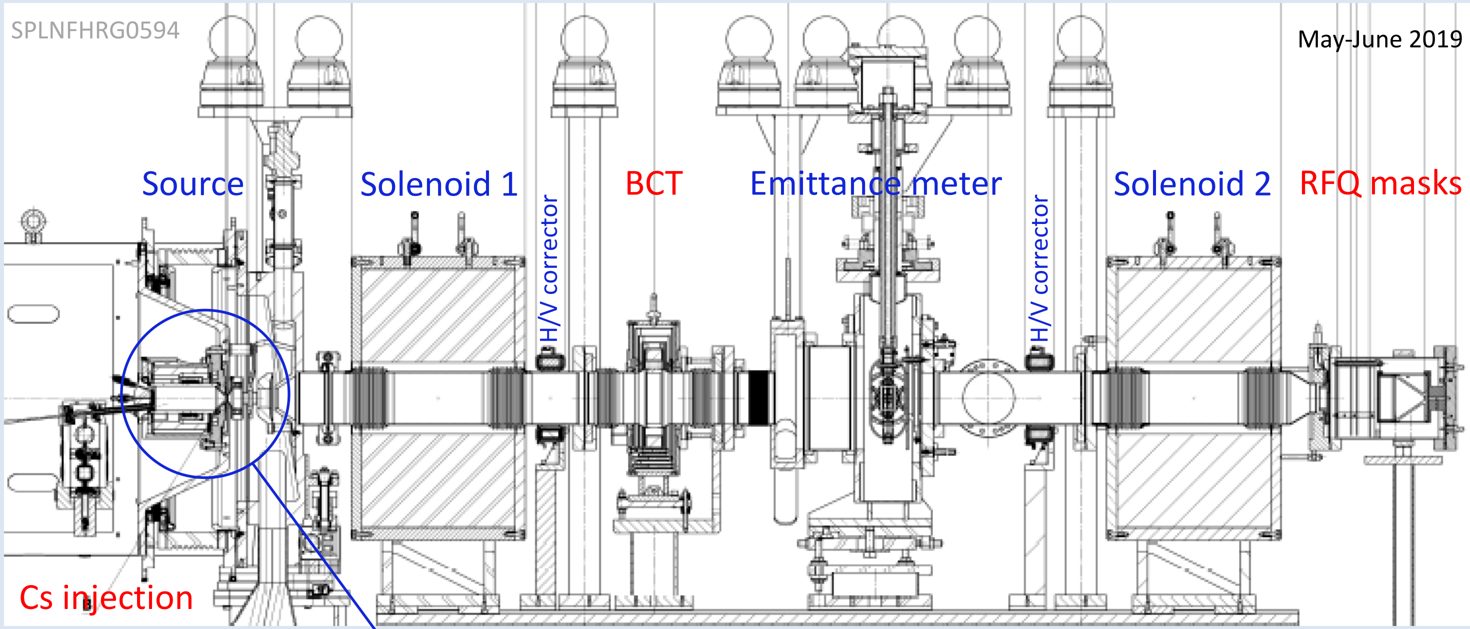
# Linac 4 ion source continuous caesiation results

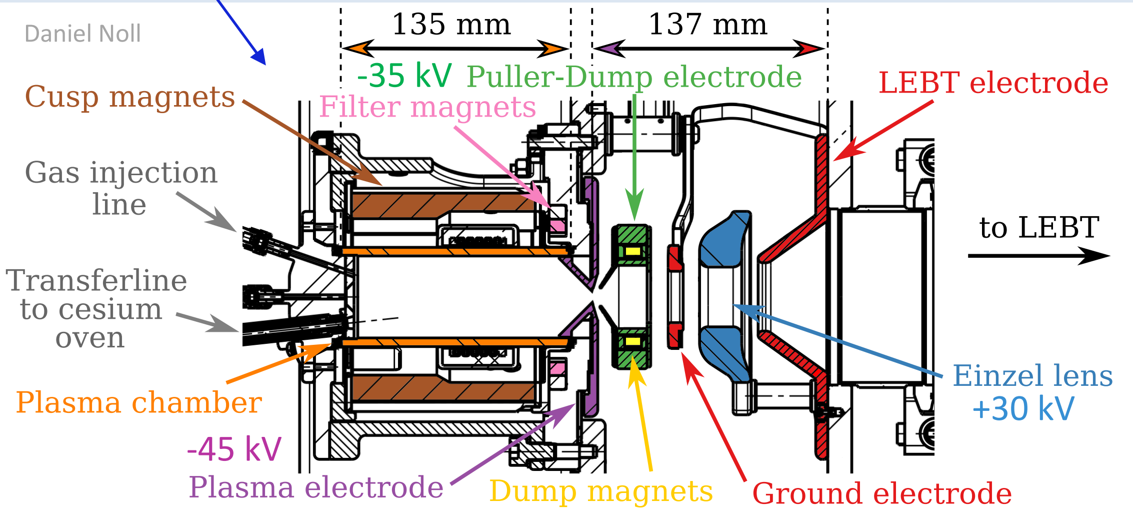
180th Machine Protection Panel Meeting, Continuous caesiation at Linac 4
CERN, 30.08.2019

- Linac 4 test stand configuration
  - Layout
  - Cs injection system
  - RFQ acceptance mask device
- Experimental program
- First continuous caesiation results
- Surface analysis of masks and samples
- Summary, Conclusion

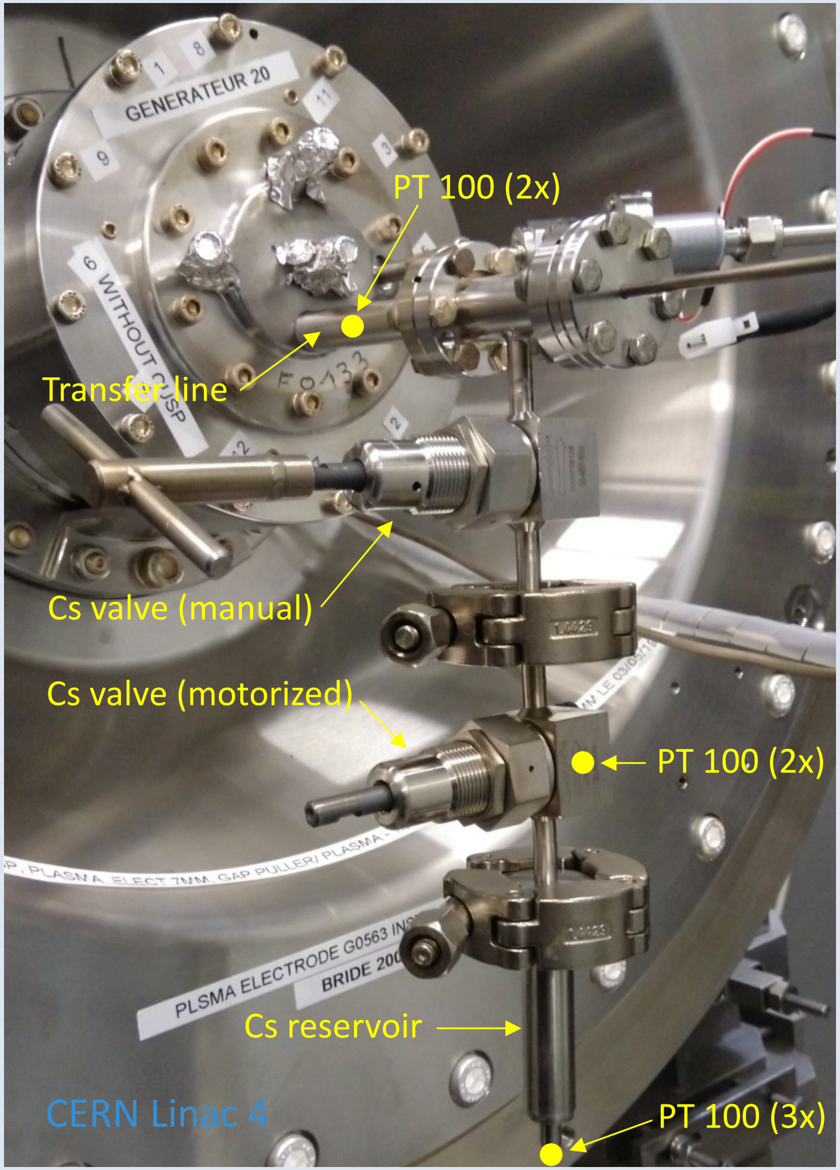
Acknowledgements
Michael O'Neil, Sebastien Bertolo, Detlef Küchler, Daniel Noll
Mauro Taborelli, Colette Charvet, Marcel Himmerlich, Ana Teresa Perez Fontenla

