PRELIMINARY RESULTS OBTAINED WITH THE LHC VACUUM PILOT SECTOR

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Abstract

The Large Hadron Collider (LHC) is affected by electron cloud that reduces the quality of the beam, provokes instabilities, and increases the residual-gas pressure and heat load in the vacuum chambers. Synchrotron radiation, via photoelectron emission, plays also an important role in the electron cloud build-up. An innovative room temperature Vacuum Pilot Sector (VPS) was installed in a straight section of the LHC to investigate these phenomena *in situ* [1]. The VPS is instrumented to monitor the electron cloud and its interaction with different surfaces. Currently the system is testing technical surfaces such as copper, amorphous carbon coating, and NEG thin films.

INTRODUCTION

The objective of the VPS system is to investigate the electron cloud (EC) and synchrotron radiation (SR) effects on the LHC's vacuum system.

Free electrons are generated in the beampipe by several mechanisms. Primary electrons can be produced by protons impinging on both beam pipes and residual gas. These primary electrons are accelerated by the electric field of the bunched beam towards the vacuum chamber walls. While impinging on the surfaces, depending on their energy and direction, the primaries can be reflected and/or release secondary electrons. The amount of secondary electrons is defined by a surface property, called secondary electron yield (SEY). If the SEY is larger than one, the number of free electrons inside the beam pipe increases.

Also, the beam structure and parameters play an important role for the electron cloud build-up. With short bunch spacing and high bunch population, free electrons can survive between bunches. Due to this, the electron density grows at each bunch passage and the first free electrons produce a cloud. This process is called multipacting [2, 3].

During the energy ramp-up, the impinging SR generates photoelectrons from the beam pipe material that contributes to the EC build-up. Depending on the photoelectron yield (PEY) and the SEY of the surface, these additional electrons can be the only measurable electron signal, trigger the multipacting process, or simply sustain the existing EC.

We examine the dynamics of the EC and SR by measuring electrical signals, pressures, and temperatures in a dedicated system. The measurements have been performed with proton beams at energies ranging from 450 GeV at injection to the present LHC collision value (6.5 TeV). We also present some preliminary time dependent data of the electron cloud build-up as measured by an oscilloscope.

VPS SYSTEM

The 18 m long VPS is a room temperature vacuum system installed in a field free area of the LHC long straight section (Fig. 1). In this part of the accelerator, the LHC protons beams circulate in opposite directions inside two separated beam pipes of 80 mm inner diameter.

The system consists of four stations, each composed by a vacuum vessel into which a liner is inserted. Surface modifications can be applied to the internal wall of the liners. In the first station, a 1.5-2 µm thick non-evaporable getter (NEG) thin film, deposited on Cu, is studied. This film was activated in the laboratory at 230ºC for one day, vented with nitrogen, and finally installed in the VPS after a limited exposure time to the air without any subsequent activation. For this reason, it is called in this context *ex situ* NEG, where *ex situ* means that the film was not activated *in situ* as the usual practice for such a material would require. The Cu liners of the second station are coated with a-C, 400-600 nm thick, deposited by magnetron sputtering. The liners of the last two stations are made of uncoated copper OFE tubes.

All liners were mildly baked at 80^0 C to degas part of the water adsorbed on the walls and in the Kapton wires of the in-vacuum instruments. Distributed and localised pumping systems are installed to reduce the mutual pressure influence between consecutive stations. Five activated NEG coated buffers are inserted in order to pump hydrogen, carbon monoxide and dioxide. Localised ion pumps with additional NEG cartridges are embedded at the extremities of each station to increase the pumping speed for the above-mentioned species and to pump methane and noble gasses, which are not pumped by the NEG.

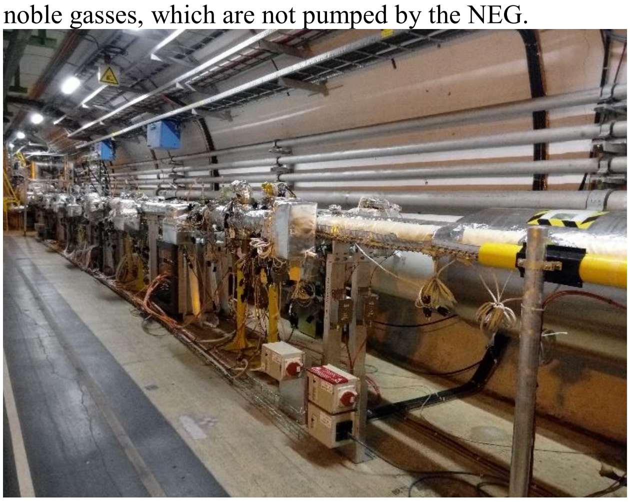

Figure 1: VPS installation in the LHC tunnel.

