Origin and Mitigation of the Beam-Induced Surface Modifications of the LHC Beam Screens

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Bangkok, Thailand

Outline

- Electron cloud and heat loads in the LHC
- Analysis of LHC-extracted beam screens
- Experiments at cryogenic temperature: how to explain the LHC heat load picture?
- Towards a curative solution
- Conclusions

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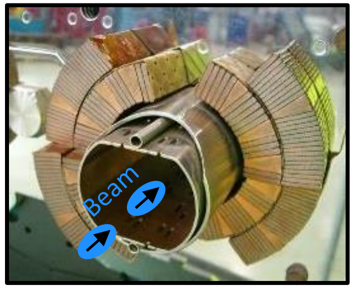
Electron cloud in the LHC

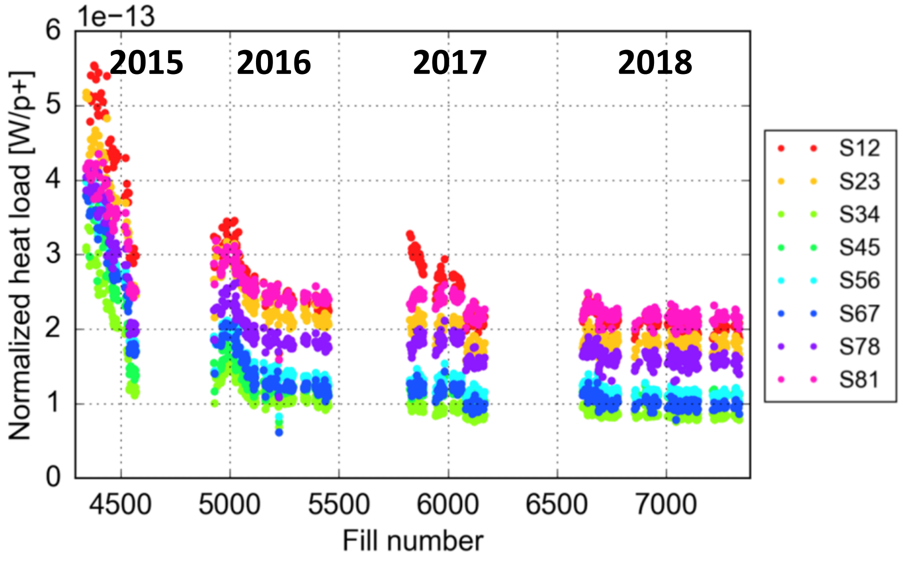
The **electron cloud** developing in the beam screens of the LHC is a **source of heat load** onto the **cryogenics system** of its superconducting magnets in its arcs. Since the beginning of the LHC Run 2 (2015), this heat load exhibits **puzzling features** which were not present during Run 1:

- **Wide spread** along the ring, in spite of an identical design of the 8 arcs
- Spread persisting during **conditioning**

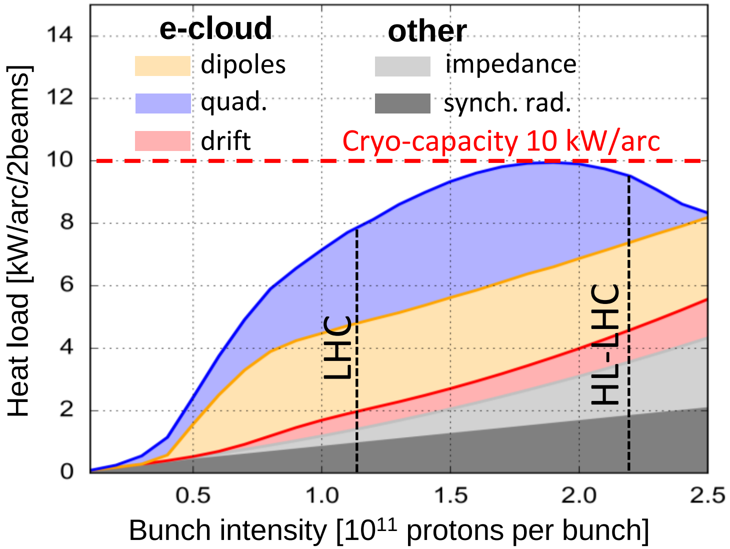
High heat load arcs are close to the **cryogenic capacity limit**

→ **critical issue** for High-Luminosity LHC





Simulations for high heat load arcs



Courtesy of G. Iadarola

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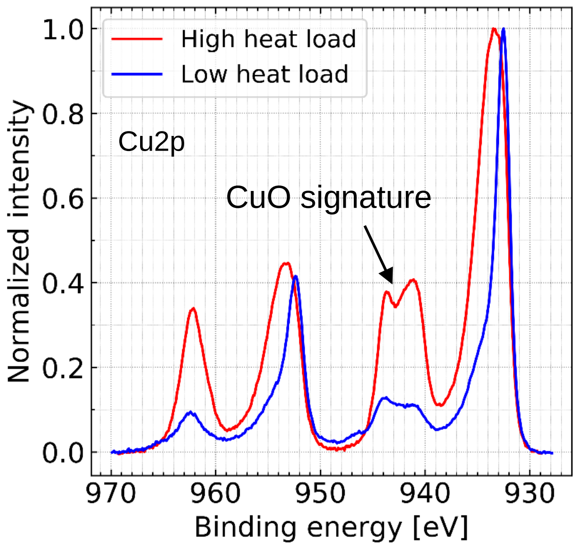
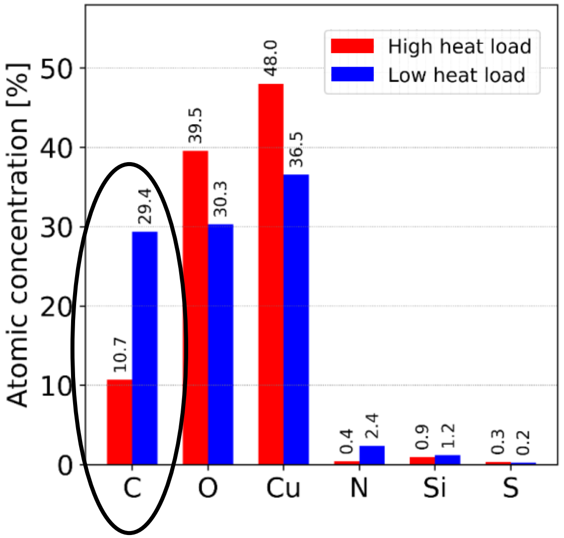
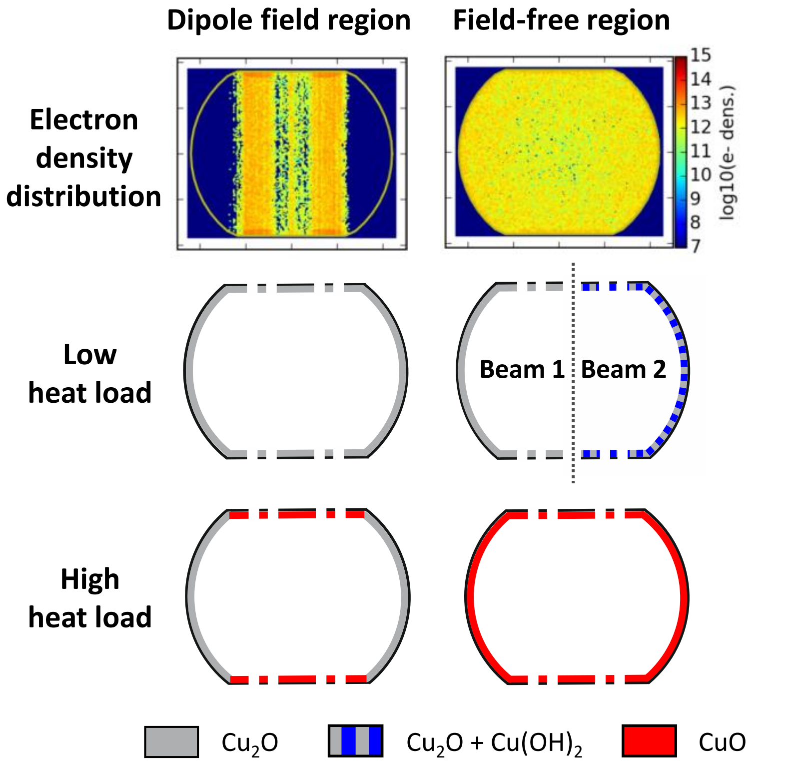
Surface analysis of LHC extracted beam screens

May-August 2019: extraction of beam screens hosted in one high and one low heat load dipoles and analysis of their surface in the laboratory
→ Surface chemistry (X-ray photoelectron spectroscopy)
→ Secondary Electron Yield measurements
→ Conditioning at RT







