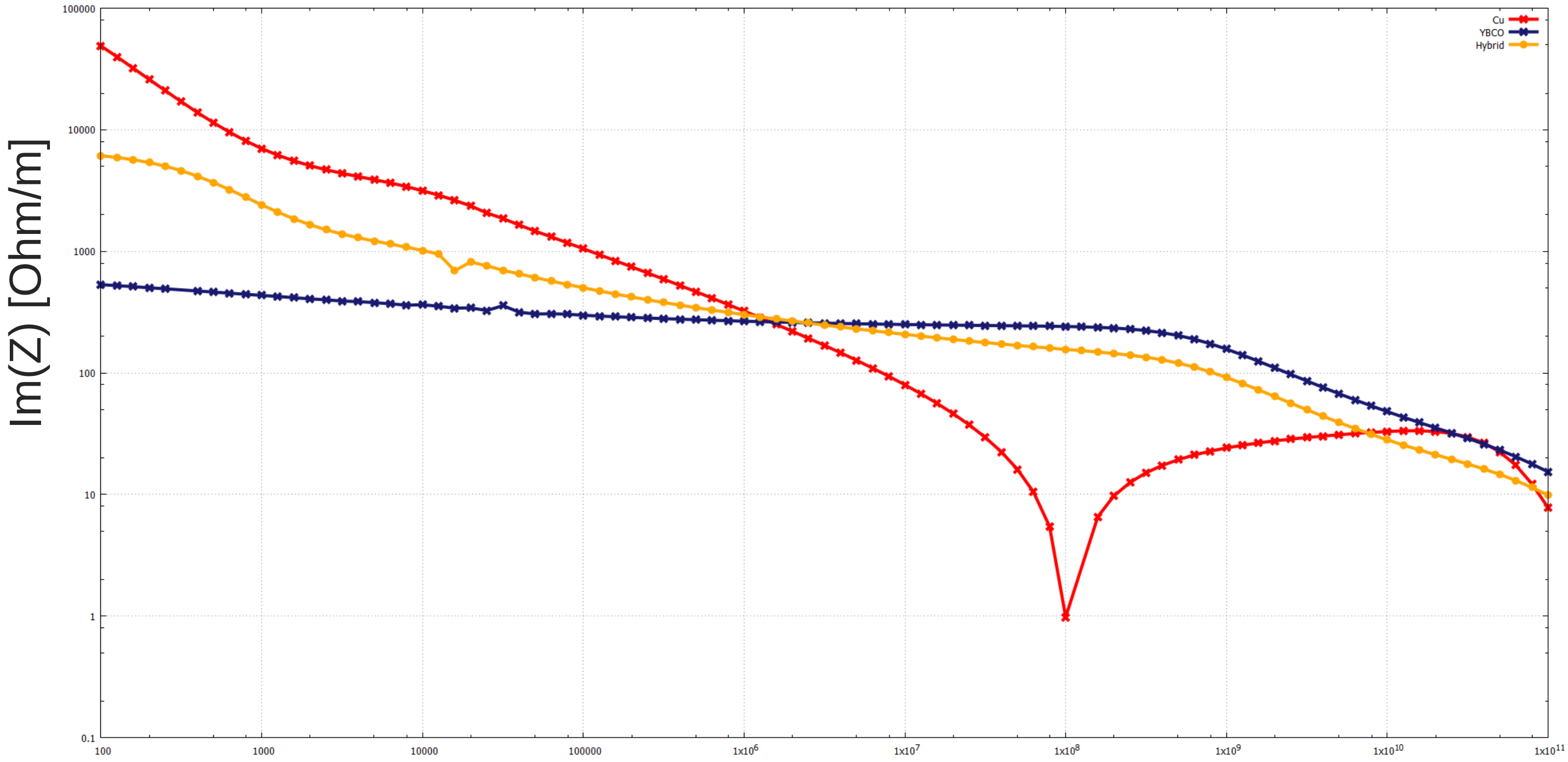

THANK YOU!