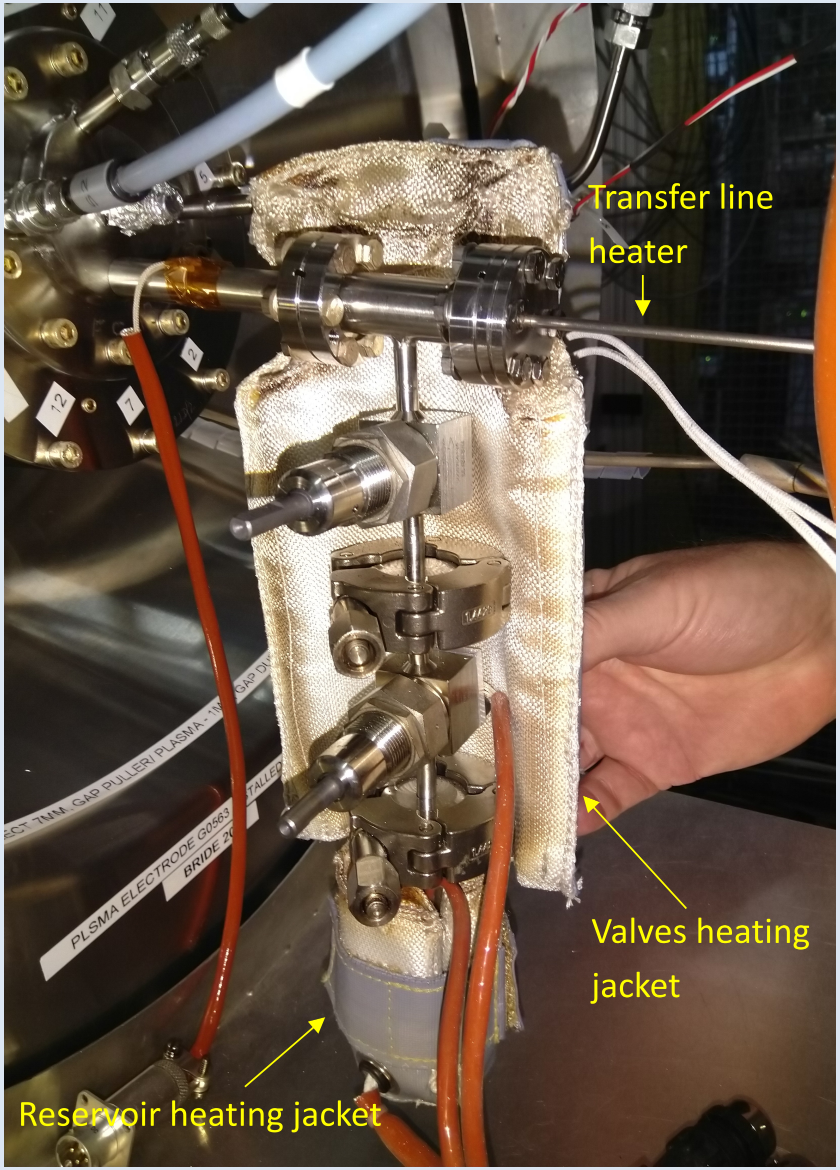
# Linac 4 test stand configuration



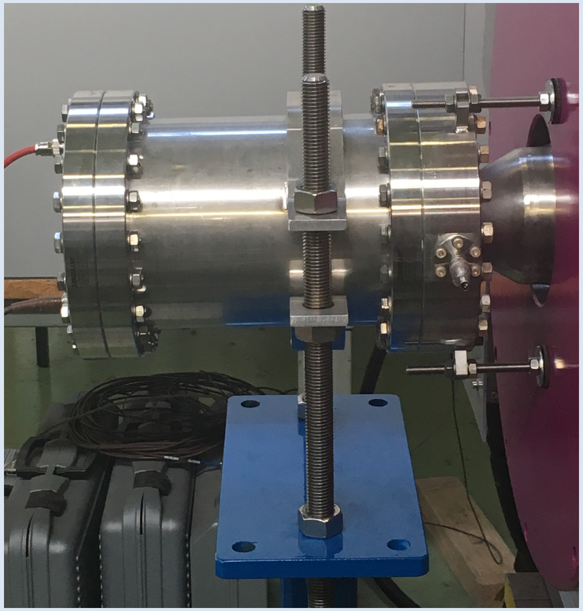


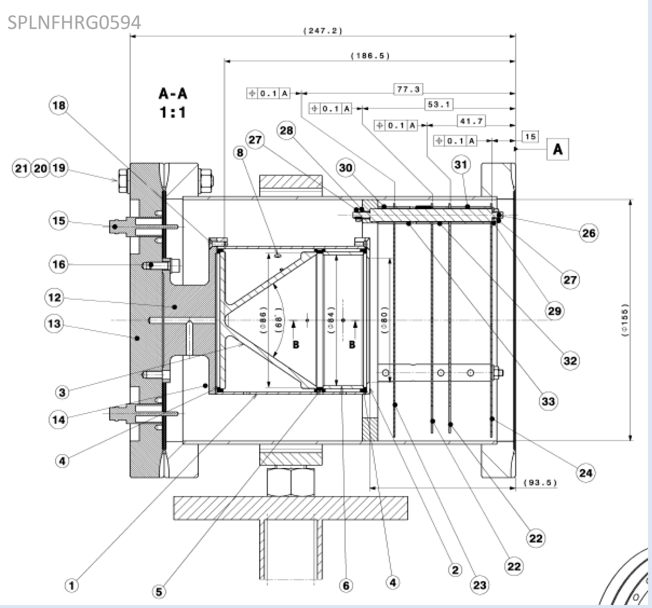
# Caesium injection system

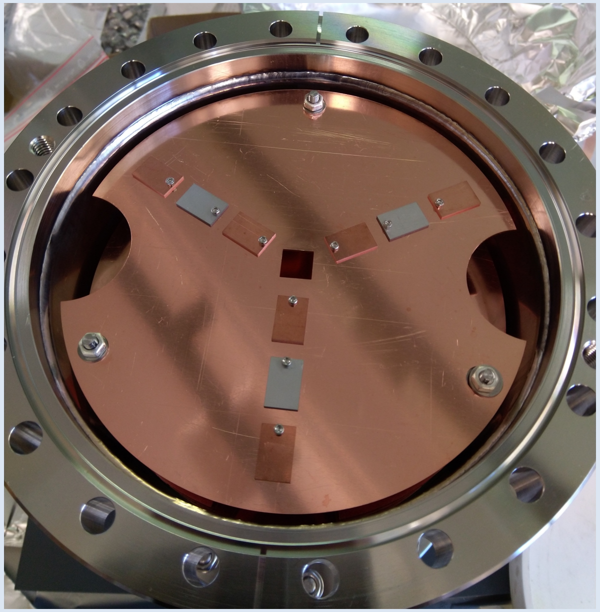


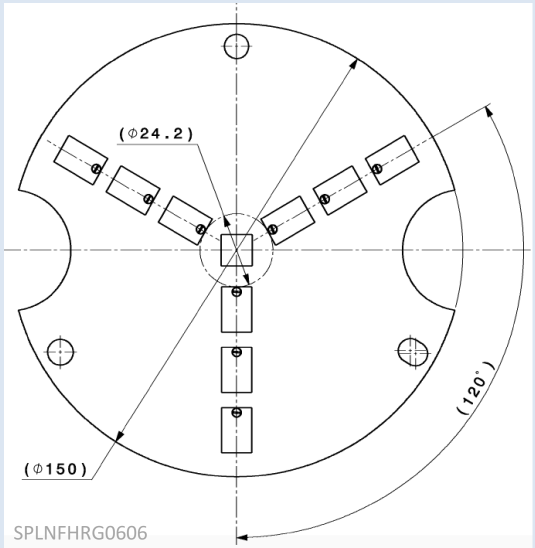


# RFQ acceptance mask device









## Setup

Four so-called **"RFQ masks"** with central holes installed
Configuration: C-B-B-A (in beam direction)
Square hole sizes: 10.4 / 4.34 / 4.34 / 9.8 mm

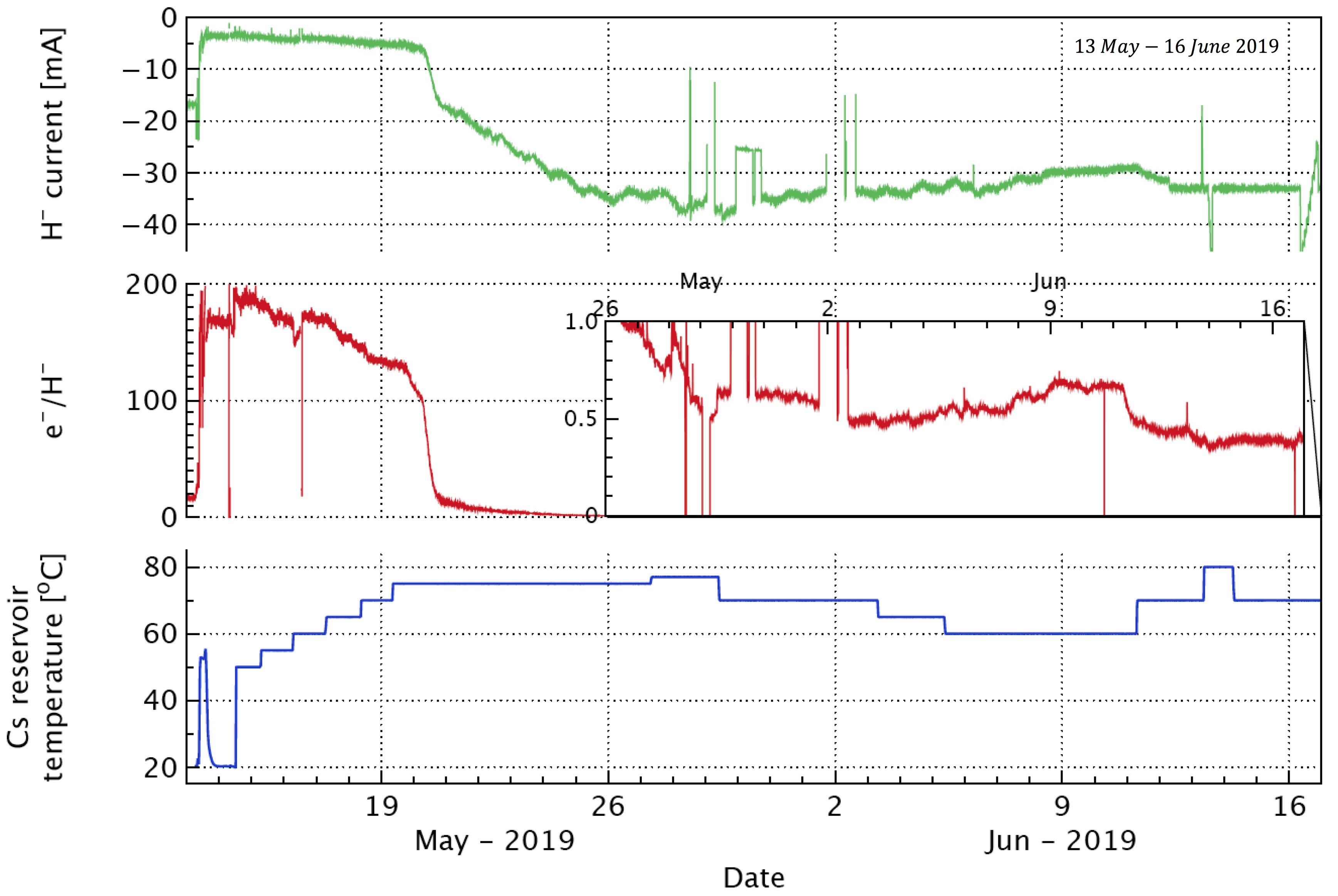
## Preparations

- Fabrication of **4 new Cu masks + 18 samples**
- **Cleaning** of entire setup (chamber, masks, samples…)
- Installation of **samples on the first mask** (front/backside)
- **Continuous caesiation** beam test for 5 weeks
- **Surface analysis** of **masks** and **samples** afterwards

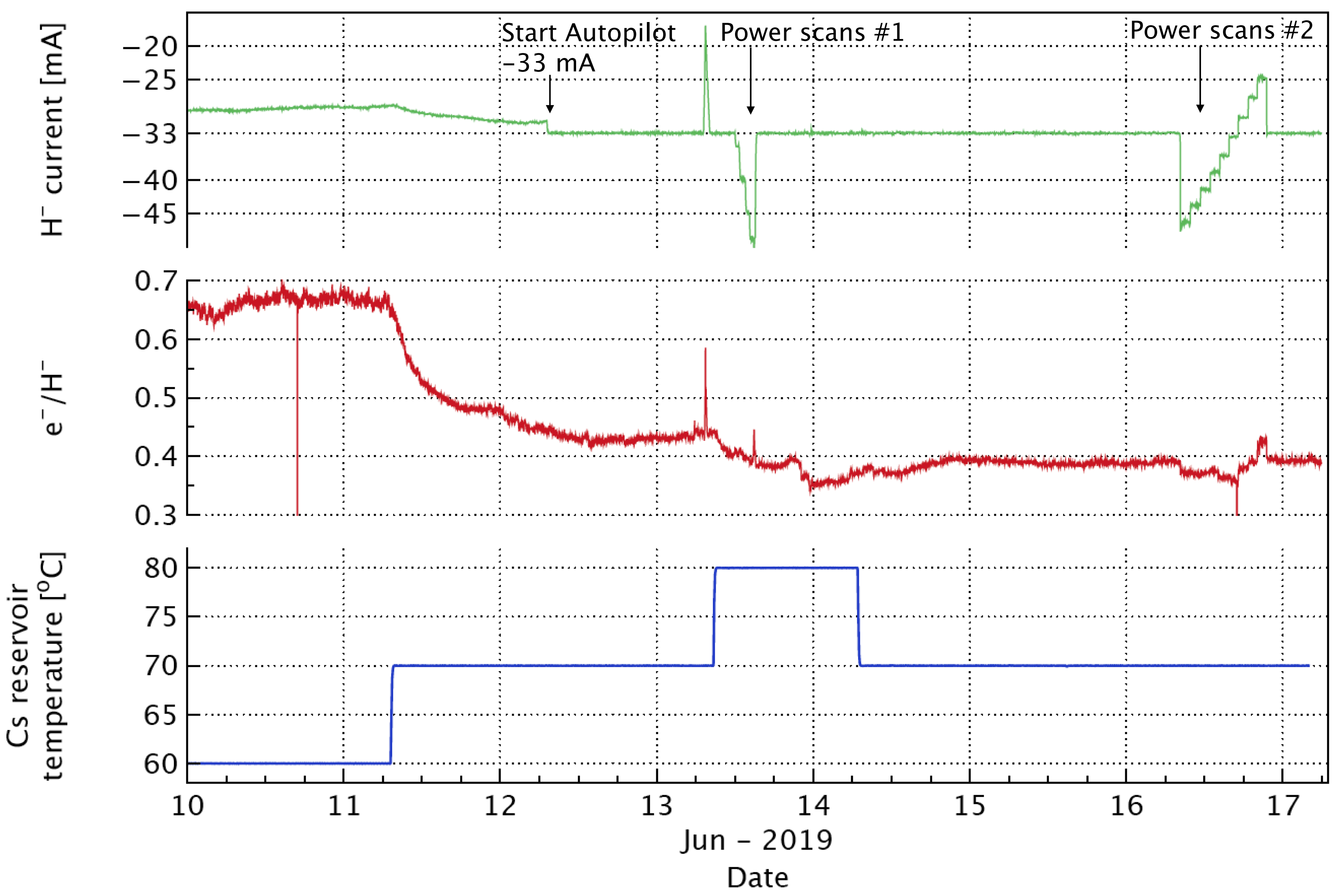
# Experimental program

- Objective
  - Test of the new continuos caesiation system for Linac 4 ion sources
  - Check for traces of Cs at the RFQ acceptance mask device
  - If possible, achieve a low $e^-/H^-$ ratio with minimal amount of Cs injected
    - The higher the $e^-/H^-$ ratio, the higher the emittance at given beam current
  - If possible, obtain long term stability of a low $e^-/H^-$ ratio
  - Test for a period as long as possible: 13.05.-16.06.2019
- $H^-$ ion source
  - IS 03c: cleaned, equipped with new plasma chamber
  - Cs injection system: new, cleaned
  - RFQ acceptance mask device: dismantled, cleaned, equipped with new Cu masks
- Parameter
  - Temperature settings for the Cs reservoir, valves, and transfer line
- Observables
  - $H^-$ current
  - $e^-/H^-$ ratio
- Unchanged settings
  - RF power
  - Gas injection
  - Source extraction voltages
  - LEBT, e.g. solenoid currents, gas injection, corrector magnets