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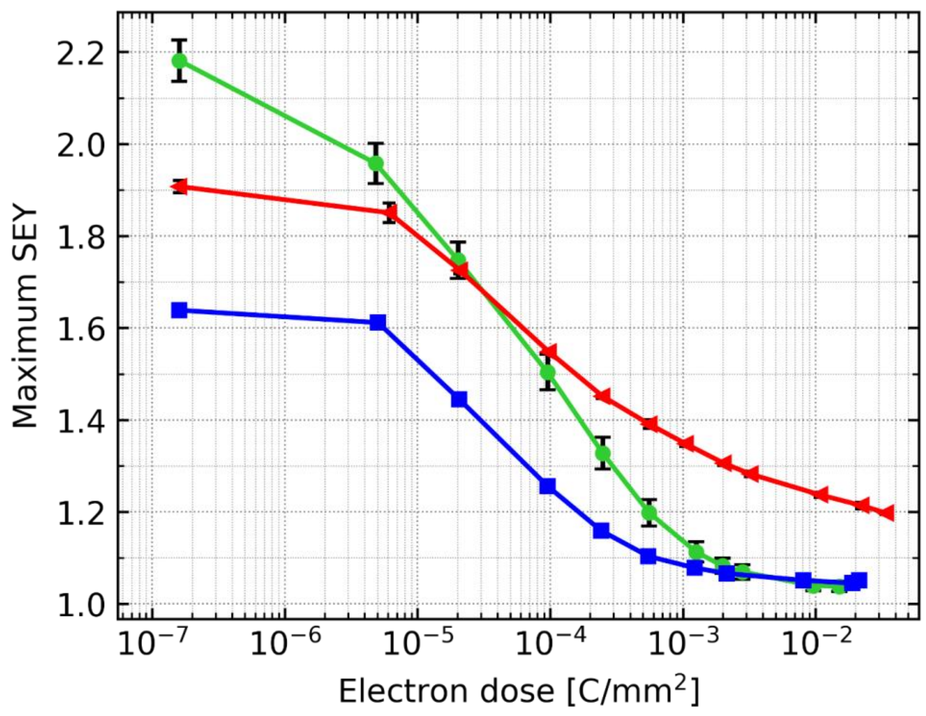
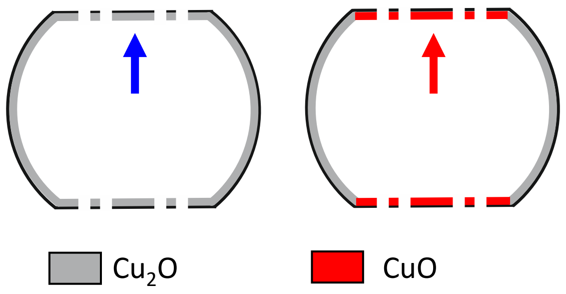
In high heat load beam screens

- Presence of **CuO (not native surface copper oxide)** with a field-related azimuthal distribution
- **Very low amount of carbon** at all azimuths

High versus low heat load – SEY and conditioning @ RT





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- **Higher SEY** in the presence of **CuO** than Cu_2O
- **Nominal** conditioning for the **low heat load** beam screens
- **Slower** conditioning for the **high heat load beam screen** in the presence of **CuO (partial reduction of CuO)**

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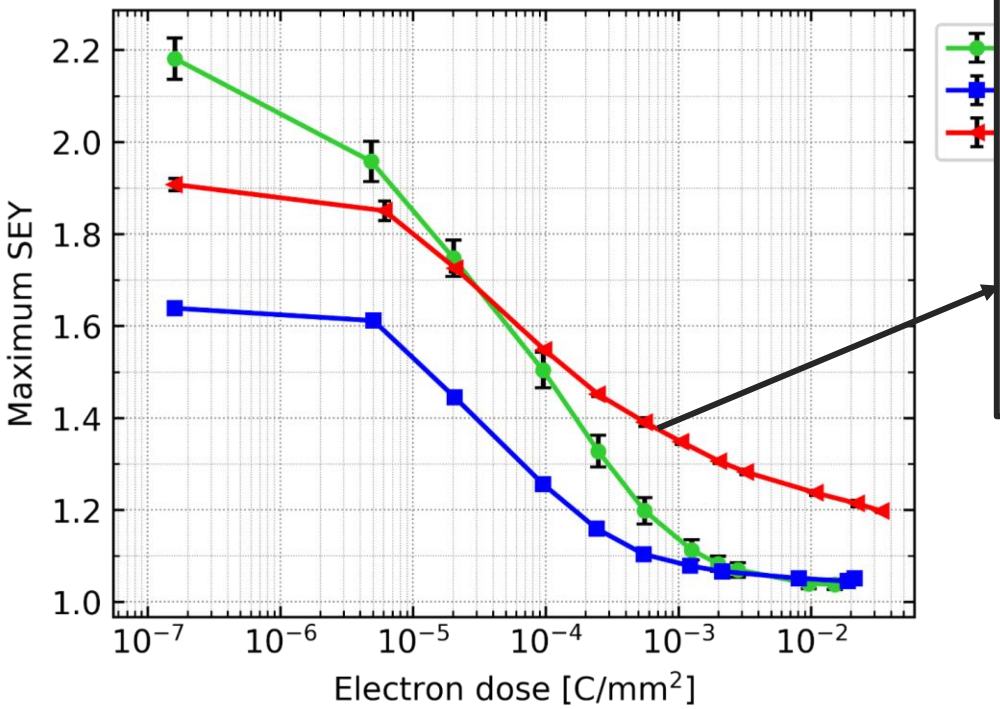

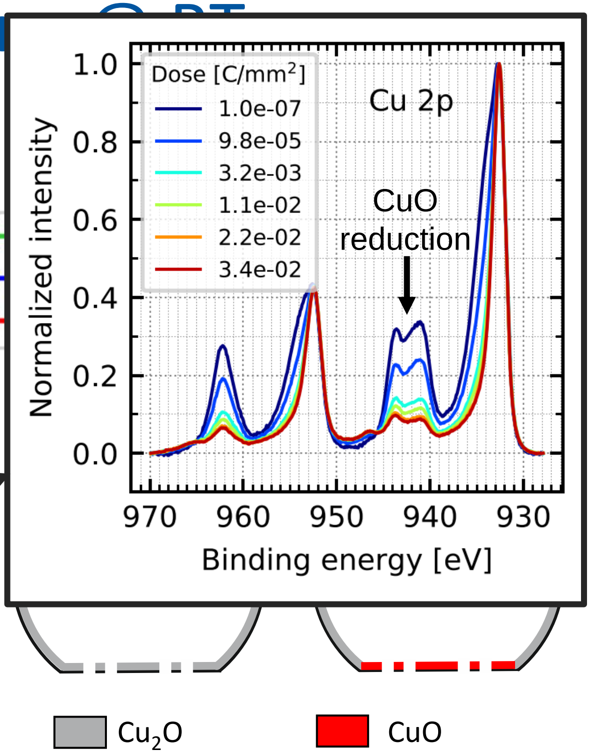

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→ what happens at cryogenic temperature?

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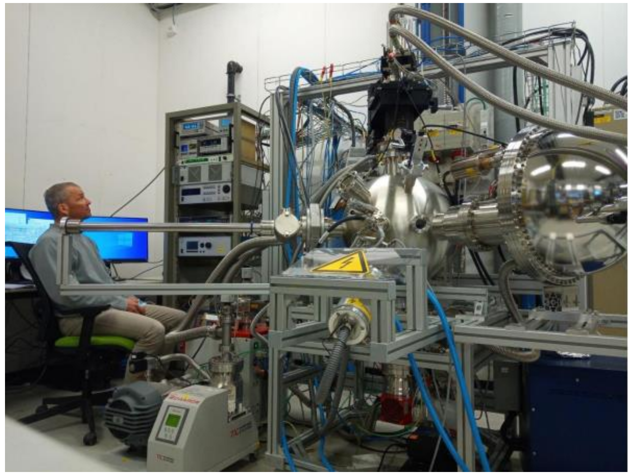
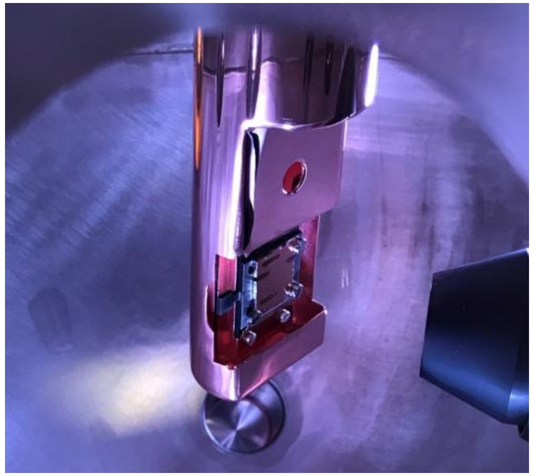
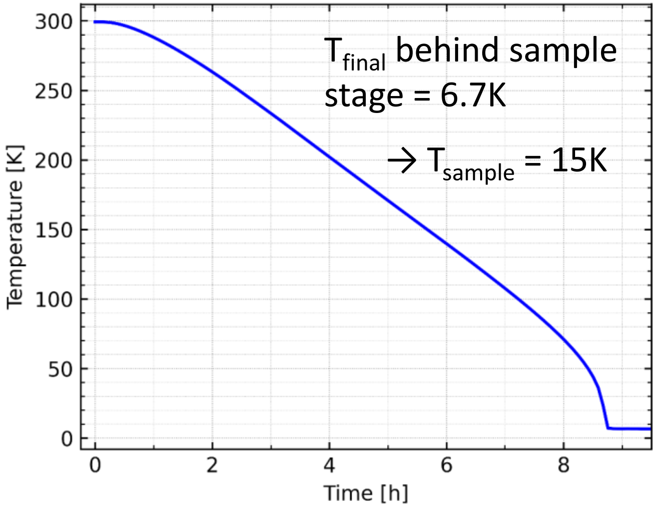
New cryogenic XPS and SEY setup: commissioning