In each station, several detectors are installed in order to characterise the EC. Shielded and unshielded pick-ups are used to monitor the electrical signals of the EC and the beam structure. Ion-trap mass spectrometers (Vacuum Quality Monitor) and ionization gauges (Bayard-Alpert gauges) are installed to measure the partial and total pressures. Calorimeters mounted along the liners are used to quantify the power deposition due to the impedance, EC and SR contributions. Each calorimeter is made of a thin copper plate onto which temperature sensors (PT100) are welded. Kapton coated wires are used to carry the electrical signals to the vacuum feedthrough. Cables are used to transport all the signals in a service gallery where the control and monitoring instruments are protected from the LHC radiation. A LabVIEW program acquires simultaneously the pick-ups currents, the pressures, the temperatures and the beam parameters.

DYNAMIC OF ELECTRICAL SIGNALS

The typical LHC filling scheme is made in three consecutive steps. First, the beam is injected from the SPS into the LHC in bunches of 10^{11}protons. The bunches are spaced by either 25 or 50 ns. A batch is then formed by a maximum of 72 bunches. The batches are in turn assembled in trains. A maximum of 4 batches can be injected from the SPS into the LHC. Second, when the LHC machine is filled with bunches, the beam energy is ramped up from 450 GeV to 6.5 TeV. Finally, the beam is set in a stable mode during which the protons collide for physics studies.

The analysis presented below compares the case of a copper OFE station, installed into the external beam pipe, with 50 ns and 25 ns bunch spacing. Table 1 gives the main beam parameters of the two fills considered in this study.

Table 1: Beam parameters of the two LHC fills.

Fill name	5980	5979
Bunch spacing [ns]	50	25
Number of bunches	1284	2556
Protons per bunch	$9.13 \cdot 10^{10}$	$1.22 \cdot 10^{11}$
Beam current [A]	0.25	0.51

50 ns bunch spacing

With 50 ns bunch spacing, no EC build up is expected at injection. Free electrons, generated by beam gas ionisation and proton losses, are accelerated during the bunch passage but the distance between bunches is so large that the number of survival electrons is negligible and no multipacting is taking place.

As shown in Figure 2, the measurements during a fill with 50 ns bunch spacing confirm the expectations: no EC current is observed at injection energy. However, above 2.8 TeV, photoelectrons are detected because a significant fraction of impinging photons has an energy above the work function of Cu (4 ÷ 5 eV).

In the absence of multipacting, the electron current measured at 6.5 TeV corresponds to the number of photo-electrons generated and is directly related to the PEY of the surface.

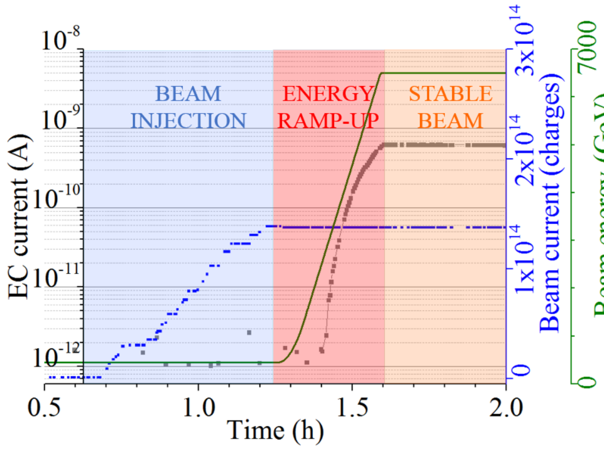

Figure 2: The photoelectron signal of a 50 ns bunch spacing beam, for a copper surface, is displayed in grey in logarithmic scale. The current of beam 1 and the beam energy are displayed in dark blue and dark green, respectively.