# First Linac 4 continuous caesiation results



# First Linac 4 continuous caesiation results



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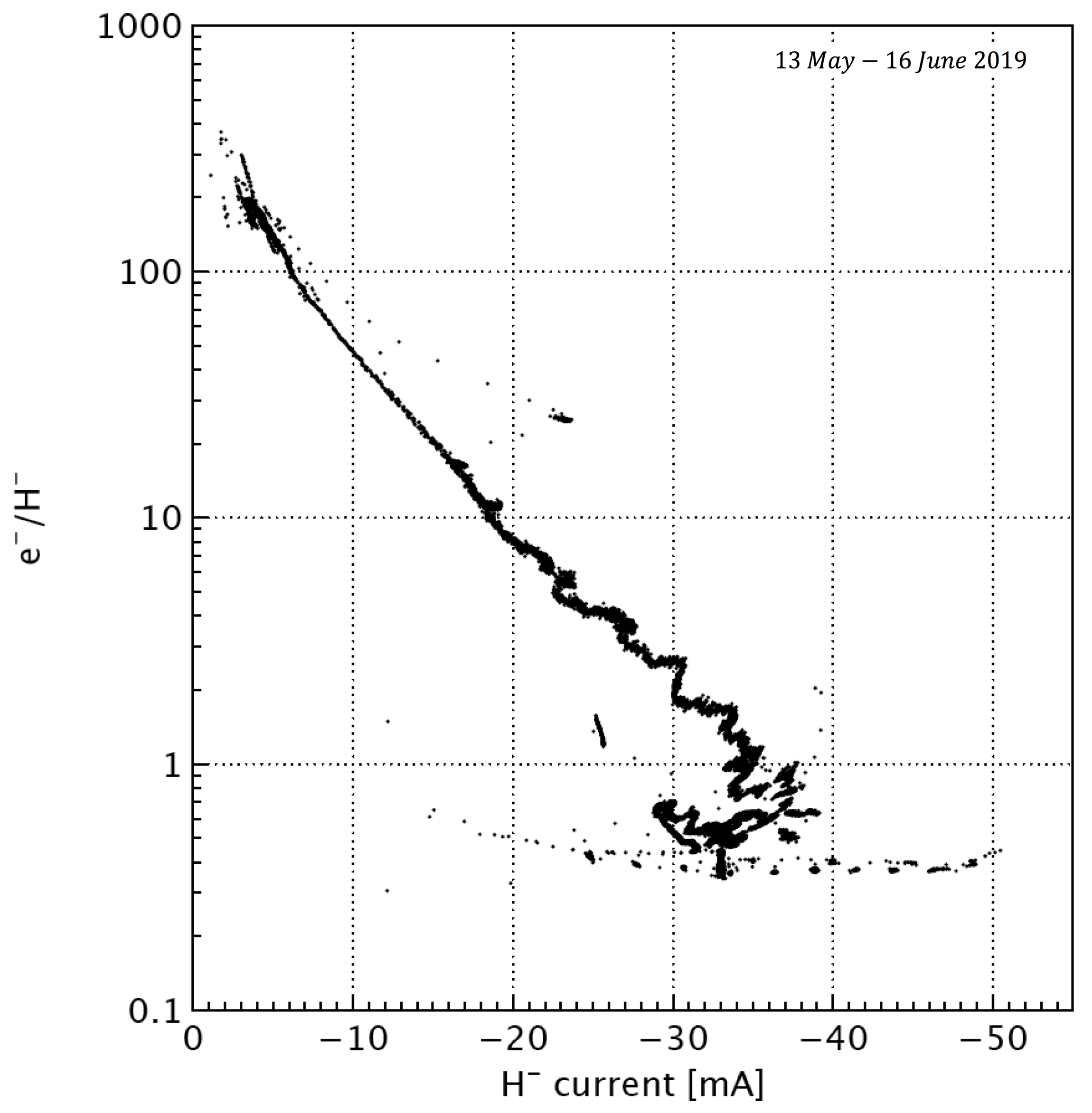
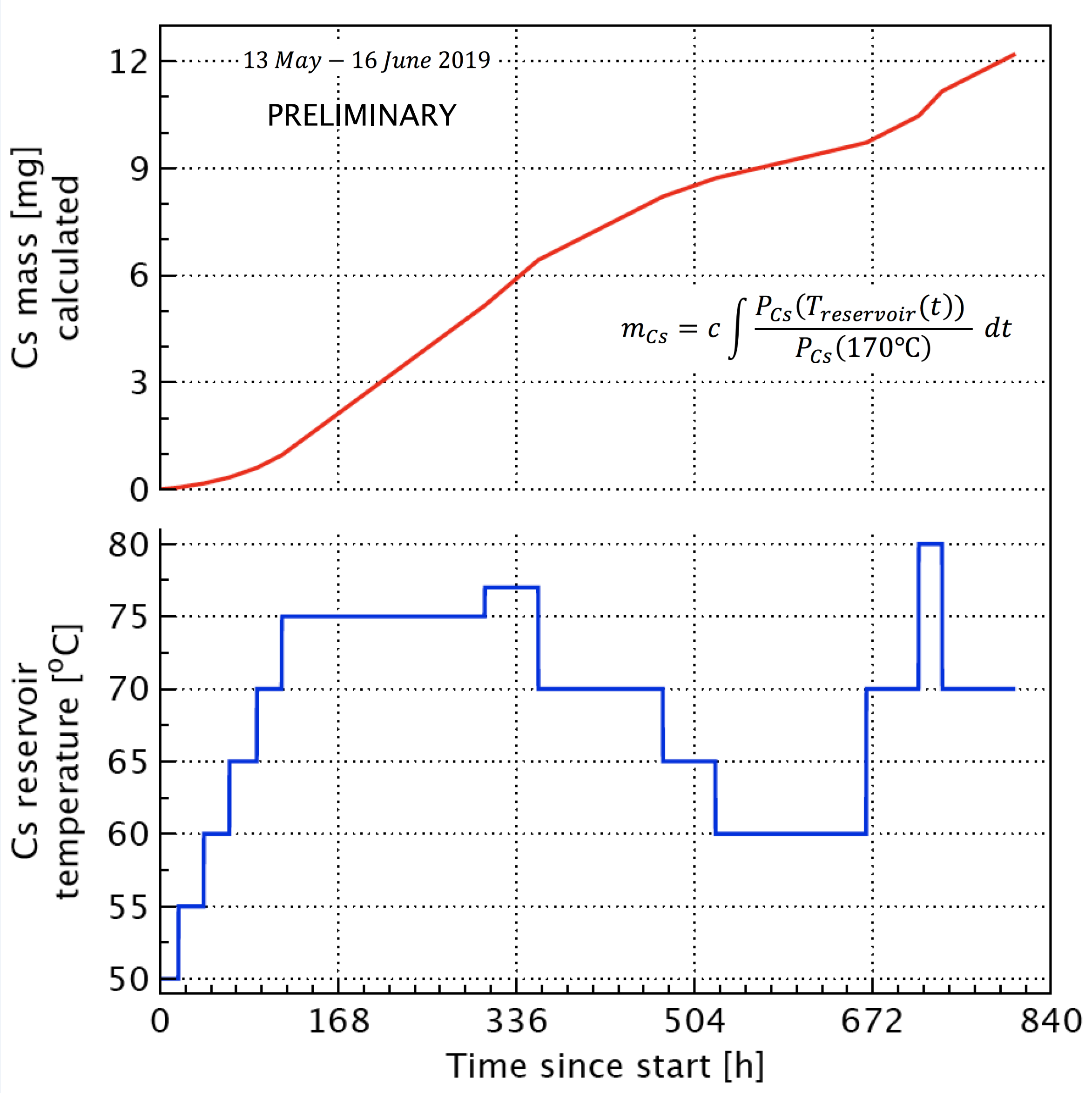
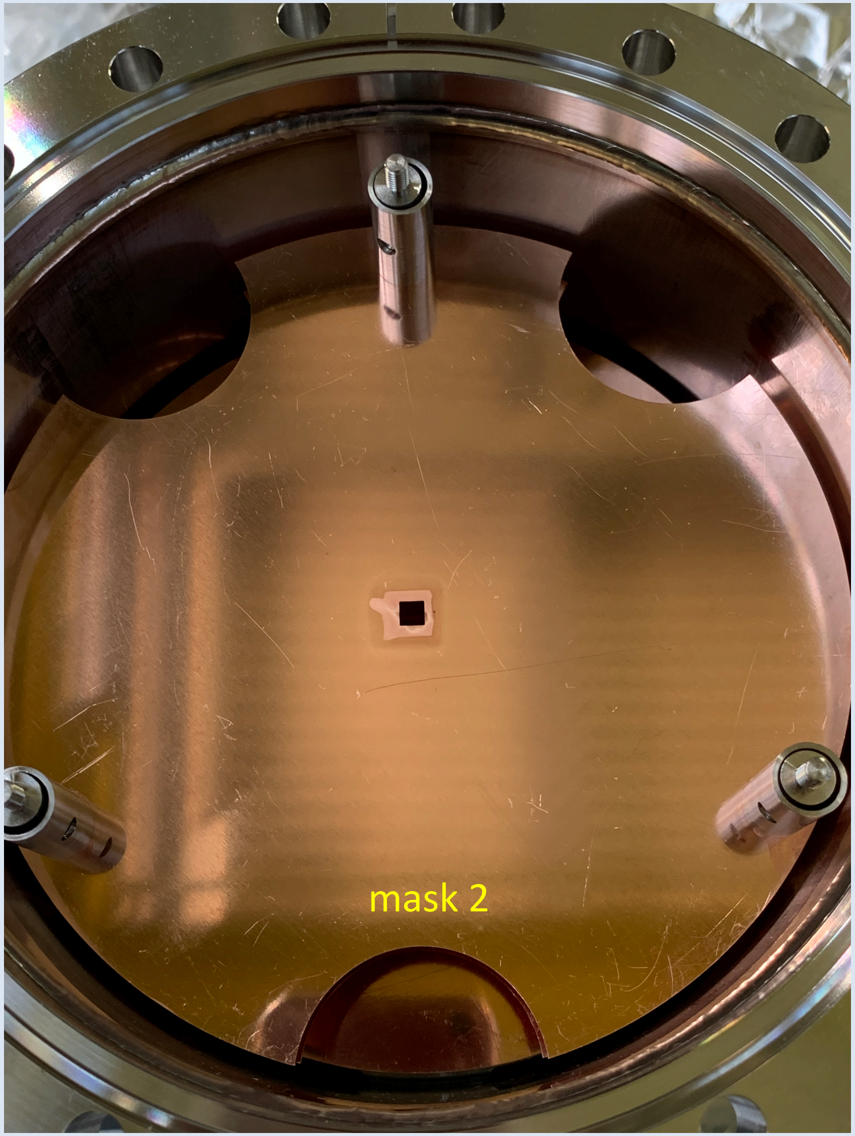


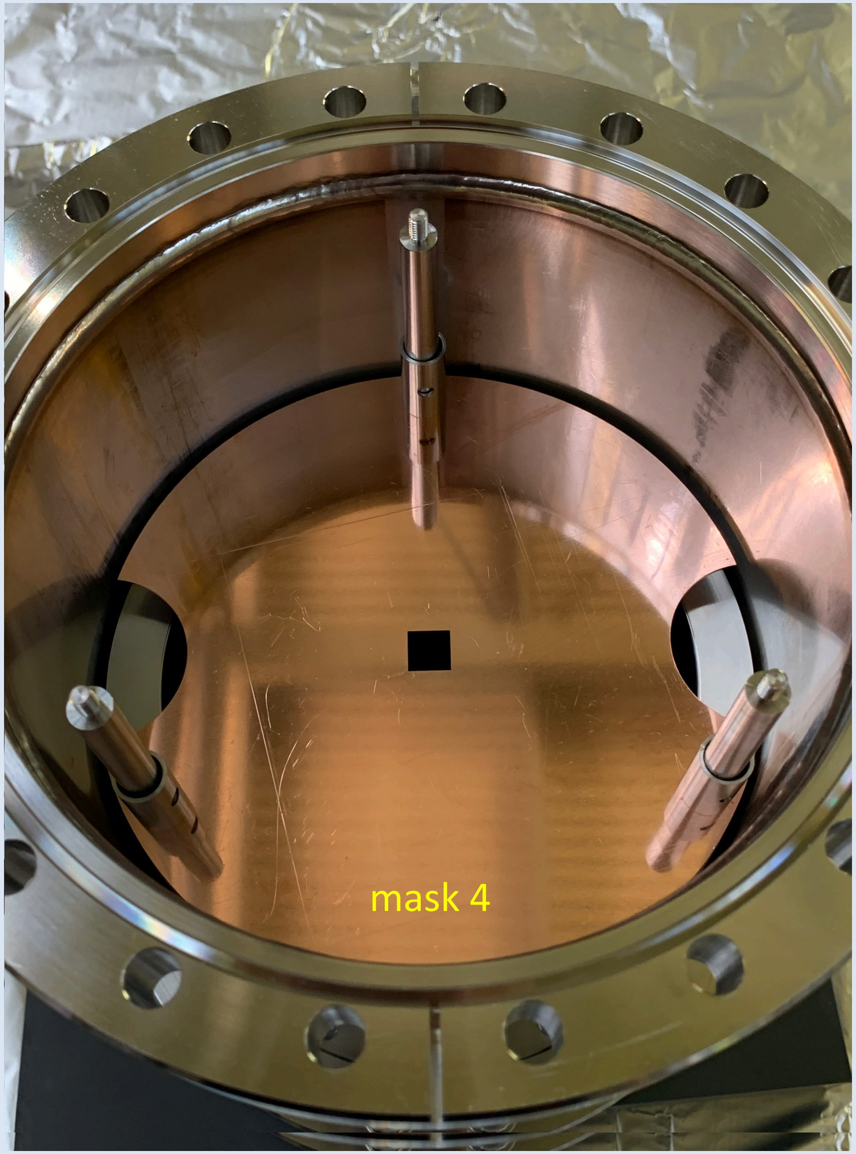
# First Linac 4 continuous caesiation results



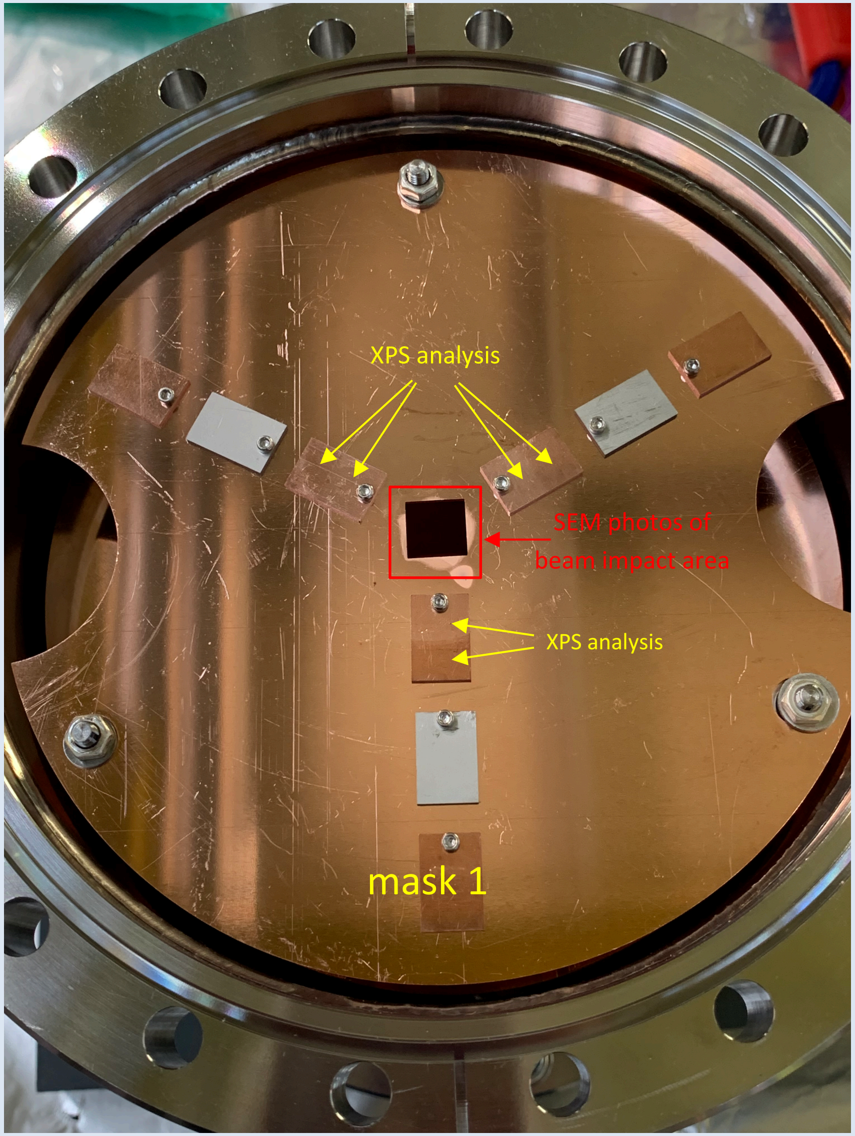
# Linac 4 test stand RFQ masks after continuous caesiation