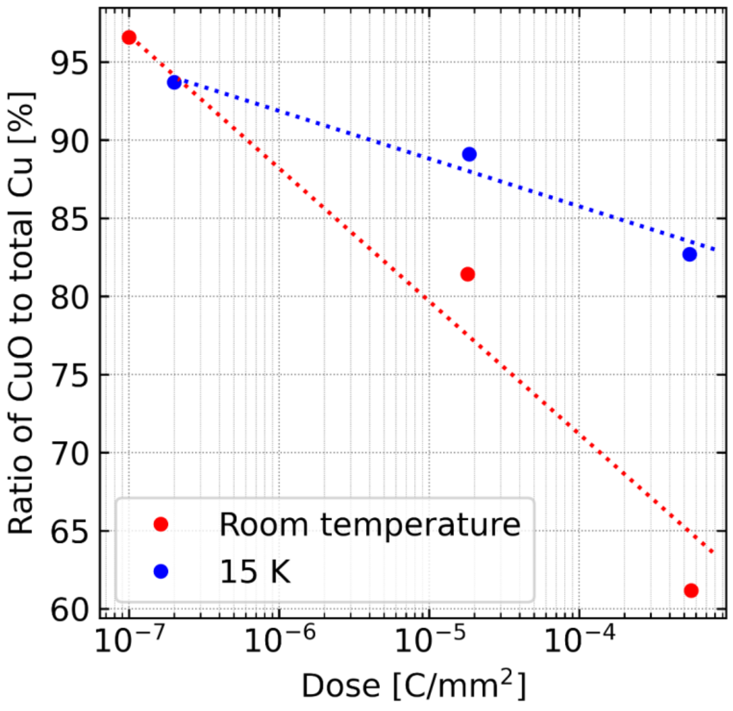


Perform surface chemical analysis (XPS), SEY measurements and electron irradiation at cryogenic temperature (< 20 K) to:

→ Assess the role of CuO and low carbon on conditioning at LT
→ Investigate the origin of CuO build-up, of the differences between Run 1 and Run 2
→ Validate curative solutions

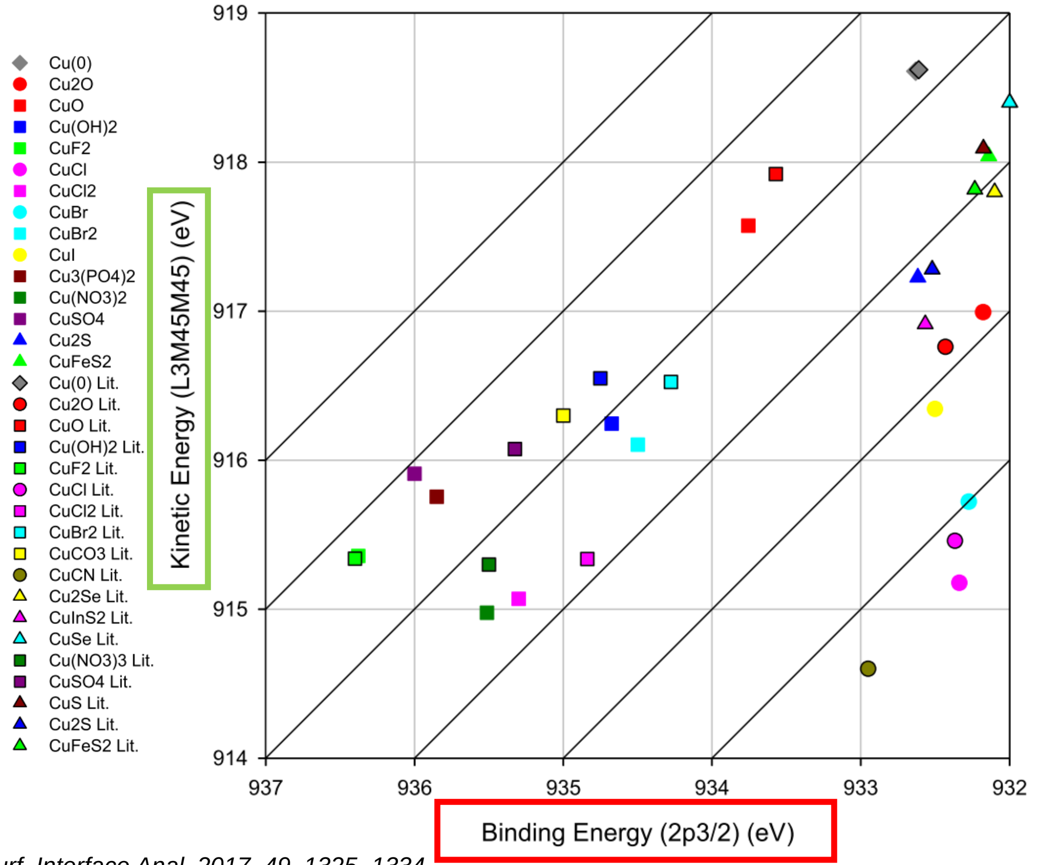
Cryogenics, XPS and electron irradiation setups: fully operational
SEY measurement setup: commissioning still ongoing

Conditioning of CuO beam screens at 15 K

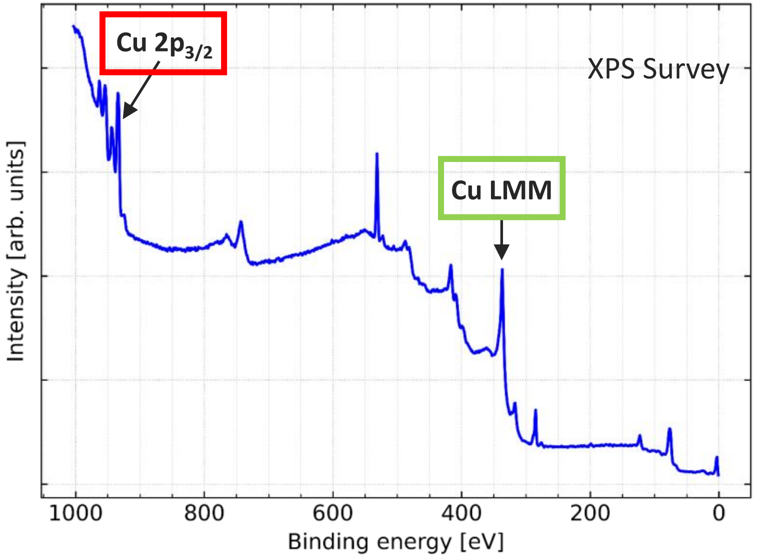


- **CuO is more stable** under electron irradiation **at 15 K** than at RT
- **CuO and low carbon amount are responsible for abnormal conditioning and therefore, high heat loads**

Mechanisms for CuO build-up: Wagner plot



Surf. Interface Anal. 2017, 49, 1325–1334



Use Wagner plot representation to distinguish copper compounds and follow the chemical evolution of copper surfaces during electron irradiation at 15 K

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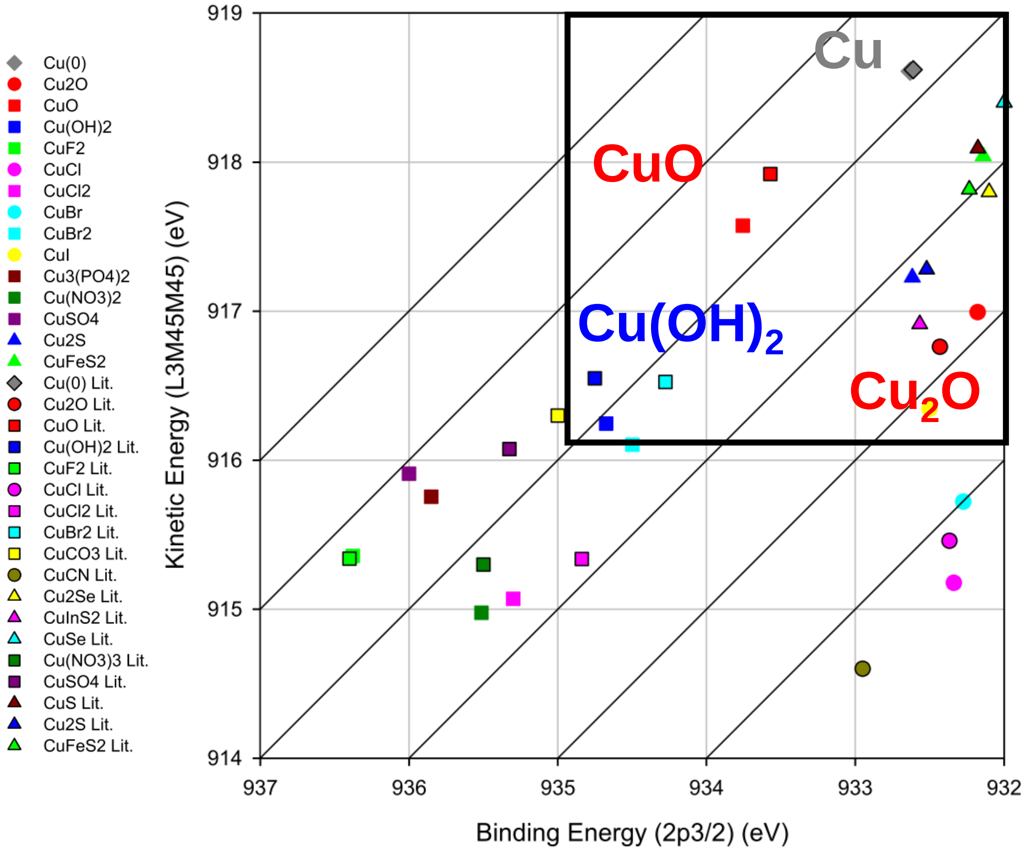