25 ns bunch spacing

With 25 ns bunch spacing, EC build-up due to multipacting is expected for a copper surface. During the beam injection, once the multipacting regime starts, the EC current is proportional to the beam current (Figure 3). When the beam injection finishes, the EC signal decreases because the proton beam intensity is reduced by losses.

In order to understand the behaviour of the EC current at the beginning of the energy ramp-up, one must take into account the bunch length parameter, which is inversely proportional to the square root of the beam energy [4]. When the energy ramp-up starts, the bunch length decreases. In LHC, when the bunch length reaches a value below 8 10^{-10} s, longitudinal instabilities arises. Thus, as shown in Figure 3, a RF noise is injected inside the superconducting cavities to increase the bunch length. In the meantime, the beam energy continues to increase, still contracting the bunch. The effect of the bunch length dynamic is also observed on the EC current. Indeed, the shorter the bunch length the higher the energy gained by the electrons kicked by the bunch. Above an energy of few hundreds eV, the electrons tends to penetrate into the surface so deeply that the number of secondary electrons decreases, consequently reducing the multipacting effect.

As previously explained with 50 ns bunch spacing, above 2.8 TeV, photoelectrons provide an additional contribution to the ecloud signals.

At the collision energy, once the LHC is tuned and the parameters set, the proton-proton collisions start. Then, the EC current behaviour is mainly driven by the beam losses.

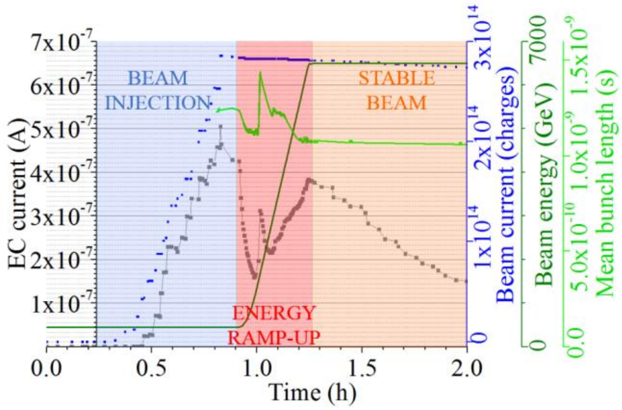

Figure 3: The EC current of a 25 ns bunch spacing beam, for a copper surface, is displayed in grey in linear scale. The current, energy and bunch length of the beam are presented in dark blue, dark green and light green, respectively.

DYNAMICS OF PRESSURE AND TEMPERATURE

Pressure trend

As shown in Fig.4, pressure and the EC current have a similar behaviour. During the beam injection, the pressure increases due to electron stimulated desorption (ESD). During the energy ramp-up, two other sources of gas are added: one due to photon stimulated desorption (PSD) and one caused by the contribution of photoelectrons to ESD.

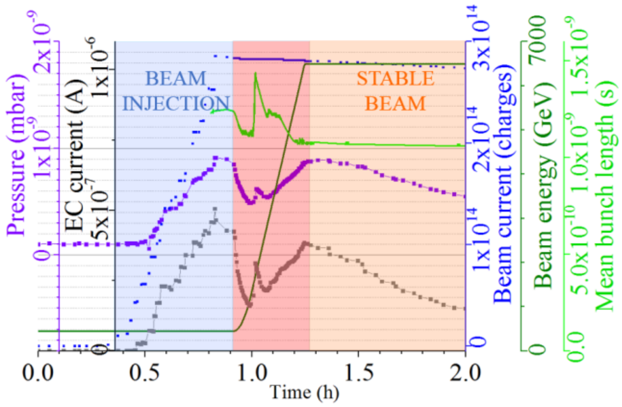

Figure 4: The pressure behaviour of a copper surface for a 25 ns beam is displayed in purple in linear scale. In grey the EC current of the corresponding pick-up is shown. The current, energy and bunch length of the beam are presented in dark blue, dark green and light green, respectively.

Temperature trend

The temperature change, shown in Figure 5, can be understood by taking into account the wall impedance, EC and SR. The calorimeter signal requires about ten minutes to reach a steady state value.

During the injection of a 25 ns spaced beam, EC and resistive wall heat loads are present and they increase linearly with the number of bunches.