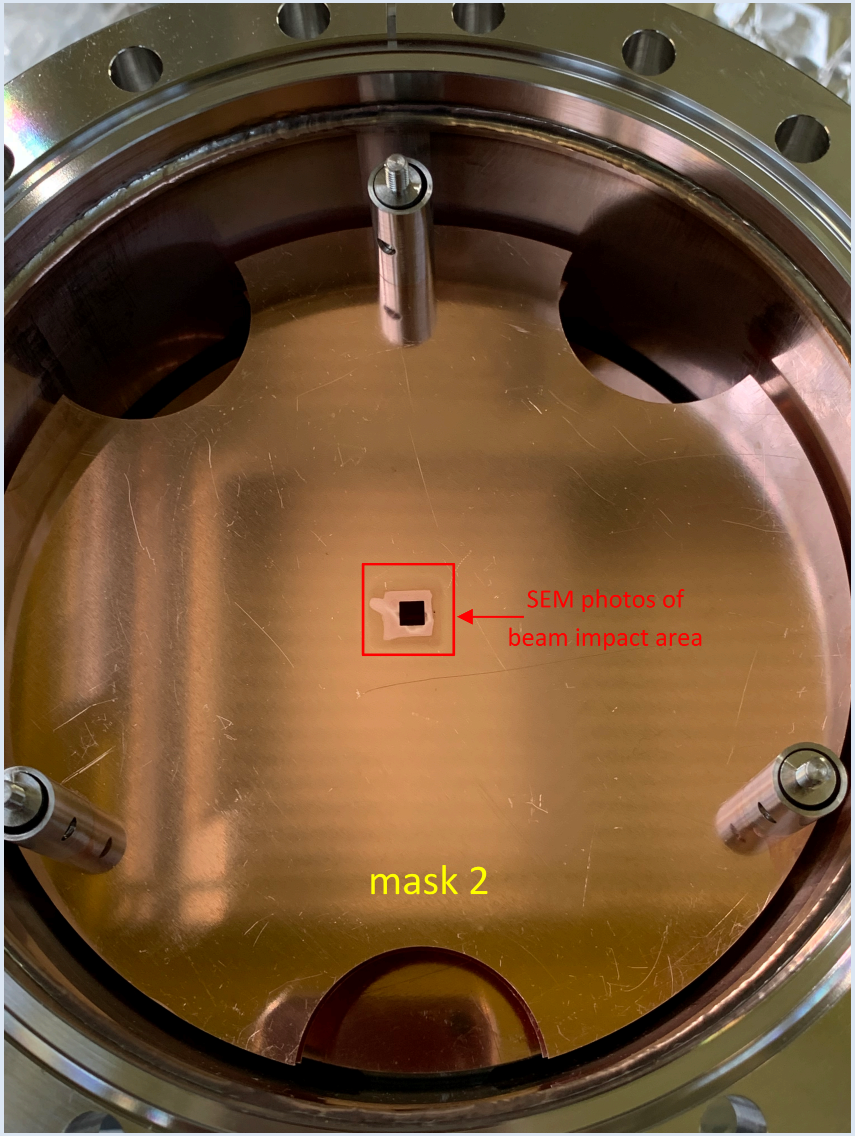


# Linac 4 test stand RFQ masks after continuous caesiation

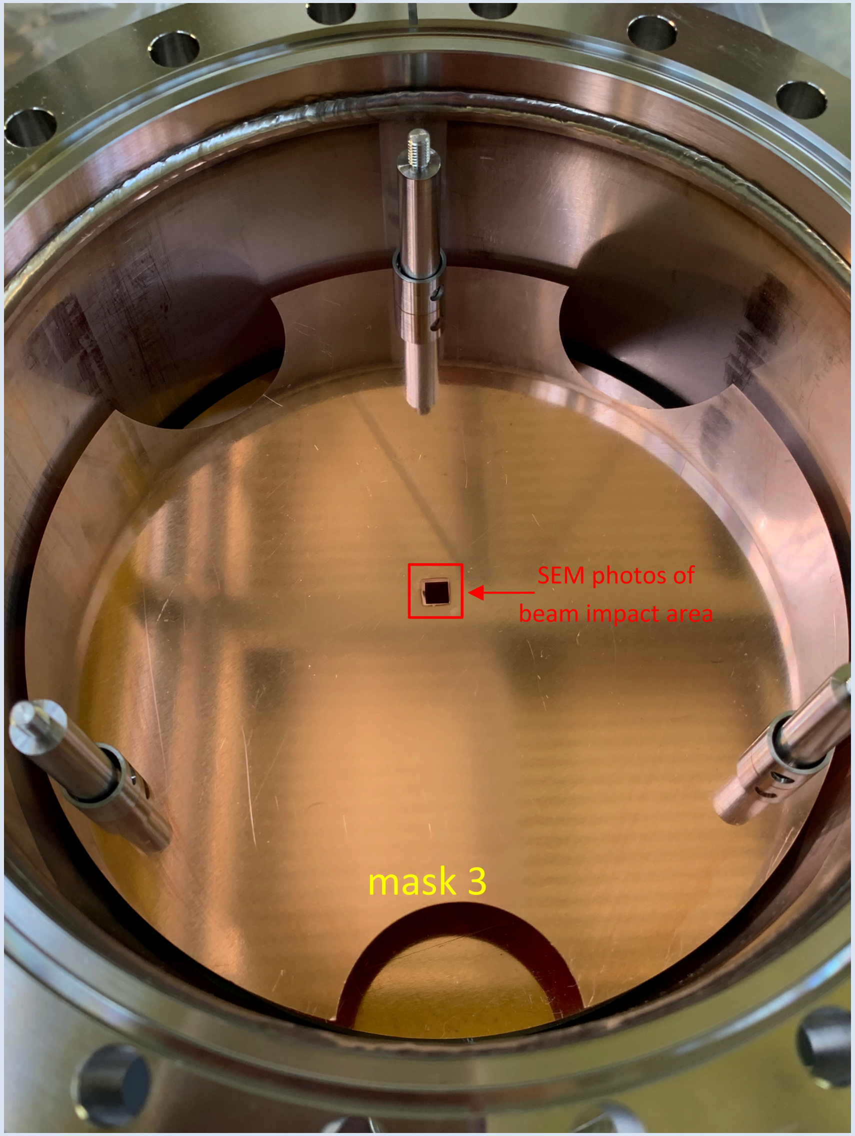


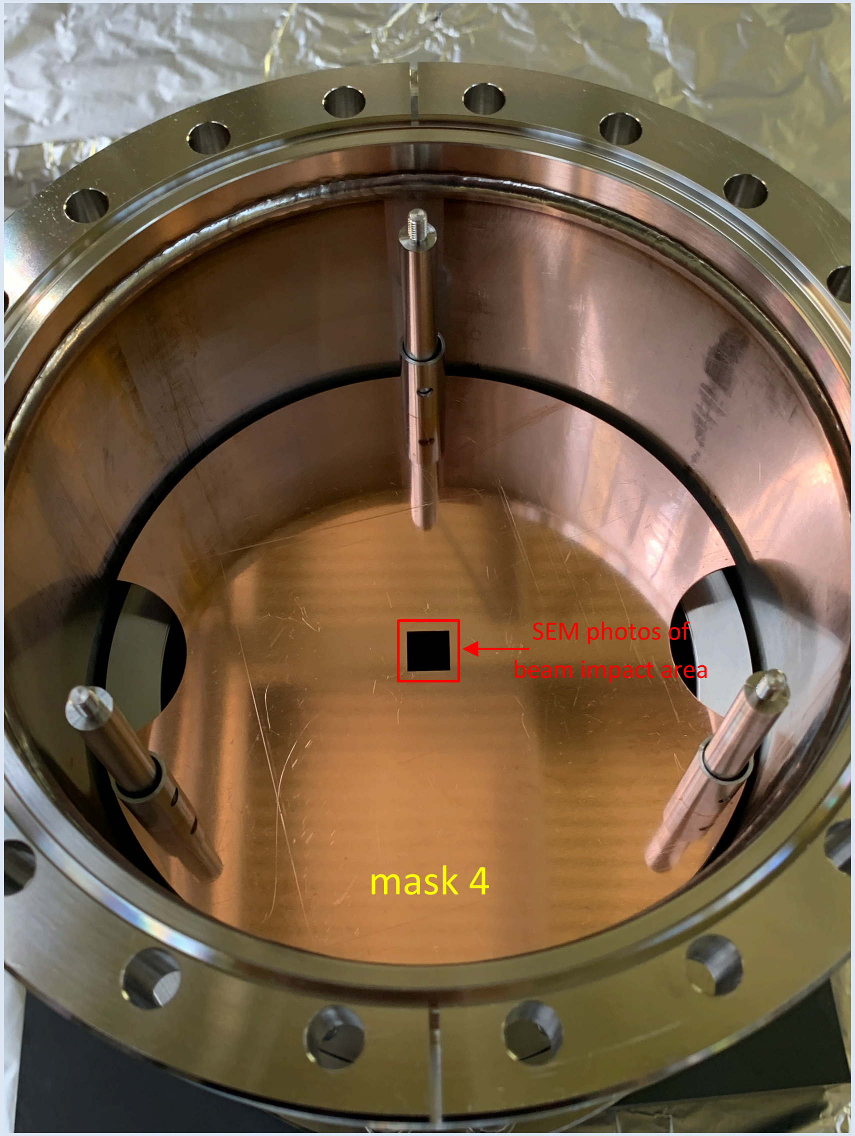
# Surface analysis of masks and samples





# Surface analysis of masks and samples

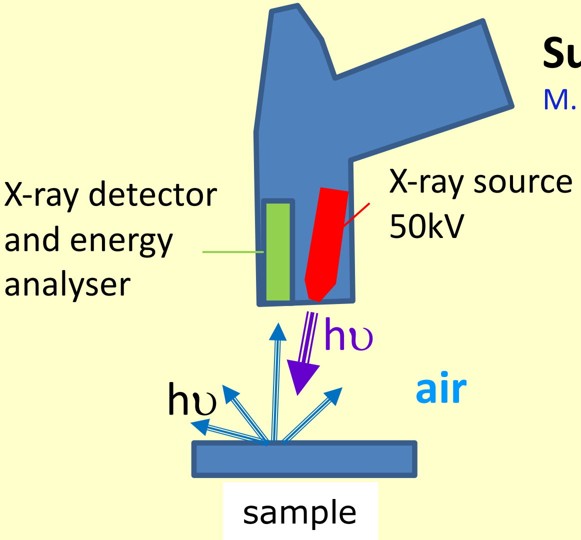




# Surface analysis techniques

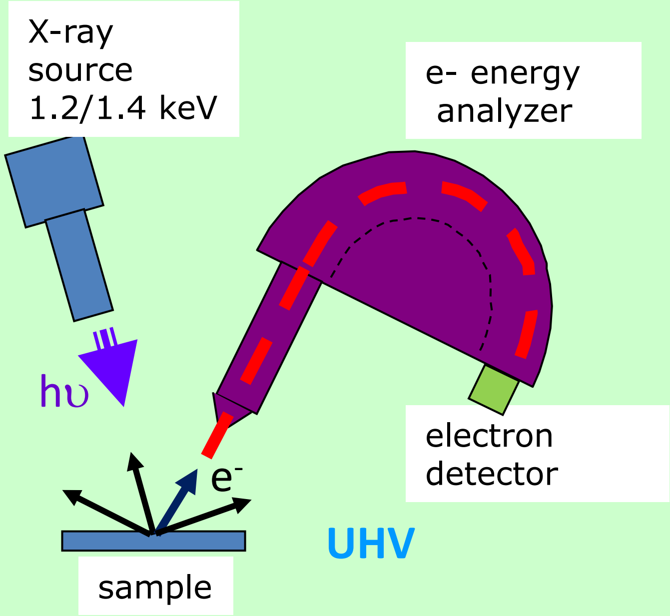
M. Taborelli (TE-VSC)

## X-ray fluorescence (XRF), portable

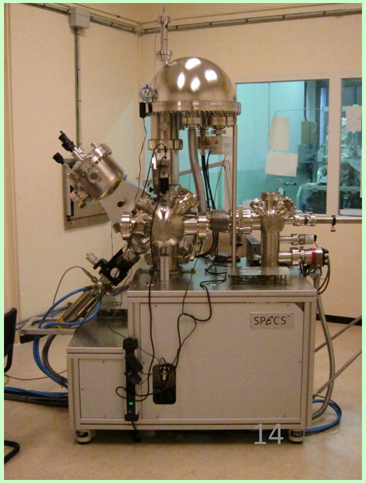


- Elemental surface composition
- Sampling of about microns in depth
- Collecting Cs from a large surface (~170cm$^2$) and re-concentrating on the probed spot gives a detection limit of 0.003 µg/cm$^2$ for water soluble Cs (the oxide is soluble)
- (NB: 0.1 µg/cm$^2$ is about one atomic layer)

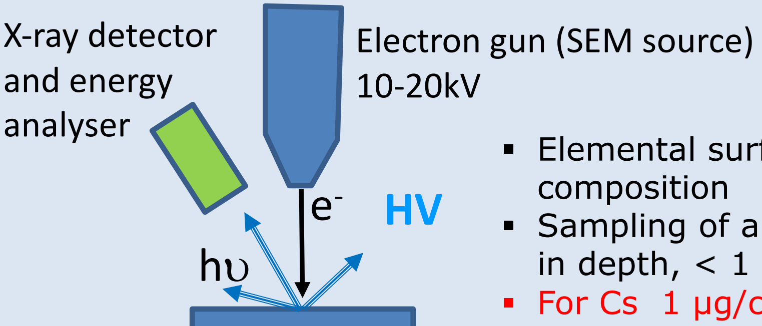
## X-ray photoemission spectroscopy (XPS)



- Elemental surface composition and some chemical bonds
- Sampling of about 2nm in depth, 1-2 mm$^2$
- Detection limit 0.02 µg/cm$^2$ Cs (layer on top of copper)