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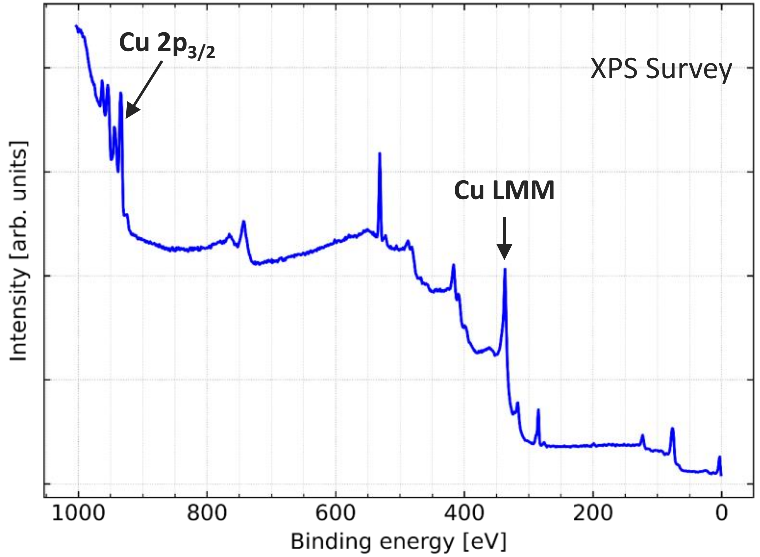

Use Wagner plot representation to distinguish copper compounds and follow the chemical evolution of copper surfaces during electron irradiation at 15 K

Conditioning of $Cu(OH)_2$: RT versus 15 K

Airborne copper hydroxide $Cu(OH)_2$ could be a precursor for CuO build-up by electron irradiation:

$$Cu(OH)_2 \rightarrow CuO + H_2O$$

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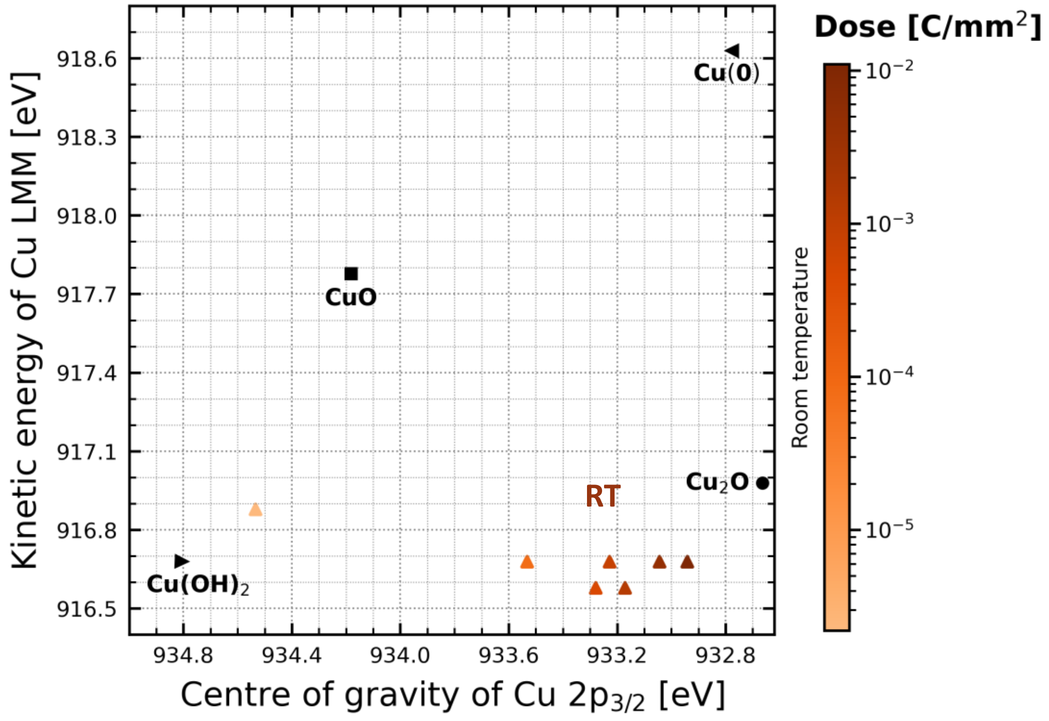

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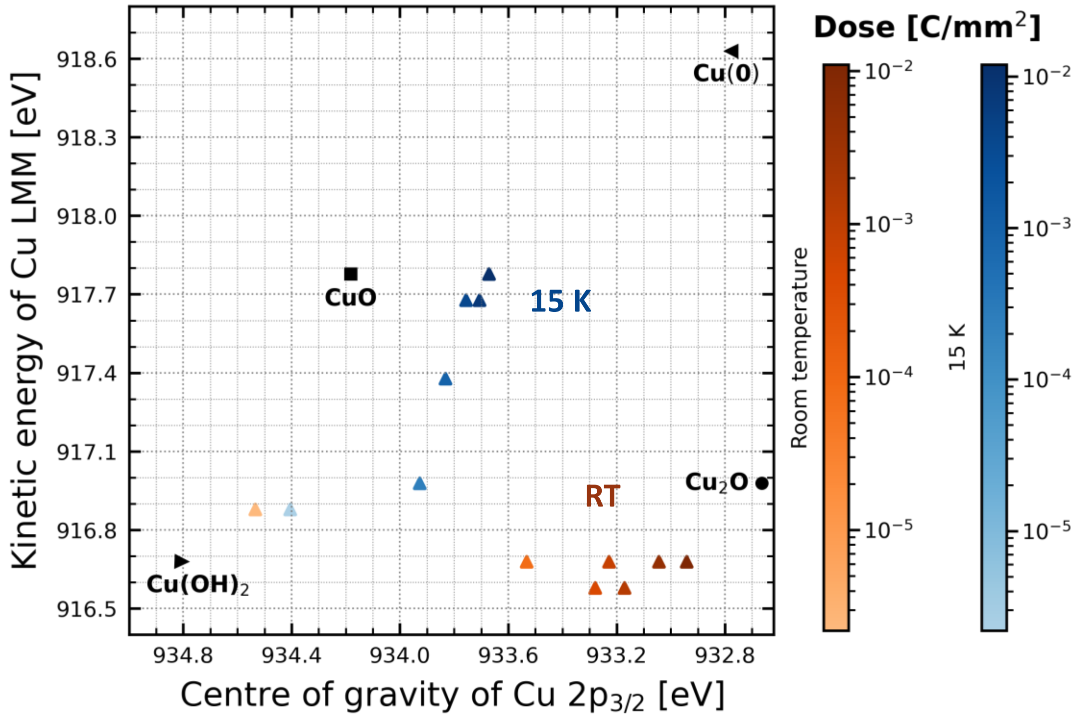

- At RT, $Cu(OH)_2$ is reduced to Cu_2O, as demonstrated in the past *Phys. Rev. Accel. Beams 22, 083101*
- **$Cu(OH)_2$** seems to be a precursor for **CuO build-up at 15 K**
  → could be explained by reduced diffusivity of Cu and O species at 15 K compared to RT

Conditioning of $Cu(OH)_2$ at 15 K: influence of carbon coverage

Carbon could influence $Cu(OH)_2$ transformation process by combination with oxygen → volatile species

Losev et al. Surf. Sci. 213 (1989) 564-579 ; Li et al. Appl. Phys. Letter 58 (1991) 1344-1346