The resistive wall power due to surface impedance is given by Eq. (1):

$$P_{RW} = \frac{1}{2\pi R}\Gamma\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b e}{2\pi}\right)^2\sqrt{\frac{c\rho Z_0}{2}}\,\sigma^{-\frac{3}{2}} \qquad (1)$$

where $2\pi R$ is the LHC circumference, Γ is the Gamma function, M is the number of bunches, b is the radius of the beam pipe, $N_b e$ is the bunch charge, ρ is the liner resistivity, Z_0 is the free space impedance, σ is the bunch length [5].

However, during the energy ramp-up, below 2.8 TeV, the bunch length dynamic has a big impact on the temperature behaviour. During the bunch length contraction (see between 0.9 h and 1 h in the time axis of Fig. 5), the resistive wall heat load increases. But, the EC heat load resulting from a given electron flux (*i.e.* EC current), and its time evolution, cannot be predicted without a dedicated simulation. Actually, the thermal balance between the impedance and the EC heat loads is, in this case, positive yielding to a temperature increase.

During the energy ramp-up, above 2.8 TeV, there is an additional heat load related to SR and to photoelectrons impinging on the wall.

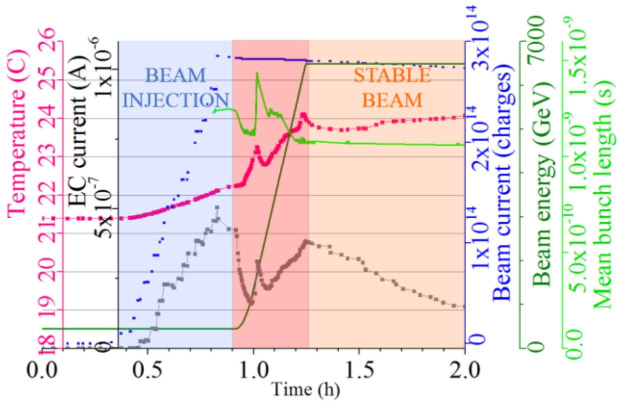

Figure 5: The temperature of a copper surface for a 25 ns bunch spacing beam is displayed in pink. In grey the EC current of the corresponding pick-up is also shown. The current, energy and bunch length of the beam are presented in dark blue, dark green and light green, respectively.

SURFACES COMPARISON

The following analysis compares 50 ns and 25 ns bunch spacing beams for the three surfaces installed in the VPS, i.e. *ex situ* NEG, a-C coating and OFE copper.

50 ns bunch spacing

With 50 ns bunch spacing, in the three samples no EC signal is measured during the beam injection (Figure 6). However, similarly to Figure 2, photoelectrons are detected above 2.8 TeV. Assuming the same SR flux and reflectivity, one concludes that among the three materials a-C coating has a lowest PEY.

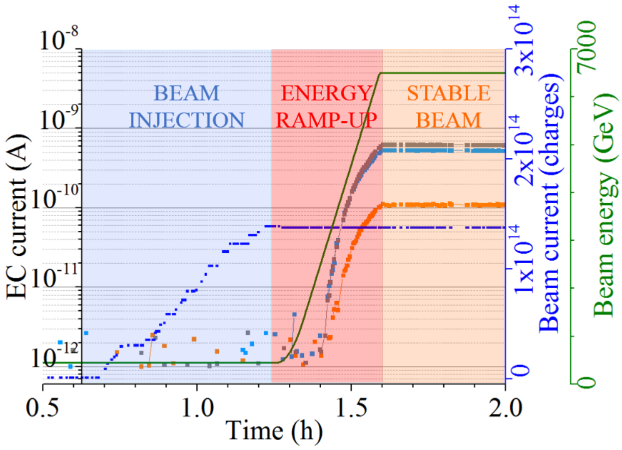

Figure 6: Photoelectrons signals of a 50 ns bunch spacing beam are displayed in logarithmic scale for different surfaces. The electrical signal measured for the copper surface is shown in grey, *ex situ* NEG in light blue, a-C coating in orange. The current of beam 1 and the beam energy are presented in dark blue and dark green, respectively.

25 ns bunch spacing

With 25 ns bunch spacing, during the beam injection at 450 GeV (Figure 7), the EC signal for the copper surface due to beam-induced multipacting is the highest. Due to its larger SEY, the copper surface has an enhanced multipacting effect than *ex situ* NEG coating. For a-C coating, no EC is visible; this confirms that this coating has a much lower SEY than the one of the other two surfaces.