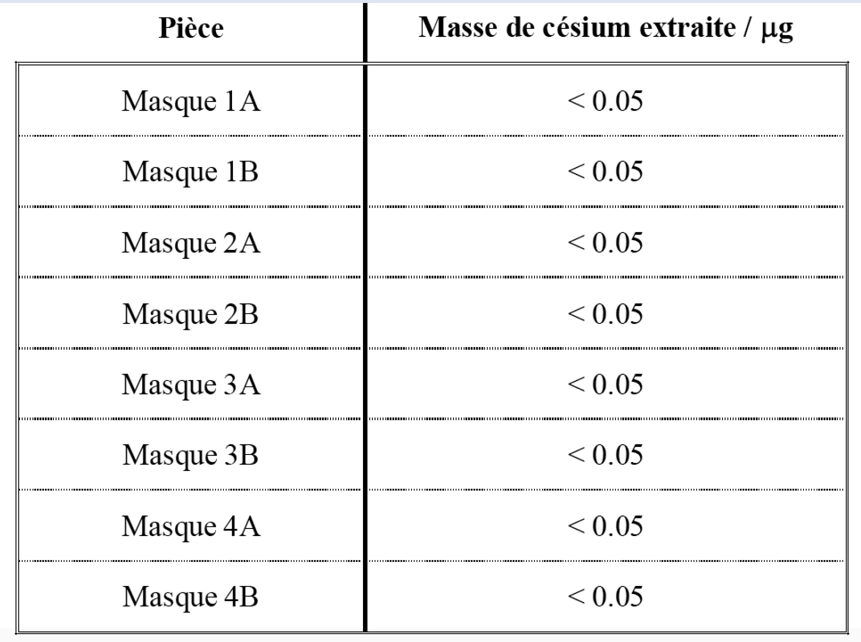
## Energy Dispersive X-ray analysis (EDX) in SEM



- Elemental surface composition
- Sampling of about 1 µm in depth, < 1 µm area
- For Cs 1 µg/cm$^2$ estimated detection limit

# XRF results

- Samples removed from mask 1
- all 4 masks analysed
- front (A) and back (B) side measured



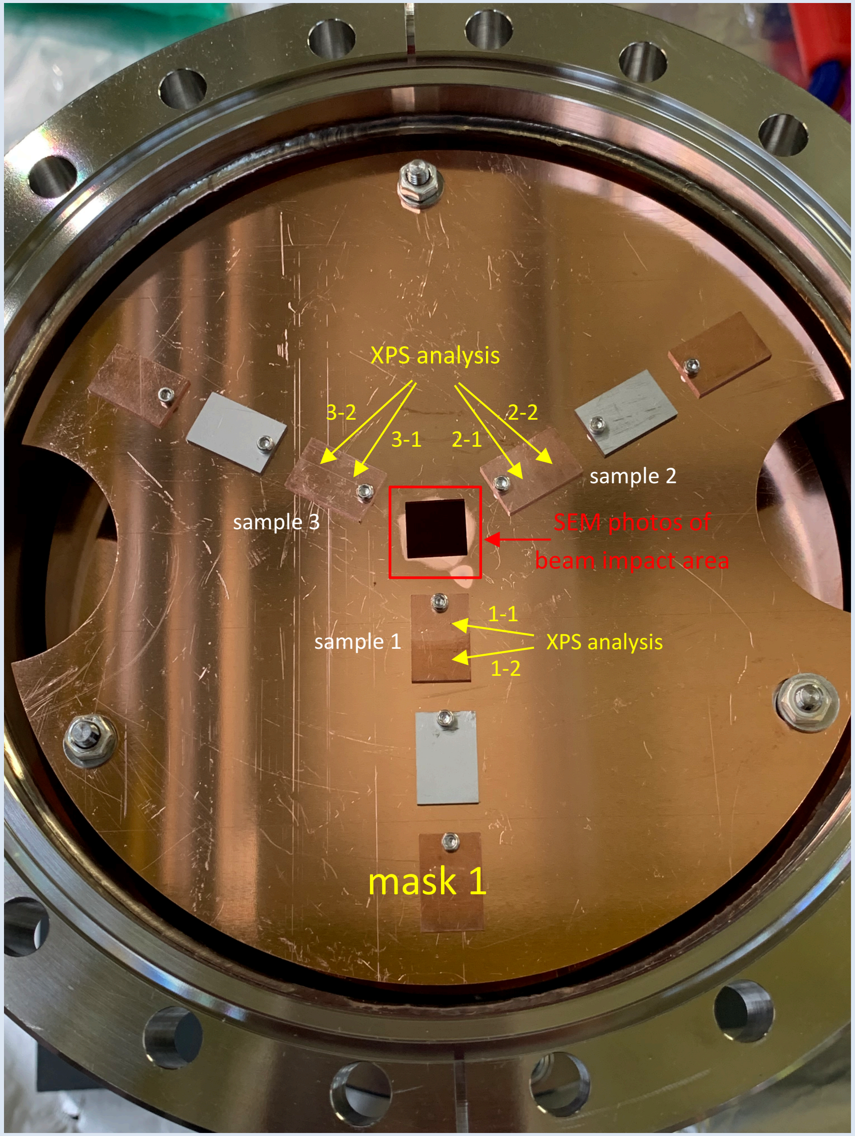
| **Pièce** | **Masse de césium extraite / µg** |
|---|---|
| Masque 1A | < 0.05 |
| Masque 1B | < 0.05 |
| Masque 2A | < 0.05 |
| Masque 2B | < 0.05 |
| Masque 3A | < 0.05 |
| Masque 3B | < 0.05 |
| Masque 4A | < 0.05 |
| Masque 4B | < 0.05 |

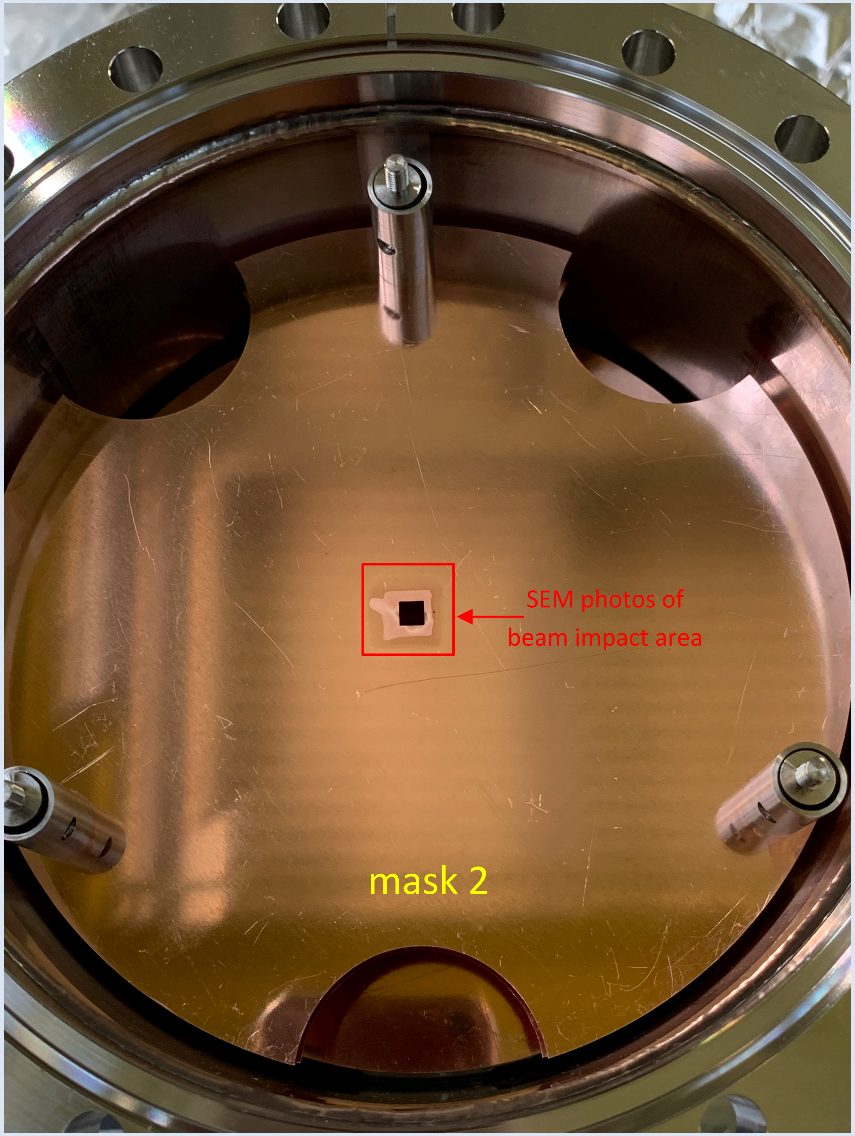
C. Charvet (TE-VSC), EDMS 2210969

No evidence of Cs found on any of the four copper mask surfaces, within the XRF detection limit of 3 x $10^{-3}$ µg/cm$^2$

1 ML = $10^{-1}$ µg/cm$^2$ -> 0.03 ML detect. limit

# XPS results


XPS analysis
3-2
3-1
2-1
2-2
sample 2
sample 3
SEM photos of
beam impact area
1-1
sample 1
XPS analysis
1-2
mask 1


SEM photos of
beam impact area
mask 2

# XPS results

M. Himmerlich (TE-VSC), EDMS 2214379

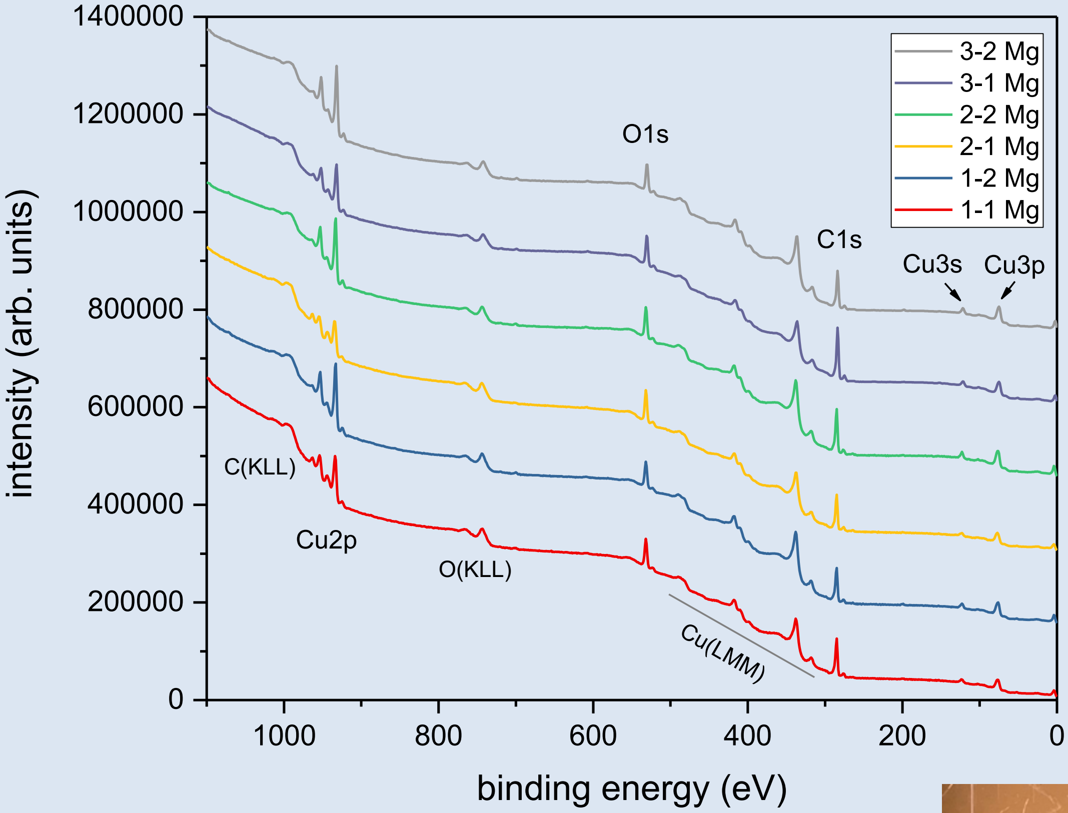
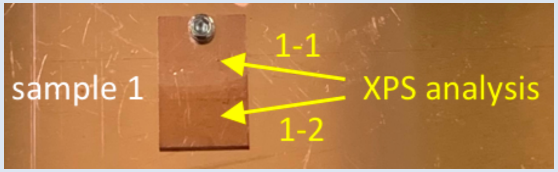


FIG. 1. XPS survey spectra



- **Measurements** were performed **on two spots of each sample** (see previous slide)
- The **survey spectra** (FIG.1) indicate the main lines detected, which correspond to **Cu, O, and C**.