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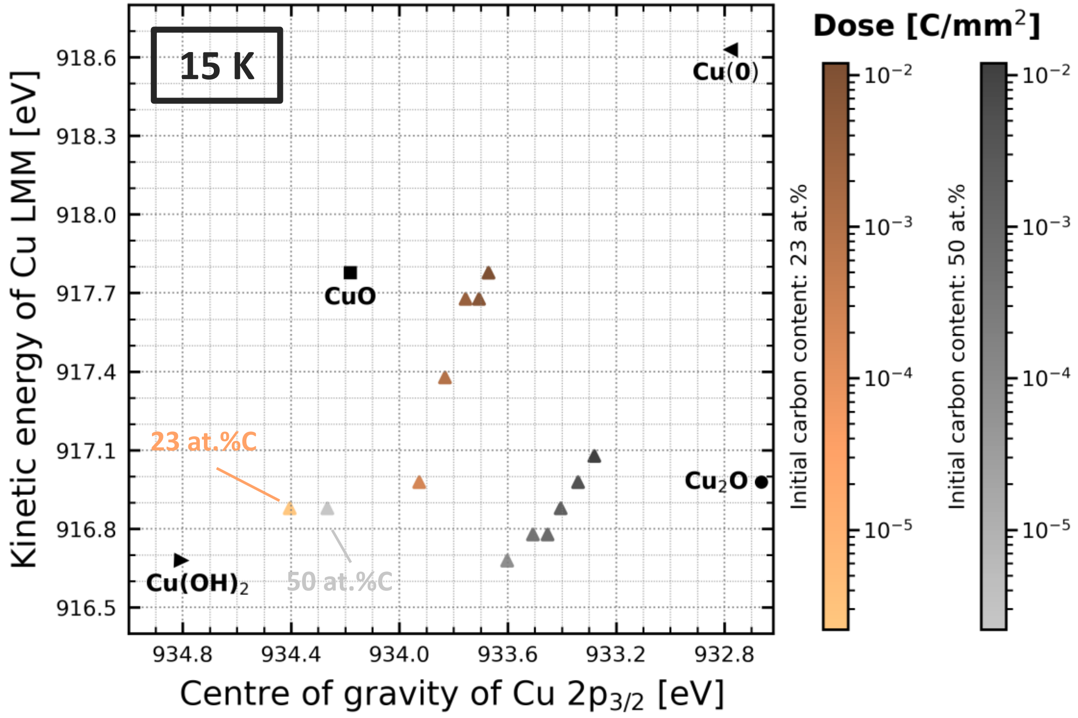
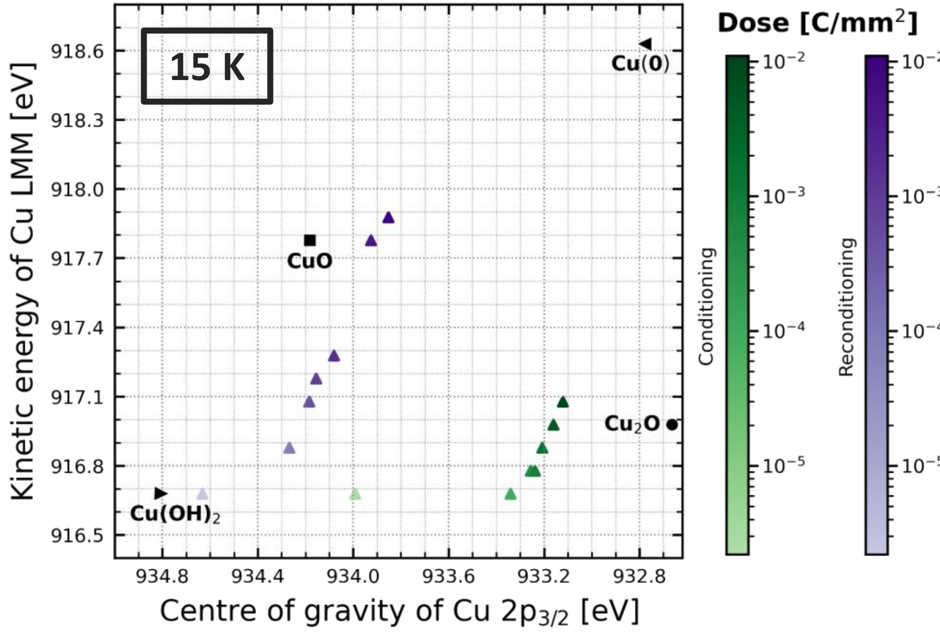


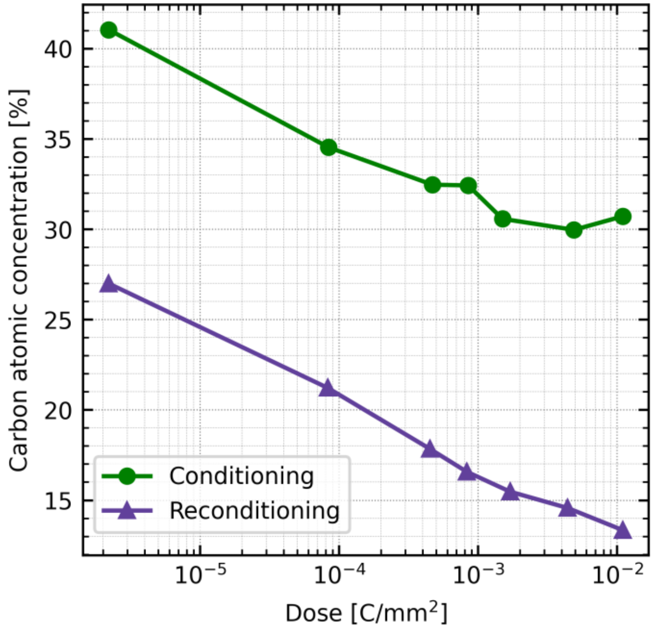
- Presence of **carbon** is **limiting** the conversion of $Cu(OH)_2$ into **CuO**

  → How to explain the LHC beam screen state?

Conditioning and reconditioning of $Cu(OH)_2$ at 15 K

Conditioning 15K → 2.5 months storage in **humid air** → Reconditioning 15 K

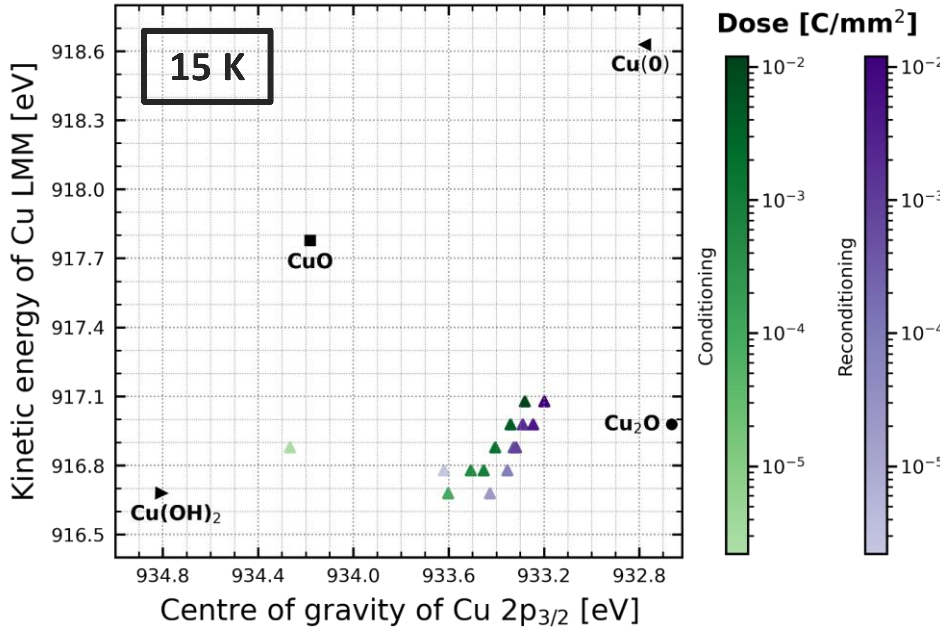


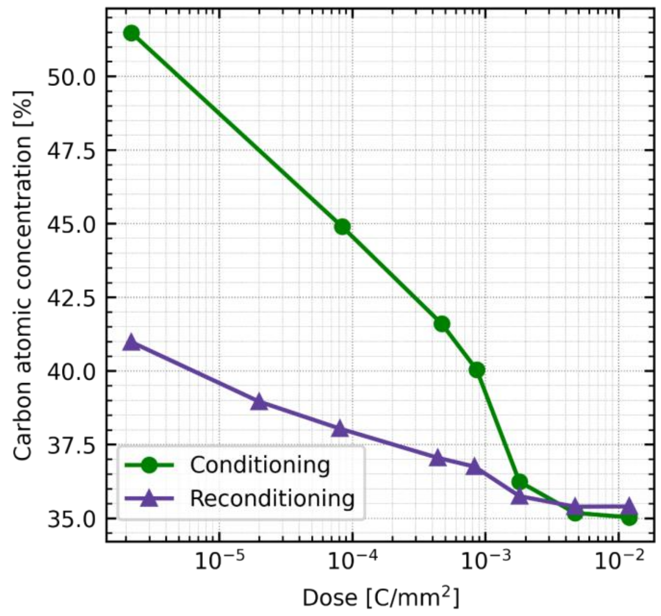


- First conditioning: **CuO-free, partial carbon depletion**
- Increased surface reactivity → **massive $Cu(OH)_2$ uptake** in humid atmosphere
- **CuO build-up** during reconditioning and **further carbon depletion**, compatible with high heat load beam screen observations

Conditioning and reconditioning of $Cu(OH)_2$ at 15 K

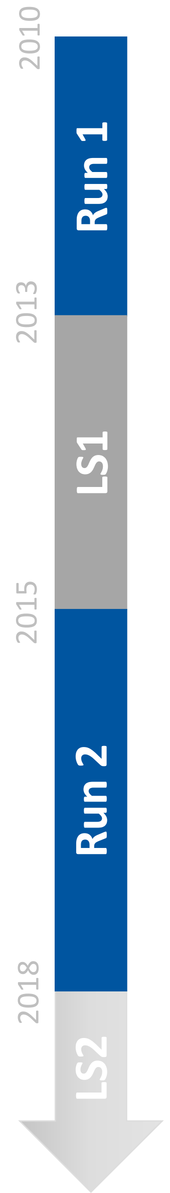
Conditioning 15K → 2.5 months storage in **dry air** → Reconditioning 15 K





- Two CuO-free conditionings, compatible with low heat load beam screen observations

Proposed scenario to explain the LHC heat load picture



Low $Cu(OH)_2$ coverage
and/or
Enough carbon to compensate for the presence of $Cu(OH)_2$
↓
CuO-free conditioning : low heat load

↓

Venting for maintenance
$Cu(OH)_2$ uptake ↔ ambient conditions, surface state at venting

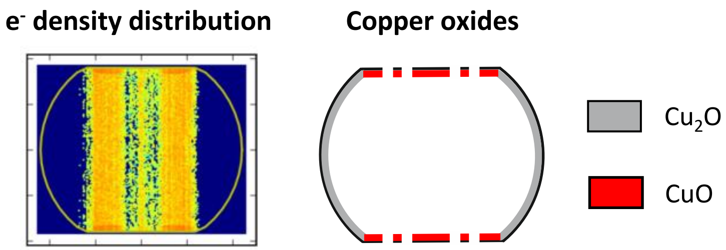
High $Cu(OH)_2$ coverage
(e.g. high humidity and/or increased surface reactivity)
and/or
Low carbon amount
↓
CuO build-up: high heat load sectors

Low $Cu(OH)_2$ coverage
(e.g. low humidity and/or “passivation”)
and/or
High carbon amount
↓
No CuO build-up: low heat load sectors

Limits and next steps

How to explain the azimuthal dependence of surface state of high heat load beam screens?