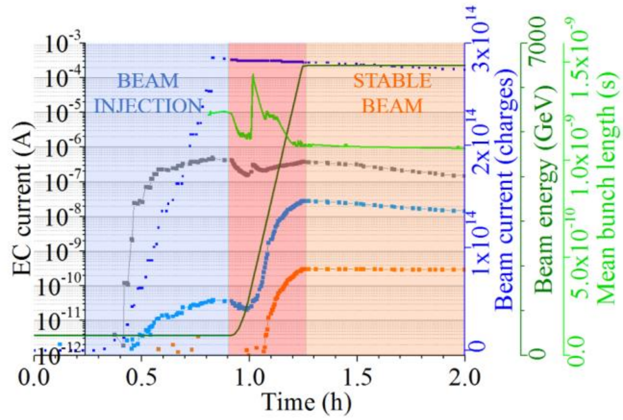

Figure 7: EC signals of a 25 ns bunch spacing beam are displayed in logarithmic scale for different surfaces. The electrical signal read on the copper surface is shown in grey, *ex situ* NEG in light blue, amorphous carbon coating in orange. The current, energy and bunch length of the beam are presented in dark blue, dark green and light green, respectively.

At the beginning of the energy ramp, the bunch length decreases. The aforementioned bunch length dynamic is observed on the pick-ups current when the electron cloud is already present in the vacuum chamber. This is the case for the copper and the *ex situ* NEG sample.

Above 2.8 TeV, the SR generates measurable photoelectrons in each station. In the copper station, the photoelectrons contribute to the existing EC multipacting resulting in a signal above $10^{-7}A$. In the *ex situ* NEG station, photoelectrons largely contribute to the electron cloud, reaching a current of $10^{-8}A$. For a-C coating, only photoelectrons are measurable and the signal reaches $10^{-10}A$.

EC AND SR CONTRIBUTIONS

In order to estimate the contribution of photoelectrons during a fill with 25 ns bunch spacing, a simple calculation has been carried out. The model assumes that the whole current measured with a 50 ns bunch spacing is only due to photoelectrons. Therefore, it is possible to estimate the SR contribution to the total electron current with a 25 ns standard beam.

As shown in Figure 8 and 9 for copper and *ex situ* NEG, after ten hours of circulating beams, the recorded current is mainly due to photoelectrons and tends asymptotically to the photoelectron contribution computed from data of 50 ns bunch spacing beams.

For the a-C coated surface (Figure 10), no EC signal is observed at injection energy with 25 ns bunch spacing. Only the photoelectrons contribution due to SR is observed at 6.5 TeV. The slight discrepancy between the data and the computed photoelectron contribution may be due to the simplicity of our model and measurement accuracy.

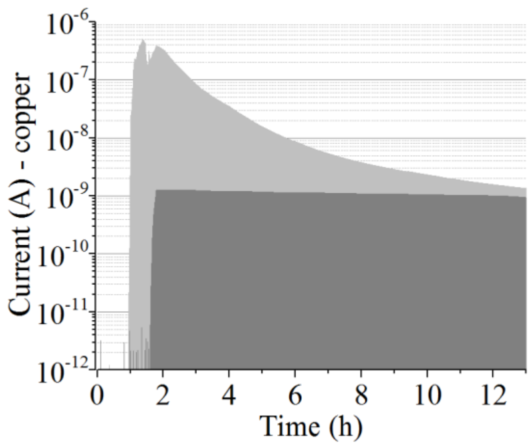

Figure 8: In light grey the EC signal and in dark grey the photoelectrons component of a 25 ns beam for the copper surface.

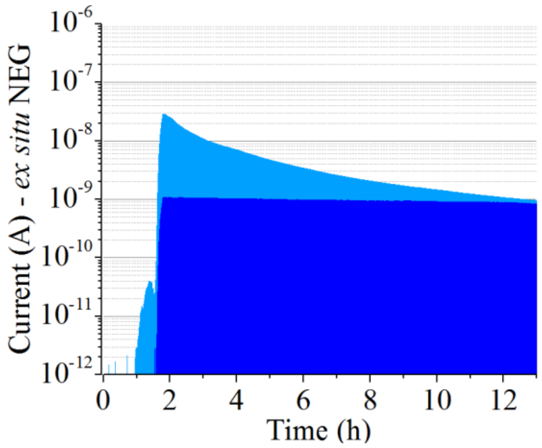

Figure 9: In light blue the EC signal and in dark blue the photoelectrons component of a 25 ns beam for the *ex situ* NEG surface.