# XPS results

M. Himmerlich (TE-VSC), EDMS 2214379

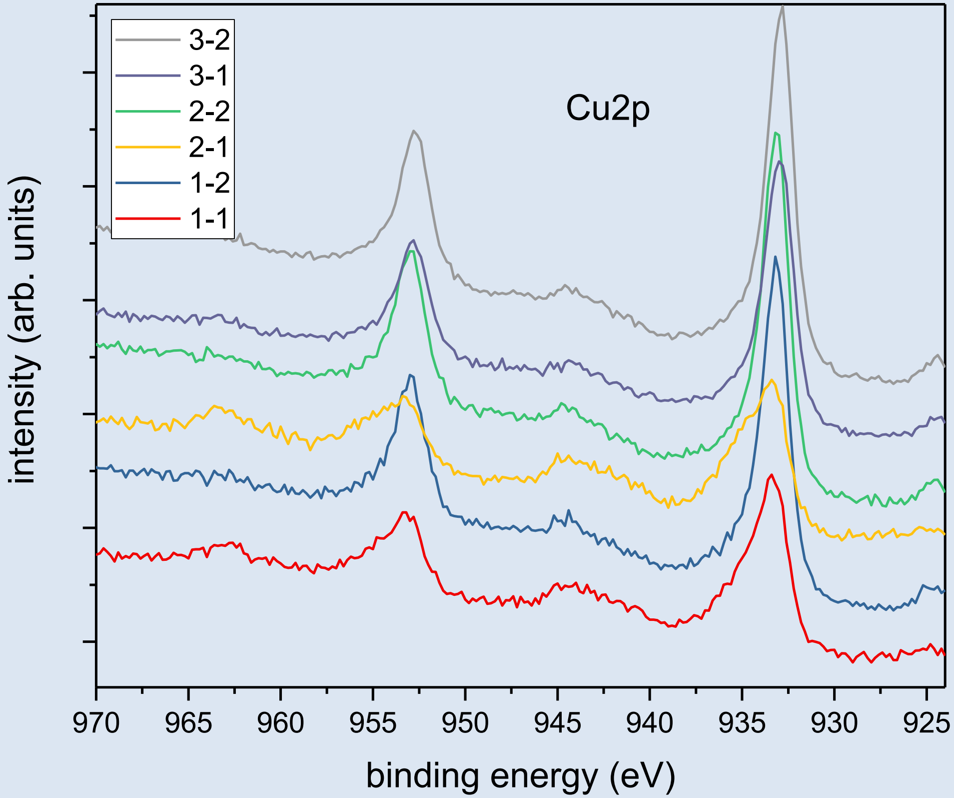
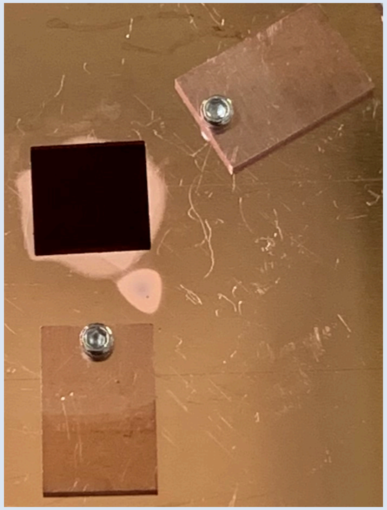


FIG. 2. XPS Cu2p spectra



- ○ Slightly **different colour shading** for the **two regions** of samples 1 and 2 observed
- ○ The colour difference **correlates with the shape of the Cu2p state** shown in Fig. 2 and points to **differences in oxidation**. This could be related to the dose from the experiment that the different regions were exposed to.

# XPS results

M. Himmerlich (TE-VSC), EDMS 2214379

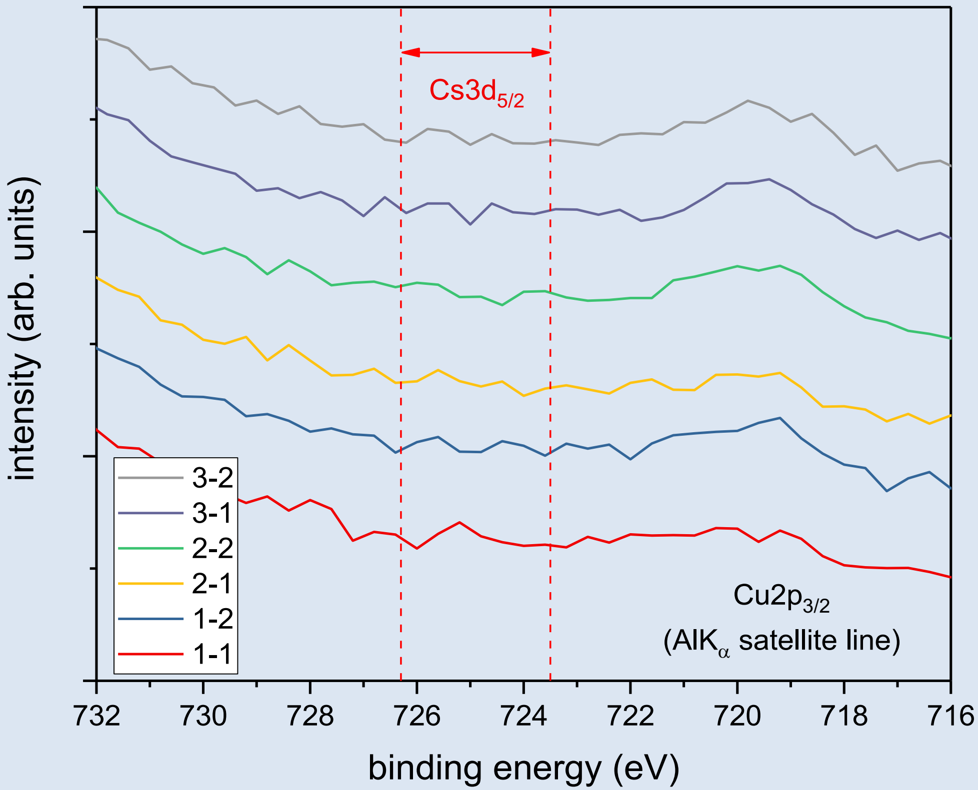


FIG. 3. XPS spectra around the Cs3d line

- ○ For Cs analysis, the spectrometer was operated at highest possible sensitivity, i.e. large pass energy of 150 eV and long integration time. FIG. 3 includes the related spectra.
- ○ **No signal** within the binding energy region **of possible Cs compounds** (indicated by red dotted line) **was detected**.

# Summary

- First long-term test of the new CERN Linac 4 ion source continuous caesiation system, performed during 5 weeks at the test stand, all objectives achieved.

- Successful test and demonstration of the reliability, the operational robustness, and readiness of the new Cs system, which was designed, built, commissioned, and operated by ABP-HSL (M. O'Neil).

- $e^-/H^- = 0.50 \pm 0.15$ achieved during the last 3 test weeks, using a (very) low Cs temperature of $T_{Cs}$ (reservoir) = 70 ± 10 ℃. No interim caesiation was necessary.

- Various applied surface analysis techniques (XRF, XPS) revealed no trace of caesium on the RFQ acceptance masks and samples, within a very low detection limit of down to 0.003 μg/cm$^2$, which corresponds to 0.03 ML.

# Summary ion source comparison (1/2)

| Status August 2019 | CERN | J-PARC | ORNL |
|---|---|---|---|
| **$H^-$ source type** | RF | RF | RF |
| **Caesiation method** | continuous | not continuous,<br>very frequent (with beam)<br>45 s each 70 min | not continuous,<br>once per ~100 day long run |
| **Cs oven fill** | 5 g, 2 g, 1 g (options) | 3 g | 30 mg Cs in Cs collar as $Cs_2CrO_4$ |
| **Cs system temperatures** | oven: 70 ± 10 ℃<br>valve: 90 ± 10 ℃<br>tube: 90 ± 10 ℃ | oven: 180 ℃<br>valve: 240 ℃<br>tube: 300 ℃ | Normally ~200 °C and raised to 550℃ for ~12 min to activate St101 getter |
| **Cs consumption** | 12 mg/5 weeks<br>0.125 g/year<br>no measurements, estimated values | 43.7 µg/70 min<br>0.328 g/year<br>no measurements, estimated values | ~40 mg/year<br>including Cs for frontend R&D |
| **Valve between Cs oven and ion source** | 1 motorized + 1 manual valve. Opened/closed remotely | pneumatic valve<br>Opened/closed remotely by compressed air on/off | not applicable because Cs collar is an integral part of the ion source |
| **Measures to protect the linac against Cs** | Cs heater system design | Cs 852 nm spectrum observation | gate valve next to RFQ is closed during caesiations |
| **Observed issues with beamline, RFQ** | no records yet | no issue in the beam line and/or RFQ observed | arcing problems resolved after introducing a 3-hour wait between caesiation and applying high voltages |
| **Source-RFQ distance** | 1.955 m | 0.64 m | 0.1 m |

All numbers and information kindly provided in July/August 2019 by A. Ueno (J-PARC), M. Stockli (ORNL)

# Summary ion source comparison (2/2)

| **Status August 2019** | **BNL** | **FNAL** | **RAL** |
|---|---|---|---|
| **$H^-$ source type** | Magnetron | Magnetron | Penning |
| **Caesiation method** | continuous | continuous | continuous |
| **Cs oven fill** | 5 g | 5 g | 5 g |
| **Cs system temperatures** | oven: 125-130 ℃ (8h) then 90-110 ℃<br>valve, tube: 300 ℃ | oven: 110 ℃<br>valve: 200 ℃<br>tube: 200 ℃ | oven: 155-170 ℃<br>tube: 300 ℃ |
| **Cs consumption** | 0.5 mg/h<br>4.38 g/year<br>measured by left over | < 5 g/600 d<br>< 3.0 g/year<br>no measurements, 600 d based on experience, weighing oven foreseen | 3 g/month<br>36 g/year |
| **Valve between Cs oven and ion source** | manual valve<br>Opened/closed only for source start/removal | manual valve<br>Only time that they need to close that is when they let up the vacuum and remove the ion source | no valve<br>Transport line as short as possible, could collect Cs and get blocked |
| **Measures to protect the linac against Cs** | none; LEBT with 45 degree bend | no method of trapping cesium coming out of the source | 90 degree dipole, cold box |
| **Observed issues with beamline, RFQ** | never had any issues with Cs in RFQ | no issues with cesium in RFQ or HV element in LEBT | no problem with beamline in 35 years |
| **Source-RFQ distance** | 2 m | 1.2 m | 1.5 m |

All numbers and information kindly provided in July/August 2019 by by D. Raparia (BNL), D. Bollinger (FNAL), D. Faircloth (RAL)

# Conclusion

- The designed, built, and commissioned caesiation system has successfully passed a 5 weeks testing period where it demonstrated its aptitude, reliability, and robustness to be deployed for systematic Linac 4 tests and long-term operation.

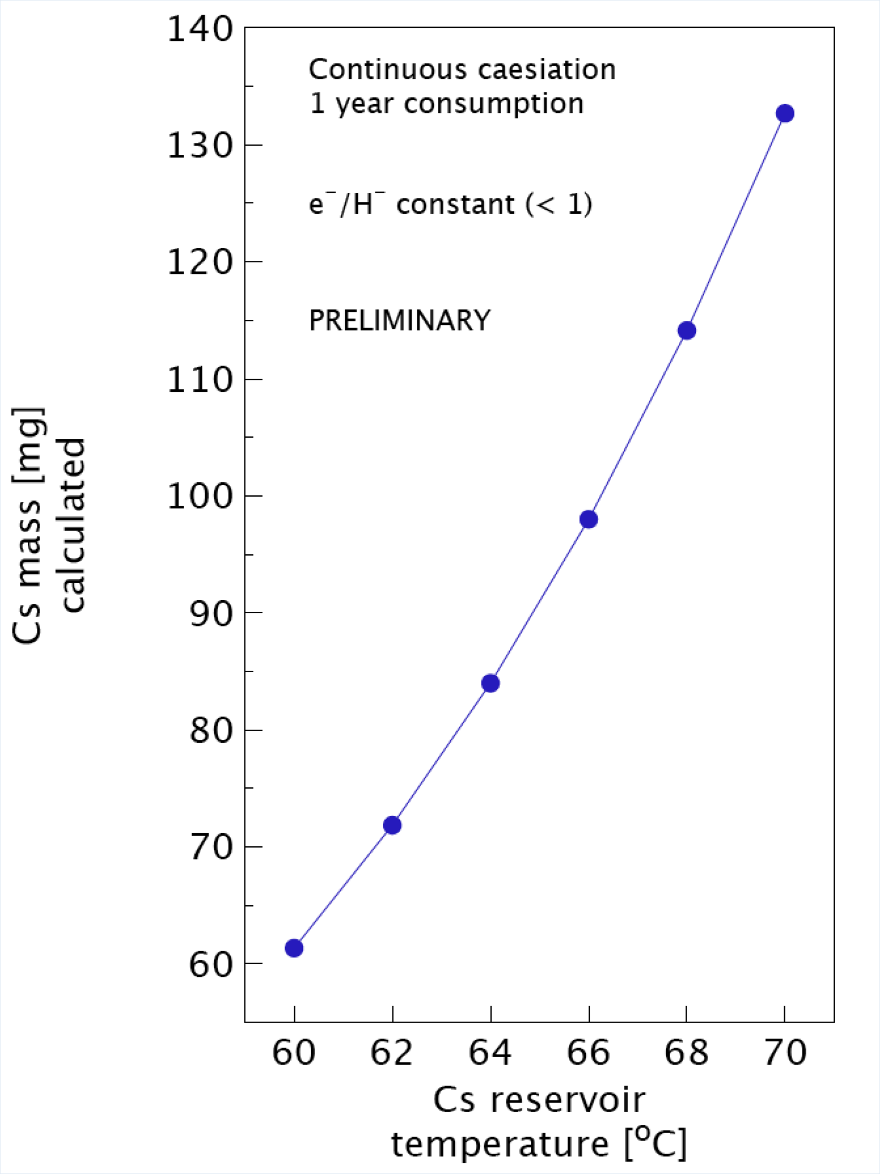
- Observations at various accelerator labs, where no beamline and/or RFQ issues have been reported, support the chosen Linac 4 approach and todays proposal.