- Absence of $Cu(OH)_2$ and CuO on the lateral sides
- Carbon depletion at all azimuths



What to expect for Run 3 of the LHC ?

During the Long Shutdown 2:

- Venting procedure was improved: venting with N_2+O_2 instead of pure N_2 before beam line opening to tunnel air
- Air exposure duration was reduced compared to Long Shutdown 1

- CuO is stable in ambient conditions: high heat loads sections are expected to remain so
- Any evolution/deterioration of CuO-free regions? Answer by the end of the year…

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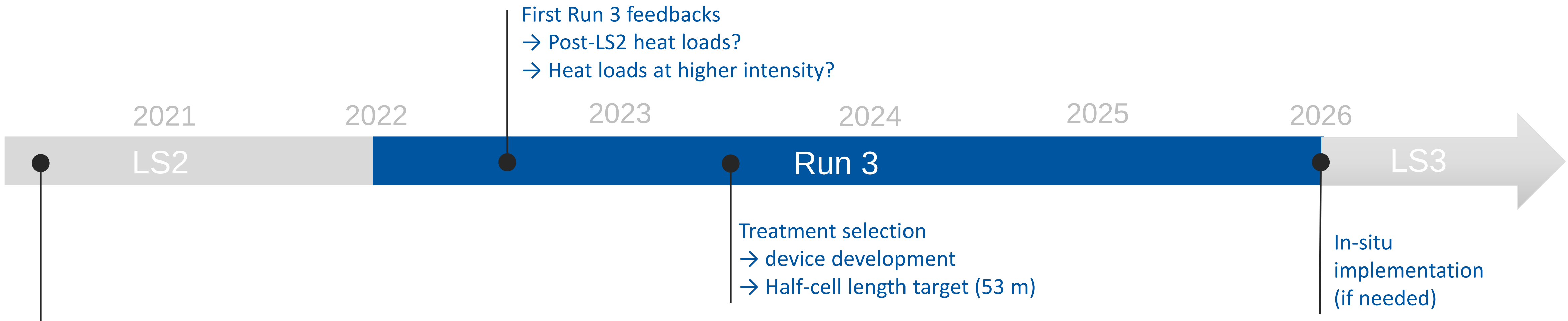
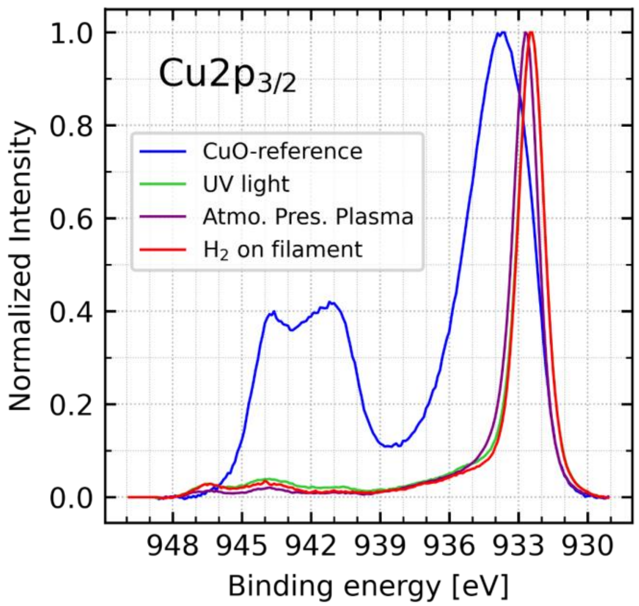
Mitigation solutions

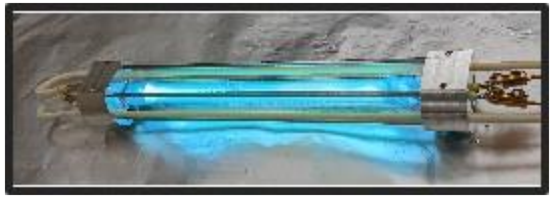


Find **a curative treatment (CuO removal and/or carbon recovery)** to be implemented in-situ in the LHC if Run 3 proves it to be necessary

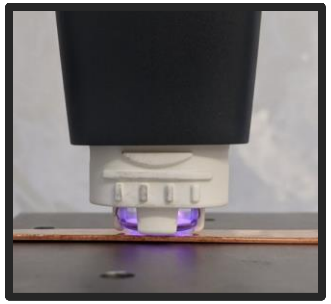
→ requirements: effective conditioning and **robustness against new CuO build-up at cryogenic T**
→ review and select mitigation techniques
→ tests in laboratory setups then in a 2-m beam screen mock-up
→ implement in-situ in the LHC if necessary

Mitigation solutions





UV light, 1 bar H_2+N_2



Atmospheric pressure plasma, 1 bar H_2+N_2

W filament, 10^{-2} mbar H_2

UV light, Atmospheric pressure plasma and H_2 cracking on tungsten filament are efficient for CuO reduction

→ promising for LHC beam screen in-situ treatment

→ compatibility of treatment parameters with in-situ application?

→ need for subsequent passivation?

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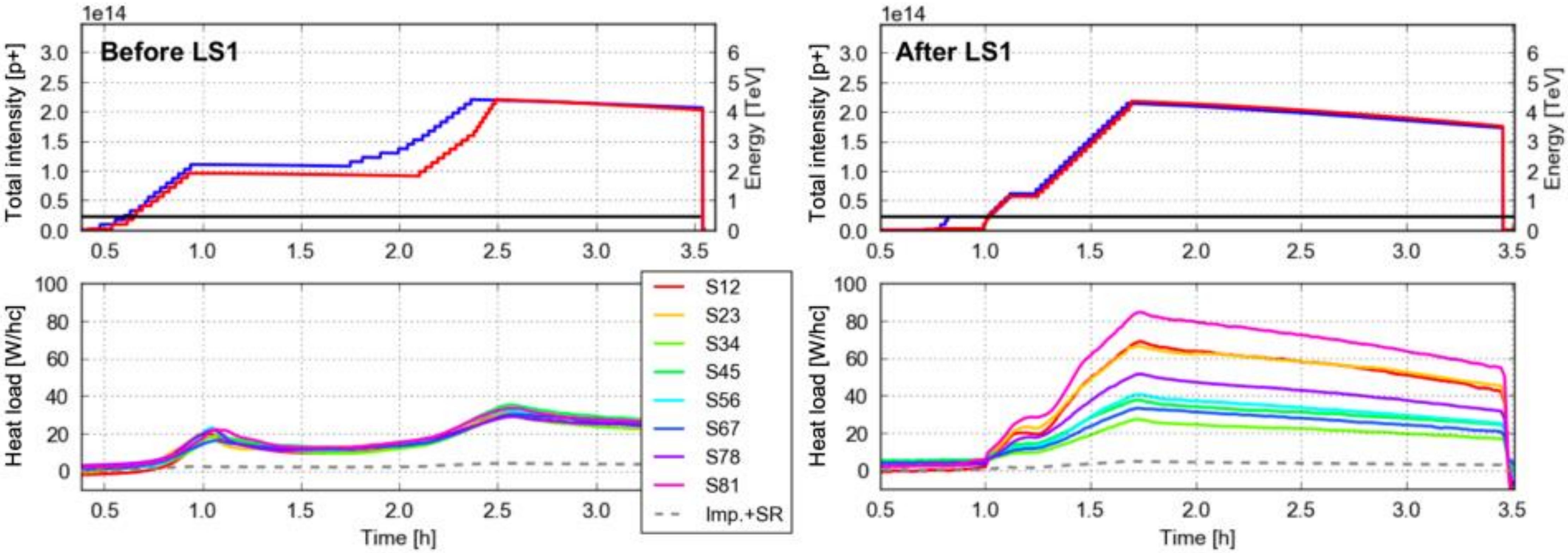
Summary, conclusions and perspectives

- **Differences of surface oxidation state** were identified between components of the LHC which could be **related to their different performances during operation**
- **Copper hydroxide $Cu(OH)_2$** is a possible **precursor for CuO** build-up in the LHC
- The **effectiveness of CuO build-up** is influenced by the presence of **adventitious carbon**
- Experimental results support a **scenario** for explaining the **LHC heat load distribution and history**
- The **current scrubbing and following months of physics runs** will tell us more about **post-LS2 heat load distribution**
- Mitigation solutions **are under investigations**

