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DUST ANALYSIS FROM LHC VACUUM SYSTEM TO IDENTIFY THE SOURCE OF MACRO PARTICLE-BEAM-INTERACTIONS

L.K. Grob[1] *, C. Neves[2], A. Apollonio, J. Descarraga Busom, C. Charvet, A.T. Perez Fontenla, E. Garcia-Tabares Valdivieso, H. Kos, R. Schmidt[1], CERN, Geneva, Switzerland
[1]also at TU Darmstadt, Germany [2]also at Hochschule Furtwangen, Germany

Abstract

Since in 2010 the first sub-millisecond beam losses were observed at varying locations all along the LHC, it is well known that dust can interact with high-intensity proton beams and cause significant beam losses. Initially the sudden localized losses were enigmatic and coined the phrase “unidentified falling objects” (UFOs), which is still widely used. These very fast beam losses have resulted in hundreds of premature beam dumps and even magnet quenches since the start of LHC. So far, the only mitigation strategy involved an optimization of dump thresholds and the beneficial conditioning effect which leads to a reduction of the UFO rate over time. To understand the physics involved in these events and to allow an active diminution, it is essential to know the chemical composition and the size of the dust particulates interacting with the protons. The exchange of a dipole magnet offered the unique opportunity to collect dust samples from inside the LHC vacuum system. They were extracted from the various components and analyzed by scanning electron microscopy and energy-dispersive X-ray spectroscopy to reveal size distribution and abundant elements. The results of this investigation will optimize the existing UFO models and the improved understanding of the phenomenon may help to prevent future performance limitations. This is also of relevance for future projects, in particular for the Future Circular Collider (FCC) under study.

INTRODUCTION TO MACRO PARTICLE-BEAM-INTERACTIONS

Two types of macro-particle interactions with the LHC proton beams were observed. The most common interaction happens when a solid macro-particle (between 1 and 100 µm in radius) gets into the proton beam. This leads to elastic and inelastic scattering, ionization and finally to the ejection of the macro-particle from the beam [1,2]. The corresponding beam losses can exceed the beam dump thresholds and even cause magnet quenches. A second type of macro-particle beam interactions was identified in 2017, when frozen gas caused localized beam losses in one location (16L2), which were accompanied by a rapidly developing beam instability [3–6]. The source is believed to be successfully removed. This is not the case for the first and most common type of UFO events. The hypothesis of solid macro-particles interacting with the high intensity proton beam was already confirmed by the observations at an injection kicker magnet findings [7]. The origin of the macro-particles in all other parts of the LHC still lacks an explanation.

* laura.grob@cern.ch

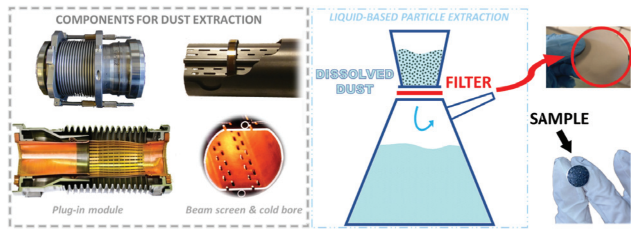

Figure 1: The available UHV components included the plug-in modules (PIMs), beam screen (BS) and cold bore (CB) which are visible in the left part. Liquid-based particle extraction was used to prepare the samples suitable for electron microscopy (middle and right part).

PROCEDURE OF DUST EXTRACTION AND ANALYSIS

At the end of 2016, a dipole magnet was removed from the LHC. This gave the opportunity to collect dust samples from inside the LHC UHV system. By extracting and analysing the particulate contamination, two crucial parameters can be analysed, chemical composition and size distribution for UFO modelling. This information can help to understand the source of the contamination and prevent similar issues in future accelerators such as FCC.

Before the mechanical removal of the dipole magnet, an RF ball test [8] was performed to verify the absence of obstructions in the vacuum chamber. A parasitic dust collection was performed during this procedure (results see Fig.2). Once the dipole magnet was removed, the open apertures of the neighbouring magnets were accessible for a position-sensitive wipe test. Dust extraction from the dipole’s vacuum components (four connecting plug-in modules (PIMs), two beam screens (BS) and cold bores(CB)) required a more complex sample preparation [9] as illustrated in Fig. 1.

The dust analysis was performed by a dedicated software employing scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). A representative fraction of the collected dust was stamped onto a standardized carbon sticker (see Fig.1), which can be directly analyzed without additional treatment. To avoid conglomerates, the surface coverage of the filter substrate was inspected for its homogeneity by optical microscopy before the transfer.

Dust Collection with Vacuum Filter unit (VFU)

After warm-up of sector 12, an RF ball travels through the vacuum chamber by an airflow transporting dust. A special filter unit (VFU) was installed in front of the vacuum pumps.

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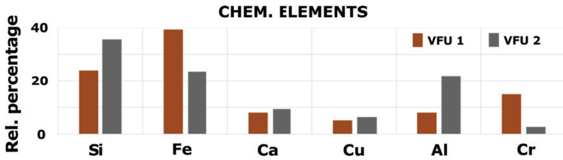

Figure 2: (VFU) EDX analysis results for the two vacuum filter units. The spectra do not reveal information on oxidation states due to the detection limit on light elements. VFU 1 also contained traces of Ti, Ag, F (<0.3% and VFU 2 showed traces (< 0.4%) of Ag and F.