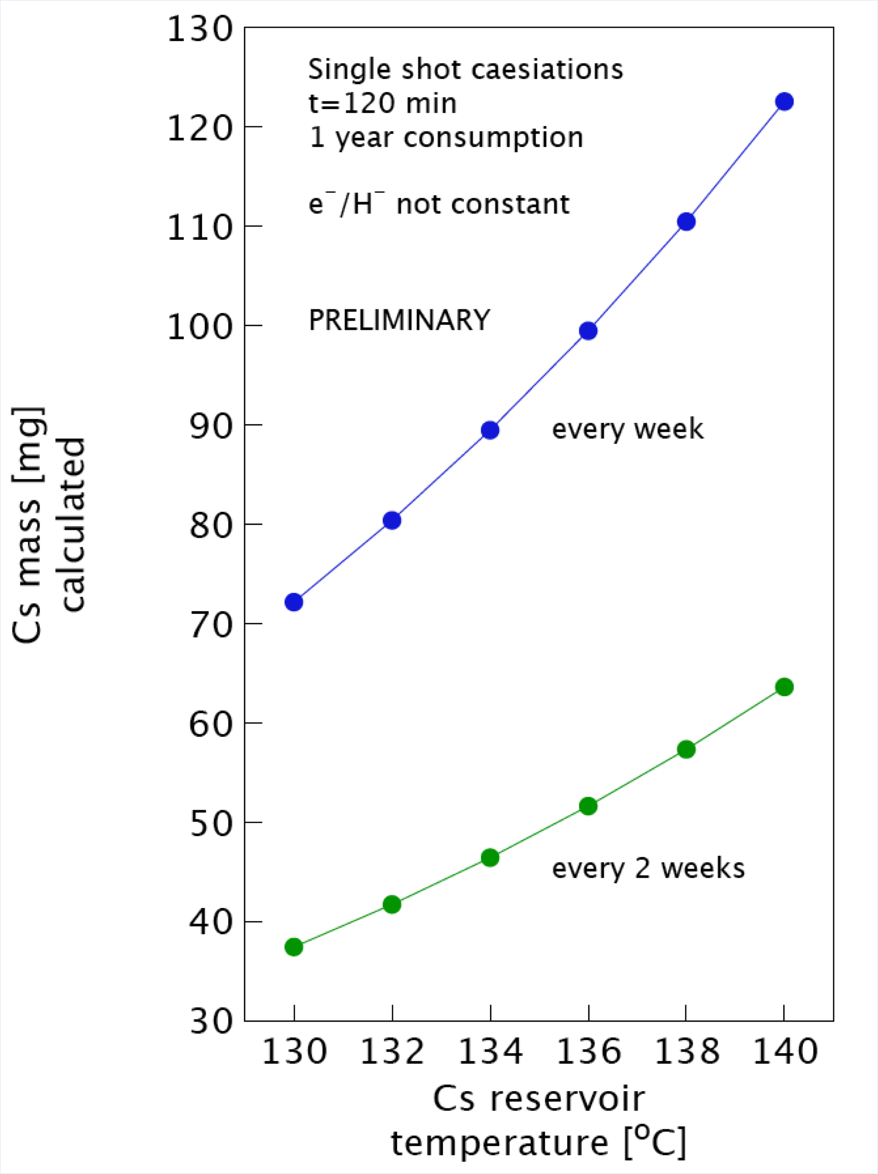
- Based on the Linac 4 $H^-$ ion source continuous caesiation tests, performed between 13 May and 16 June 2019 at the Linac 4 test stand, and taking into account the presented results at todays MPP meeting, the ABP group suggests a formal MPP recommendation to employ continuous caesiation under operational beam conditions (no valves closed) starting with the next Linac 4 (LBE) run in September 2019.

- Effect(s) of long-term (months, years) continuous caesiations of the Linac 4 ion source and any potential impact on machine performance and/or reliability can neither be predicted nor excluded.

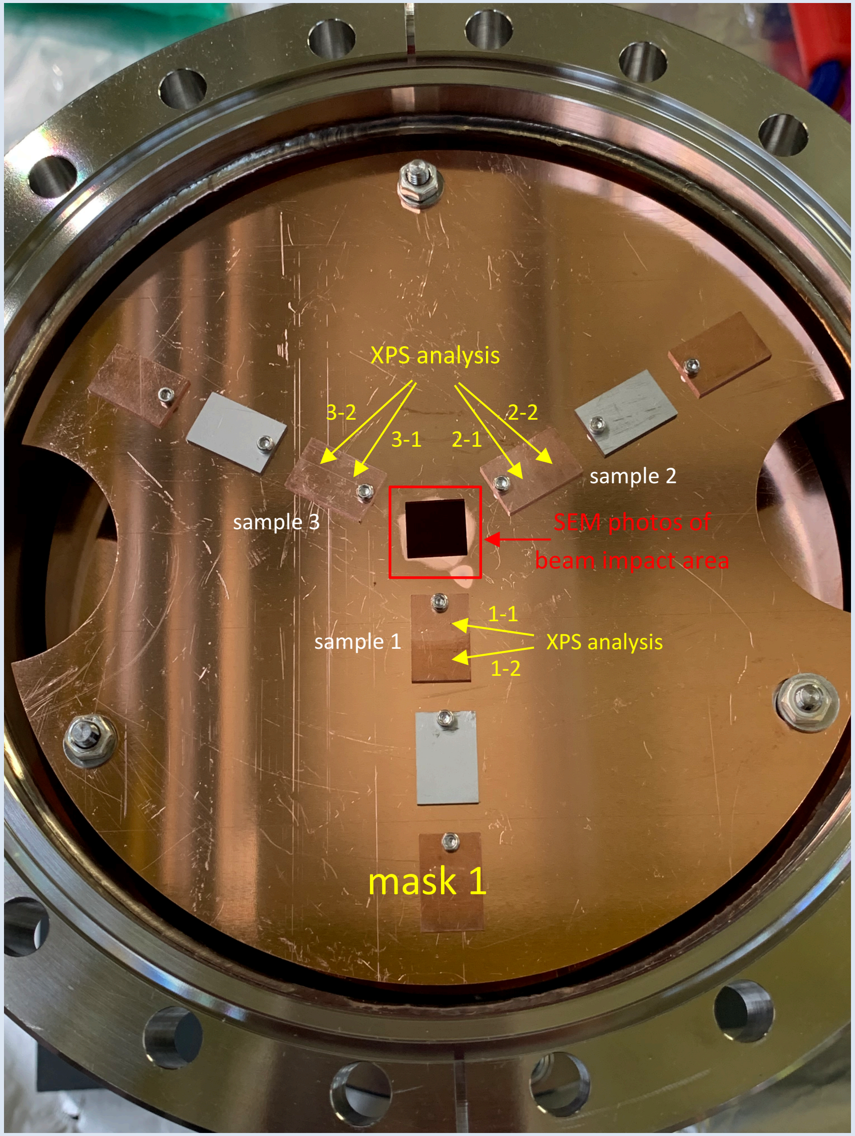
# Spares

# Comparison of Cs consumptions



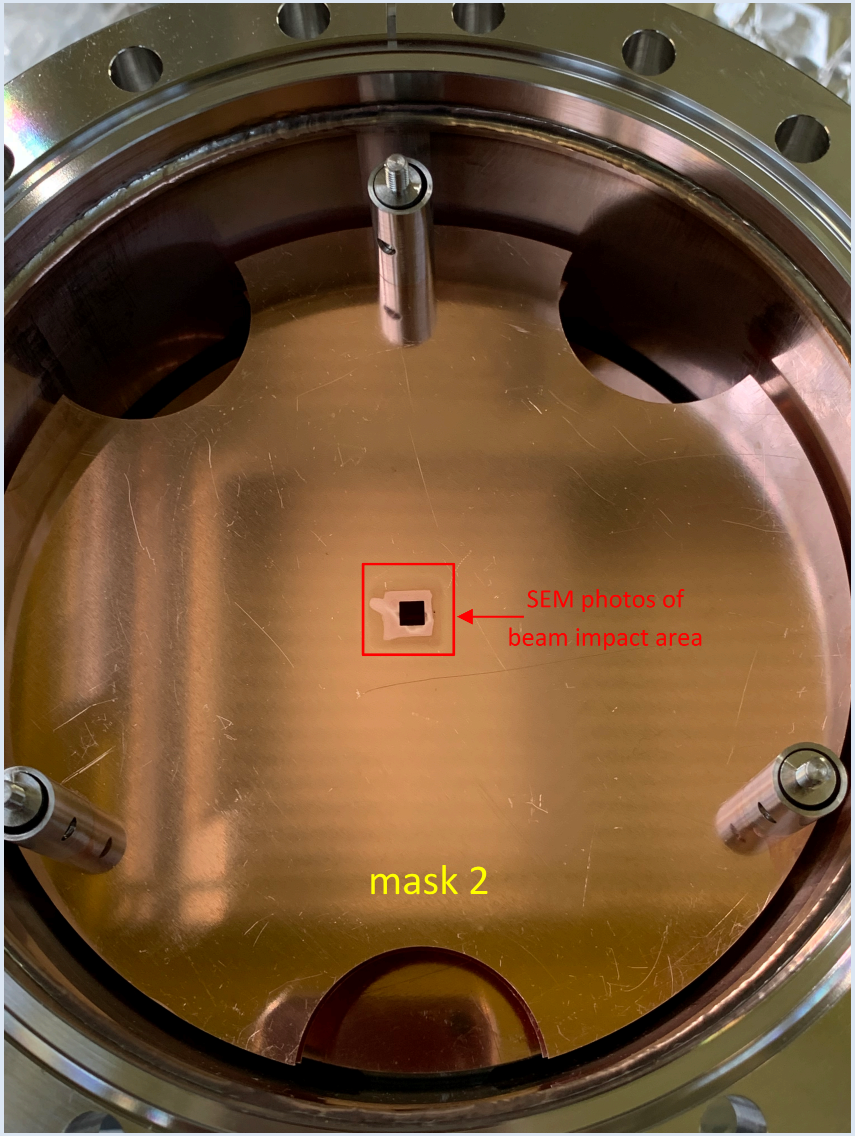


# SEM results


XPS analysis

SEM photos of beam impact area

XPS analysis


SEM photos of beam impact area

# SEM results

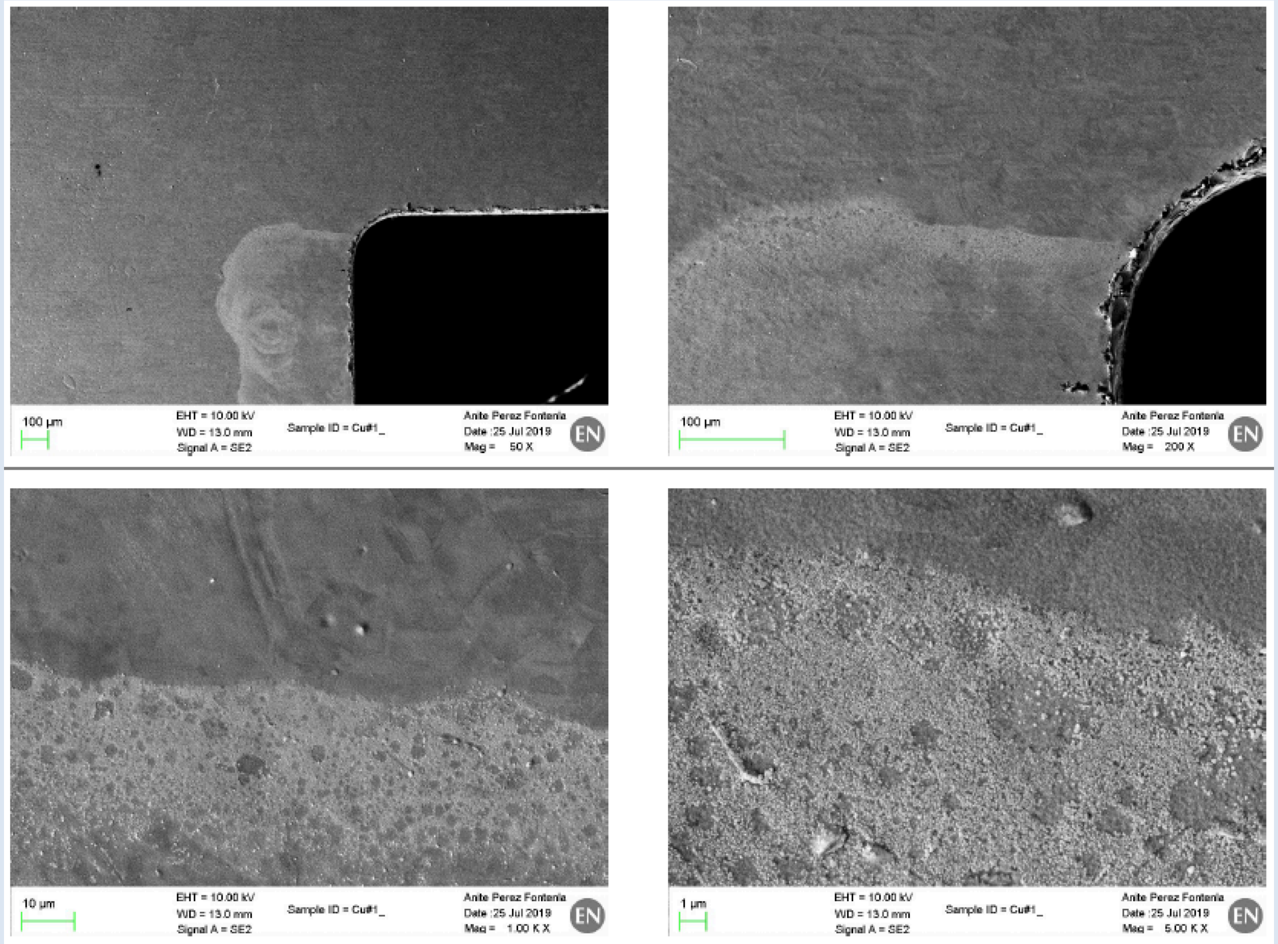


FIG. 2. SEM images of the roughness heterogeneities depending on the area at 50 x, 200 x, 1 kx, and 5 kx

- In all the samples, the **surface areas around the hole** present **roughness heterogeneities** (most probably depending if they were higher or lower affected by the beam interaction). Representative images are displayed on FIG. 2.