Thank you for your attention

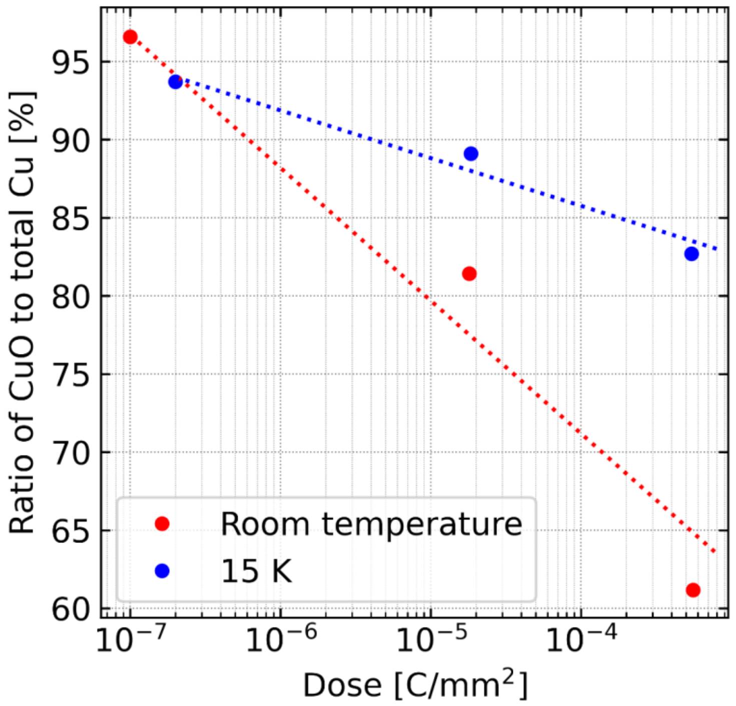
Spare slides

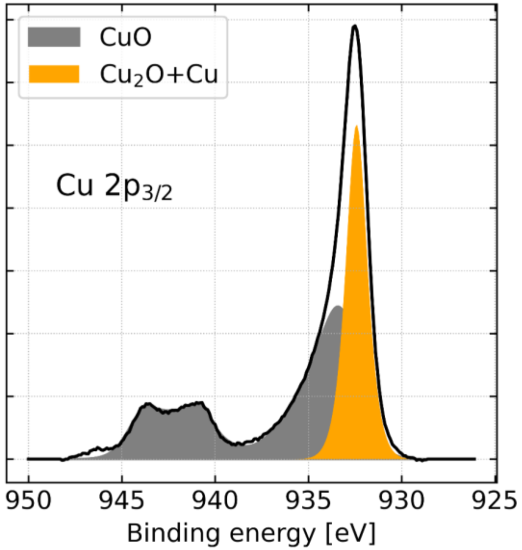
LHC arcs heat loads: Run 1 versus Run 2



Courtesy of G. Iadarola

Conditioning of CuO beam screens at 15 K





$$\%CuO = \frac{A_{CuO}}{A_{CuO} + A_{Cu_2O+Cu}}$$

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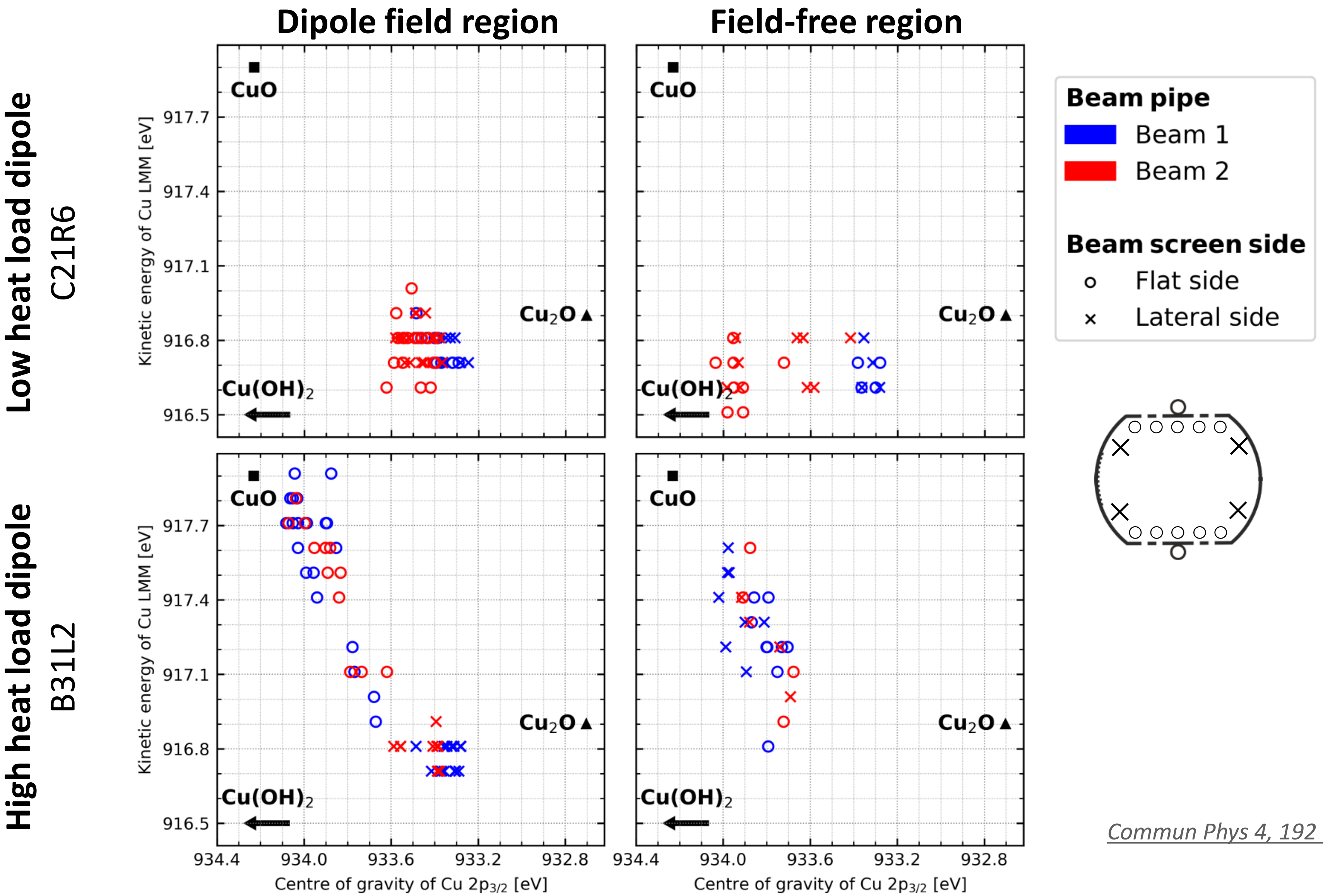
LHC extracted beam screens



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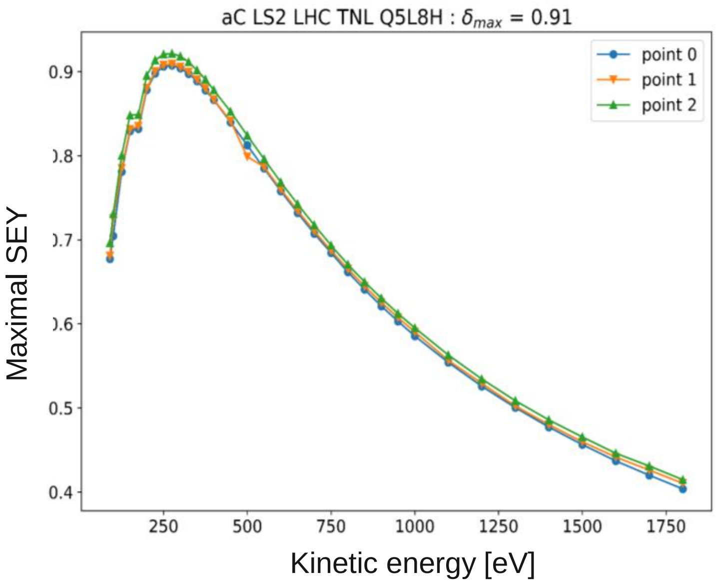
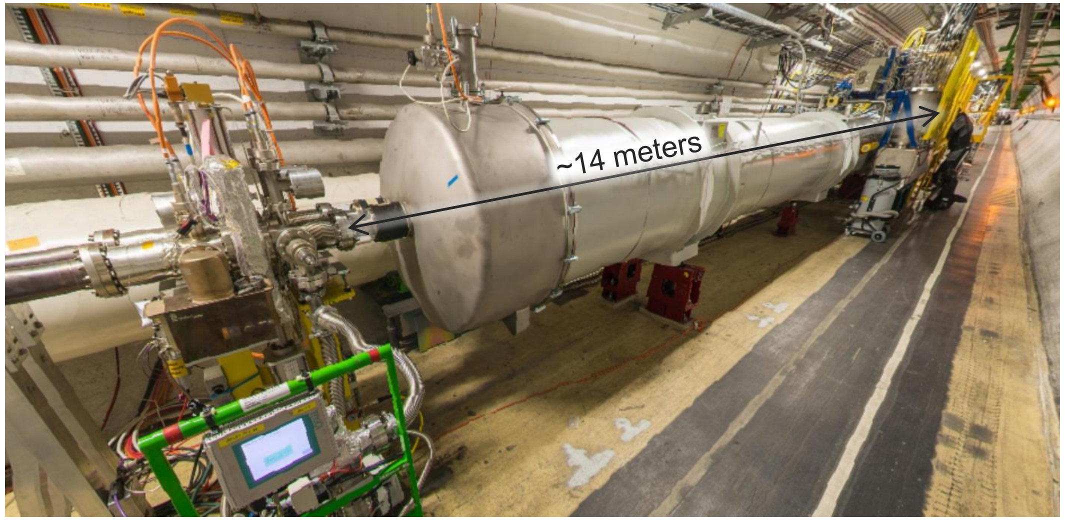
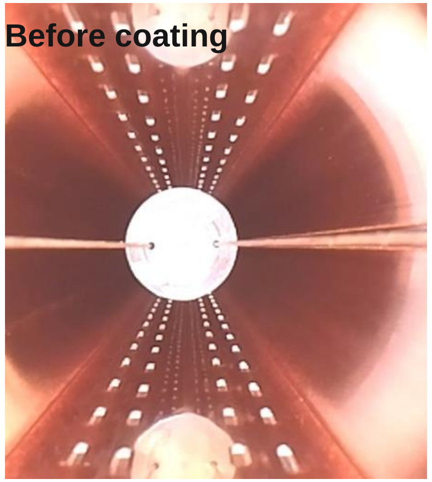
Carbon coatings for e-cloud mitigation in the LHC