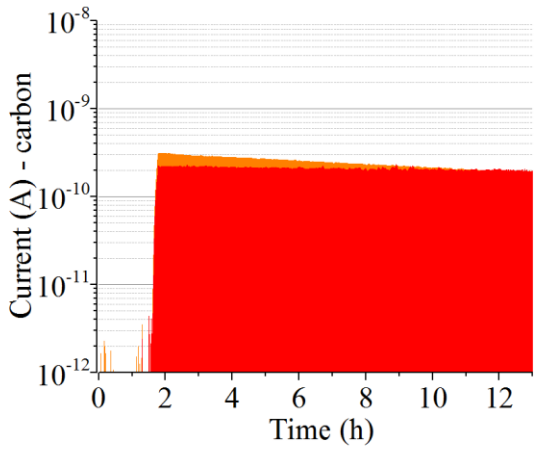

Figure 10: In orange the electron signal and in red the photoelectrons component of a 25 ns beam for the carbon surface.

OSCILLOSCOPE MEASUREMENTS

In addition to the use of a picoammeter that integrate the signal, a fast measurement was also carried out with an oscilloscope coupled with amplifiers and filters.

With unshielded pick-ups, the beam structure signal is then observed (dark blue curve in Figure 11). Here, 12 pilot bunches and 3 batches are shown at injection energy with 25 ns bunch spacing. In light blue, the EC signal of the *ex situ* NEG surface is shown.

The EC signal starts when the first bunch passes in front of the pick-up. Due to the surface reflectivity, some free electrons, called "survivals", remain in the beam pipe in between two bunches. With the passage of the second bunch, the electron density increases. Along the batch, after a few bunches, the EC density grows up to a quasi-stable value.

Between two batches, the EC signal totally disappears and it is restored with the next batch.

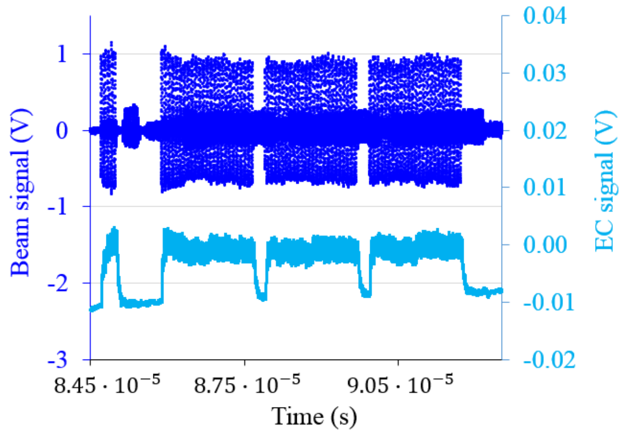

Figure 11: The beam signal recorded by the oscilloscope is displayed in dark blue, while the EC signal for the *ex situ* NEG surface is in light blue.

CONCLUSIONS

In the LHC vacuum system, primary electrons can be generated by beam-gas ionisation or by proton losses. These electrons are accelerated by the beam EM field towards the vacuum chamber wall. Secondary electrons can then be generated on the surface and, if the SEY is above one, the number of free electrons increases. When the LHC bunch spacing is set to 25 ns, the electrons density is amplified at each bunch passage, resulting in a multipacting regime.

The EC dynamics was studied for typical LHC fills, comparing different bunch spacing and surface materials. The EC behaviour is closely linked to the beam current, the beam losses, the bunch length dynamic and the beam energy. The SR generates photoelectrons above 2.8 TeV that have an additional effect on the EC. These two contributions can be disentangled by a simple method. The vacuum behaviour is dominated by EC multipacting when the SEY is high, as for copper, or by photoelectrons if no multipacting is taking place, as for the a-C coating case.

For the first time in the LHC, EC observations were also done in their time domain with an oscilloscope.

Due to its low SEY, the a-C coating results to be the best sample, among the three installed, with no EC multipacting. The only recorded electron current signal is generated by SR via the extraction of photoelectrons.

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