# SEM results

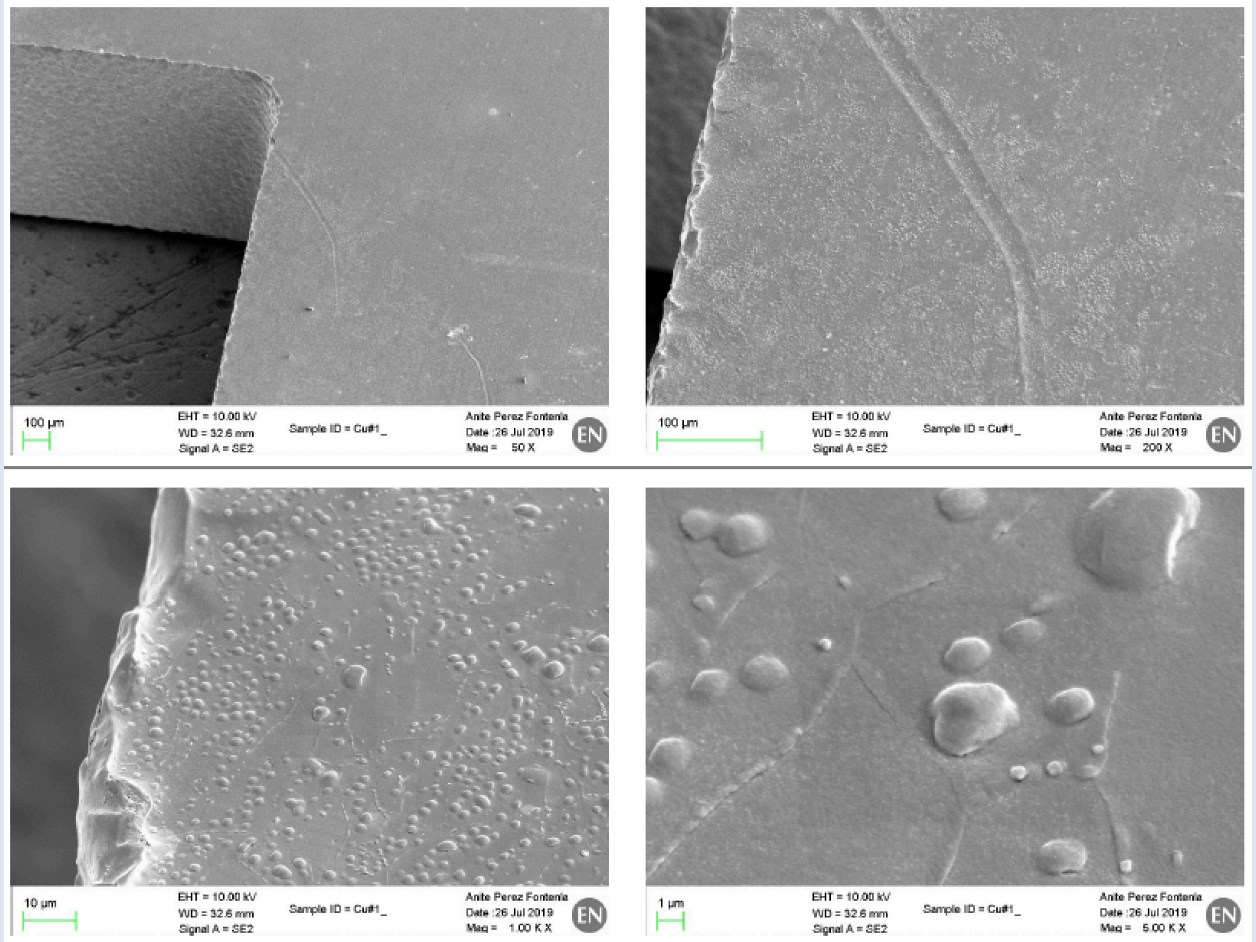


FIG. 3. SEM images (Cu #1, tilted 30$^o$) of the observed hillocks around the square hole at 50 x, 200 x, 1 kx, and 5 kx

- Apart from the surface roughness, **some regions** of samples (Cu #1,2,3) **present hillocks** o few microns diameter, with higher density closer to the square (see FIG. 3).

# SEM results

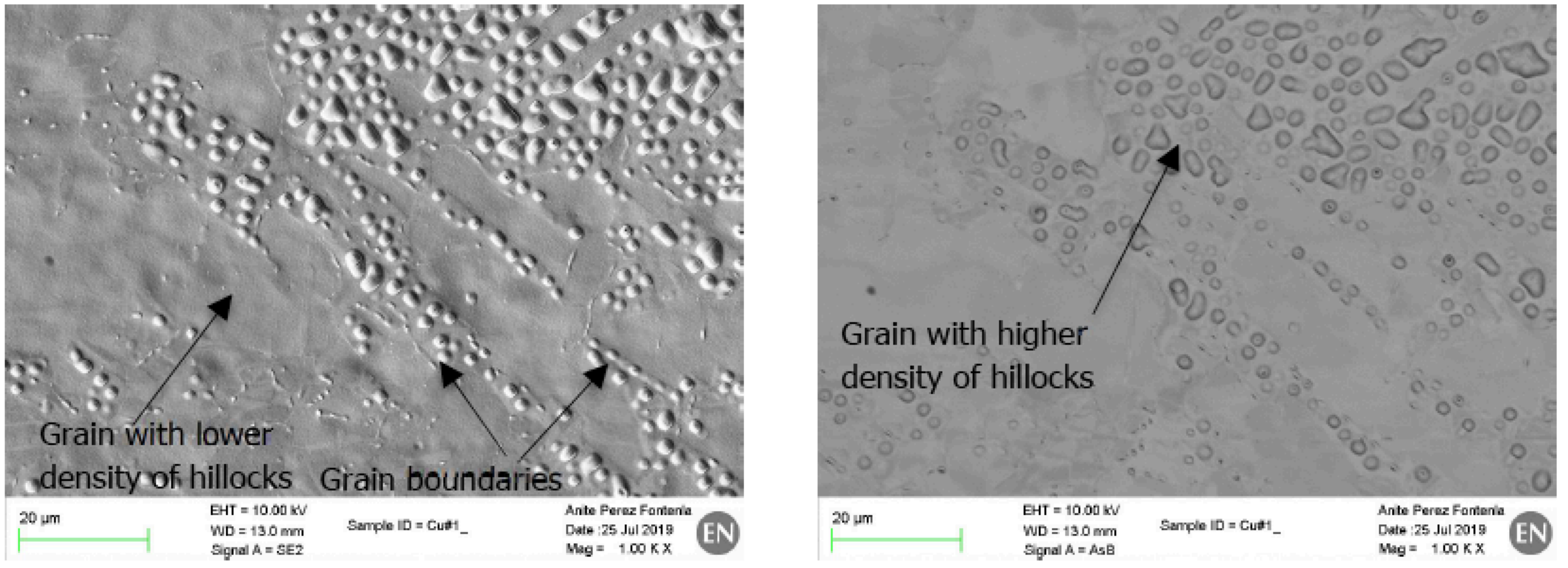


FIG. 4. SEM images (Cu #1) of the observed hillocks around the square hole at 1 kx

- It was noticed that **those features (hillocks)** have a **preferential location** on the **grain boundaries** and their presence is more numerous in some grains (maybe related to crystallographic orientation) as shown in FIG. 4.

# SEM results

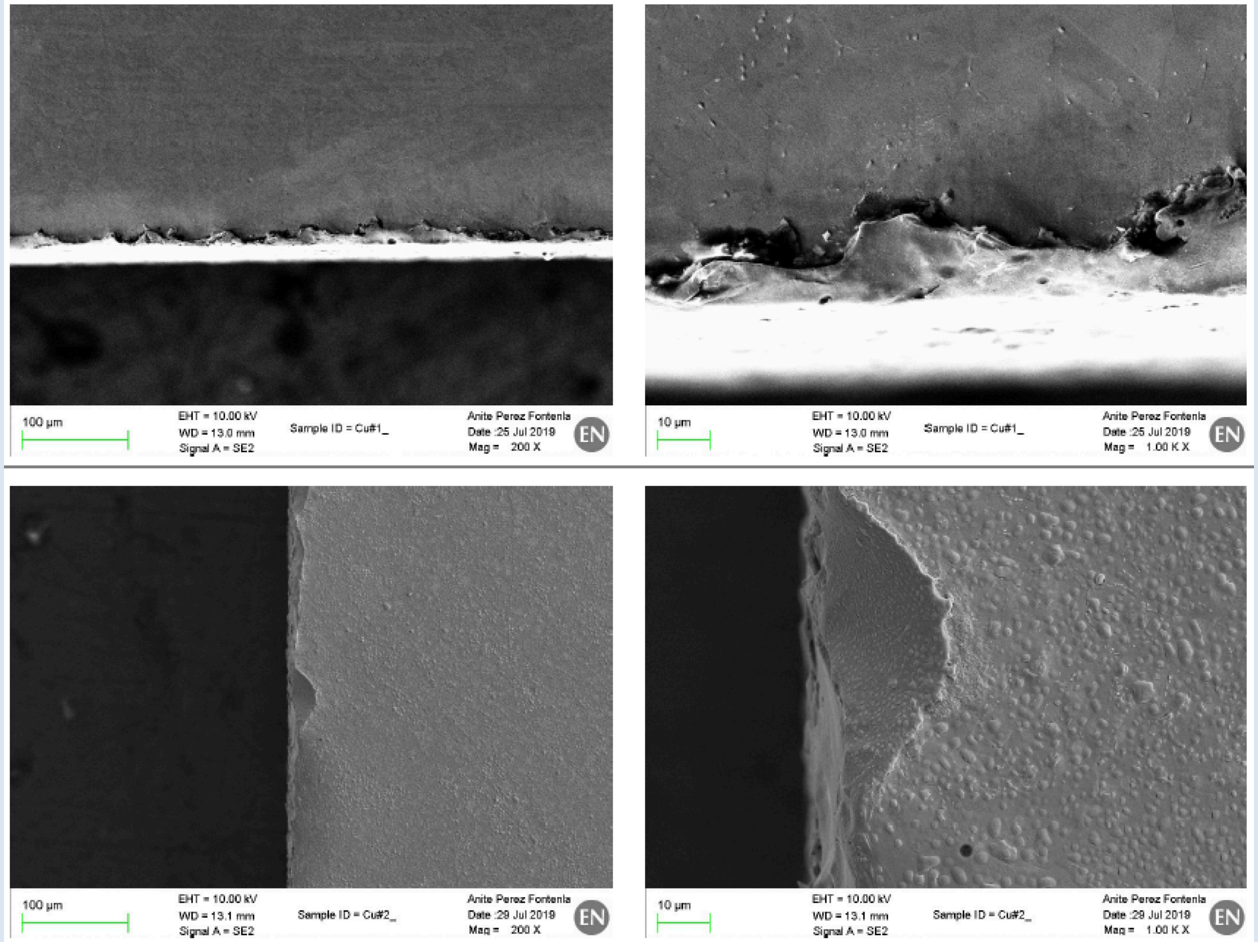


FIG. 5a. Comparison of SEM images at the edges of the holes in the two copper samples (Cu #1, Cu #2) at 200 x and 1 kx

- For all samples, the **edges of the square holes** presented **splashes of molten material**, see FIG. 5a

# SEM results

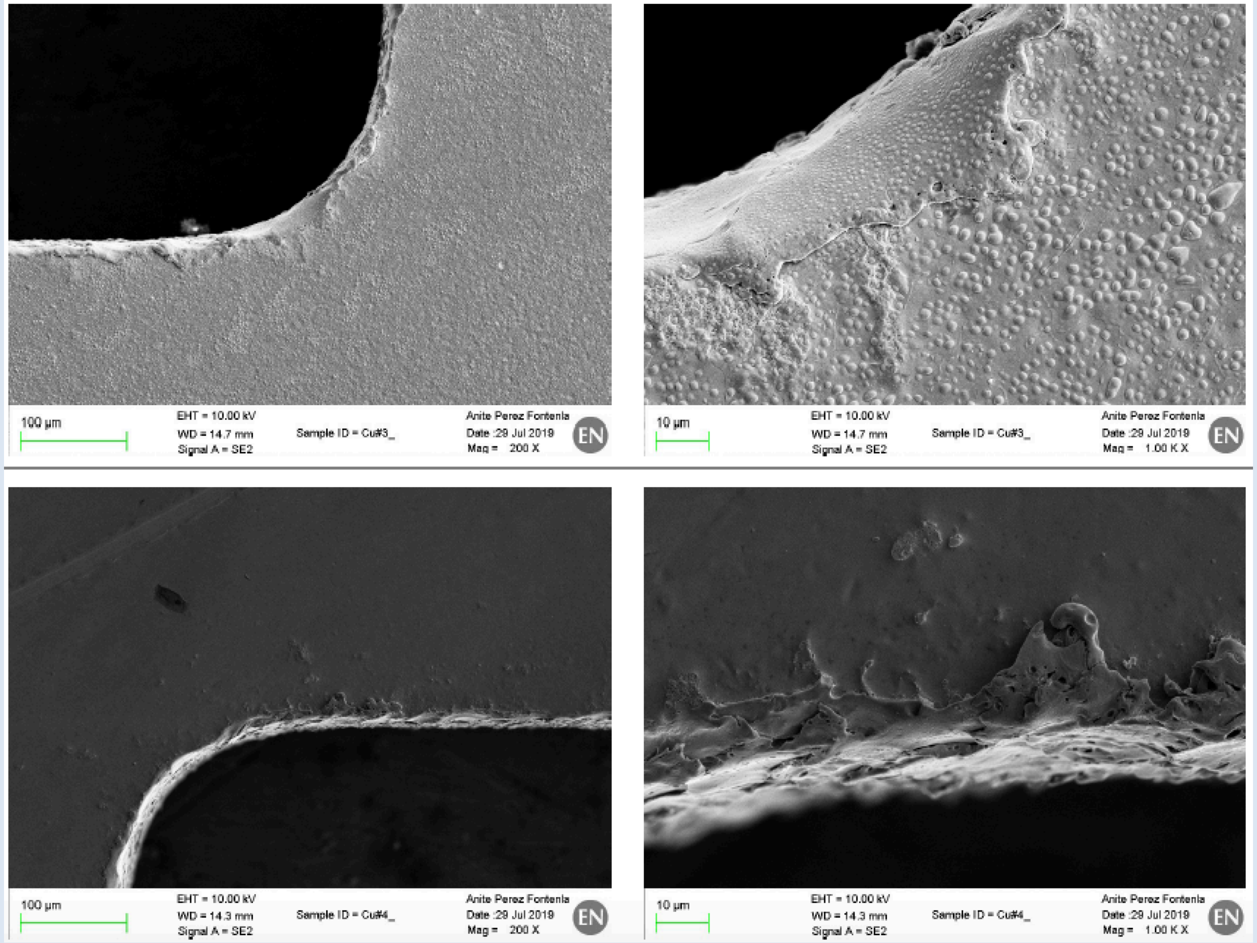


FIG. 5b. Comparison of SEM images at the edges of the holes in the two copper samples (Cu #3, Cu #4) at 200 x and 1 kx

- For all samples, the **edges of the square holes** presented **splashes of molten material**, see FIG. 5b