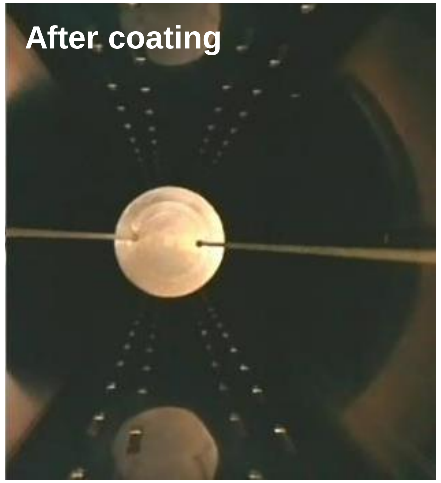
- The two beam screens of Q5L8 have been a-C-coated ***in situ*** during LS2
- **Maximum SEY ≈ 0.9**
- **Current main limitation for a full half-cell a-C coating: going through several magnets (UHV compatible and self-driving device going through the interconnections)**



Courtesy P. Costa Pinto

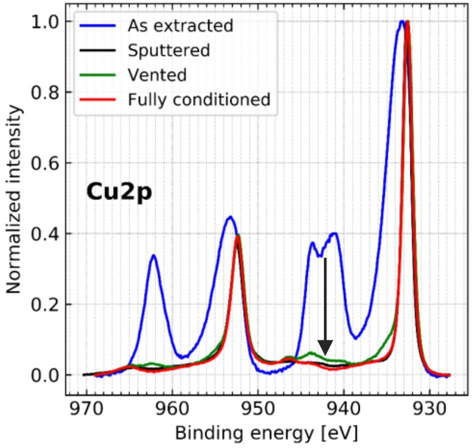


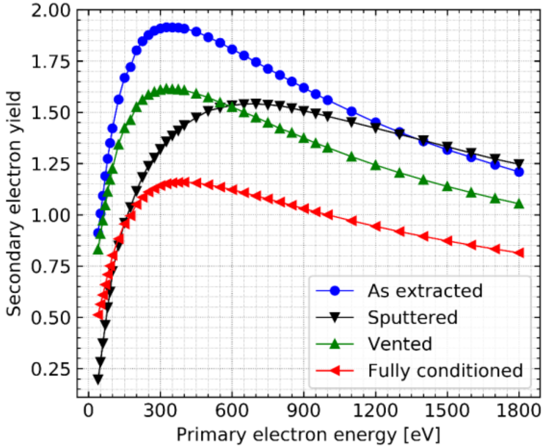




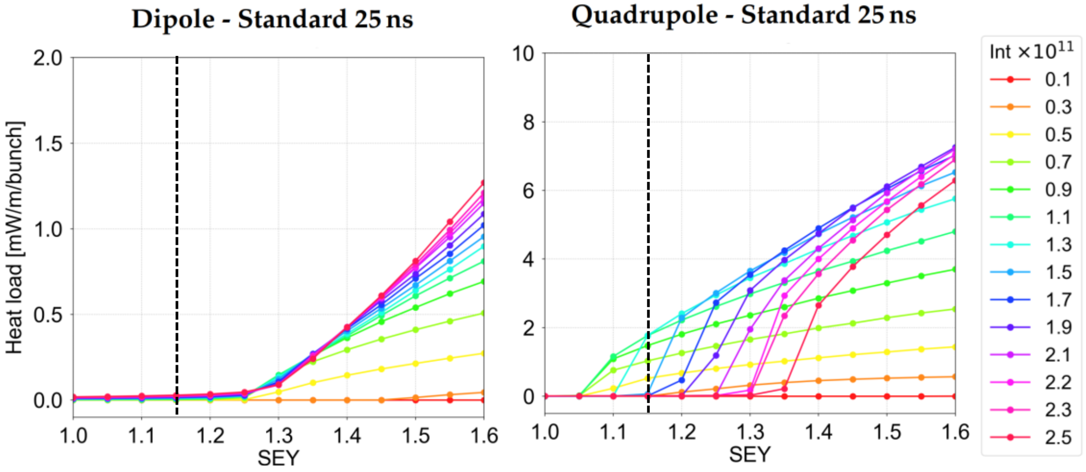
Ion etching and re-oxidation of the beam screen

Would an **ion etching and re-oxidation in air** of CuO beam screen surface efficiently reduce the heat load?





- **CuO is efficiently removed** by etching, the surface is partially reoxidized to Cu_2O during venting
- The surface is almost **carbon-free**
- **The maximum SEY reaches 1.15** after full conditioning at RT (below e-cloud threshold for dipoles, above for quadrupoles)



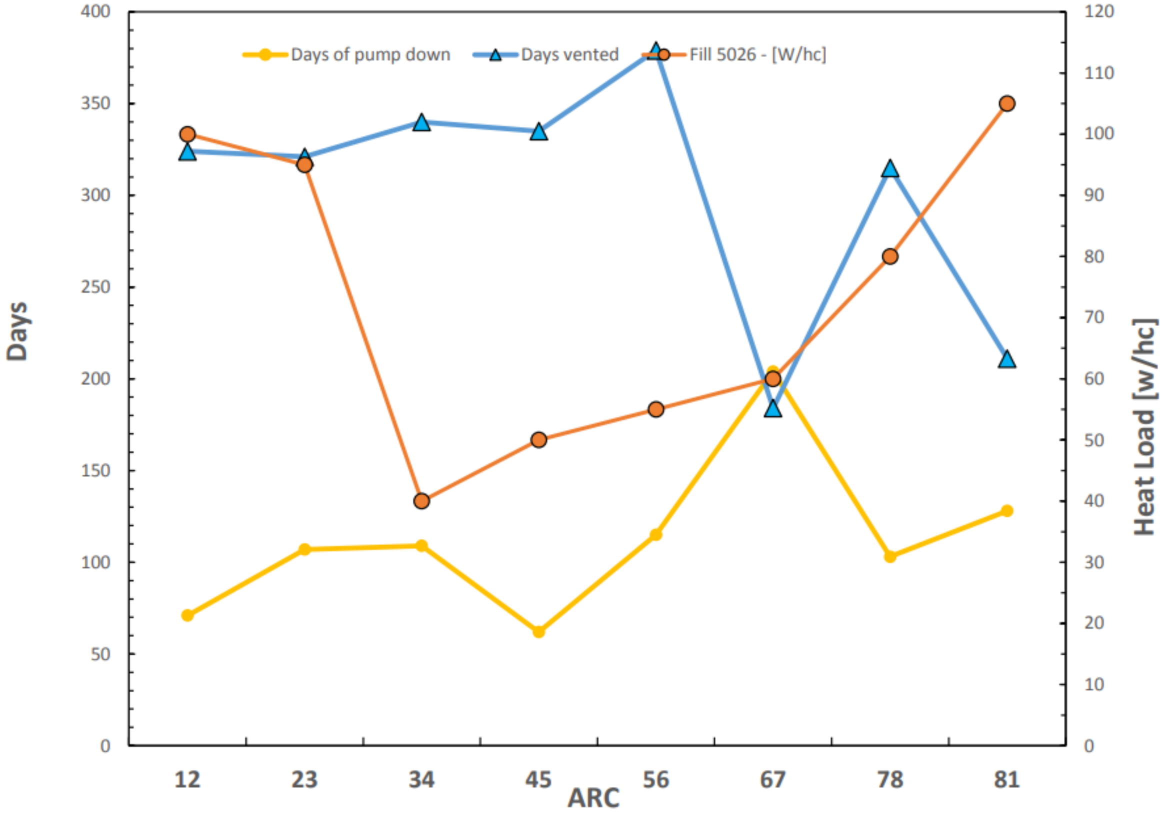
- Implementation in the machine would require the **insertion of a sputtering device (feeding HV and passing the RF fingers)**
- **Ageing and robustness against new CuO build-up to be assessed**

CERN-ACC-2019-0041, G. Skripka et al.

Venting duration LS1 vs LS2

Courtesy of G. Bregliozzi

LS1



LS2