This filter contained the same metallic mesh with a pore size of below 10 µm, also used for the filtration after the liquid-based particle extraction (see Fig. 1).

Fig. 2 shows the chemical composition of the dust collected during the RF ball test. Particles with a size below 5 µm were excluded from the analysis, since their impact on the LHC operation is considered negligible.[1] Iron, copper and chromium are intrinsic materials of the LHC vacuum system, as the majority of the vacuum system is manufactured from stainless-steel and copper. They could be related to remaining macro-particles after production and installation or to wear and tear after assembly. Silicon, calcium and aluminium are considered to have an external origin. Potential sources could be residues from polishing procedures or the airborne particles in the tunnel containing concrete dust, which might have entered during installation and maintenance.

Position-Sensitive Wipe Test

Considering gravity being involved in the UFO mechanism, the particle density inside the beam pipe is of special interest. Directly after the removal of the dipole a wipe test was performed on the open apertures of the adjacent magnets remaining inside the ring. A gloved finger (clean UHV-grade glove) was inserted into the opening to collect a small portion of particles. Those were transferred to the designated carbon stickers and stored in a clean box to prevent external contamination. The different positions of the wipe test are illustrated in Fig. 3 with top (1), right (2), bottom (3) and left (4). So far, the results shown in Fig. 3 only cover one of the four apertures (left aperture of QBBI.A31L2).

The bottom position sticks out with a high amount of indium present in the sample. The three other positions mainly exhibit Al, Si and Ca and only small fractions of gold and indium. The size distribution was analyzed without any size restriction and shows the maximum of particles below the critical diameter of 5 µm, which was chosen as lowest limit for UFO-relevant particulates, see Fig. 4.

Results for Plug-in Modules (PIM)

The plug-in modules compensate expansion and contraction during warm-up and cool-down. They contain gold-coated RF fingers and static RF contacts, which are vacuum

[1] In VFU 1 more than 80 % of the dust particles were below 10 µm and in VFU more than 65 %. Such small macroparticle are unlikely to cause excessive beam losses [2].

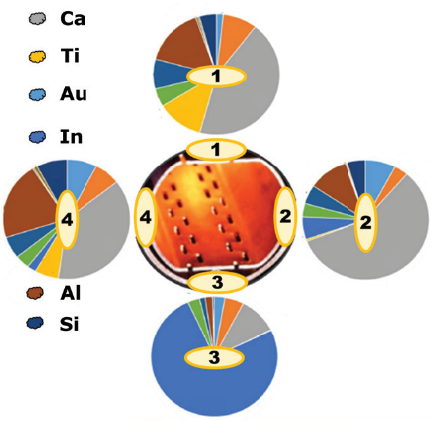

Figure 3: (Wipe test) Beam screen and four positions of wiping. The materials for each position are illustrated by separate pie charts arranged clock-like around the beam screen.

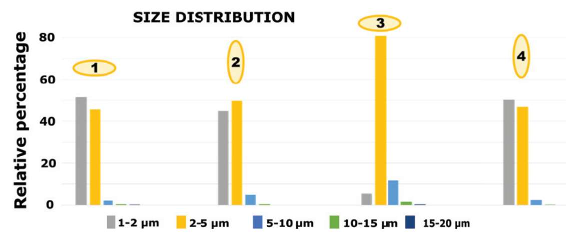

Figure 4: (Wipe test) The size ranges differ from other plots as the samples were the first once to be analysed. Later on, smaller sizes up to 5 µm were excluded. The table includes the total number of particles as a reference.

brazed to the copper structure (refer to the left side of Fig. 1). The relatively high amount of indium found in PIM 2 (compare Fig. 5) could either indicate contamination after manufacturing or flaking during the assembly and thermal cycle due to friction or wear and tear.

Results for the Beam Screen (BS)

About 2 m long ends of the two beam screens were manually cut off and used for other measurements not related to dust sampling. To avoid swarfs entering the beam screen, expanding foam was inserted to bind the loose particulates before fully sealing the beam screens in foil and transporting them into the laboratory. The foam is water and alcohol resistant and its material is not used in LHC (no analysis bias). The findings of the SEM and EDX analysis for the first beam screen can be found in Fig. 6. Comparing the sizes of the analyzed dust, the second part (BS1_2) exhibits a larger amount of small sized particulates in the range below 10 µm and the distribution in BS1_1 suggests that a large number of particles were actually in the excluded range smaller than 5 µm in diameter. This is consistent with the initial findings of the wipe test, where most dust particles were below this value.

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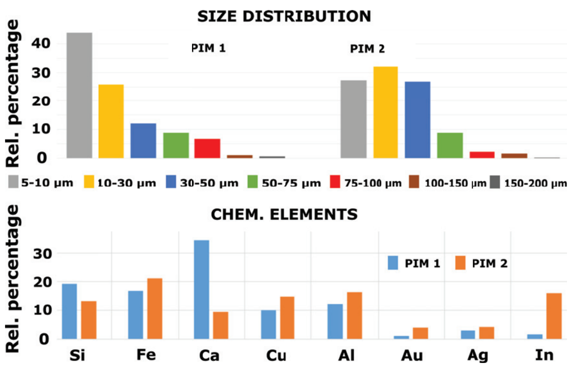

Figure 5: (PIM) The upper part shows the size distributions for particles extracted from PIM 1 and 2. The corresponding chemical composition can be found directly underneath.

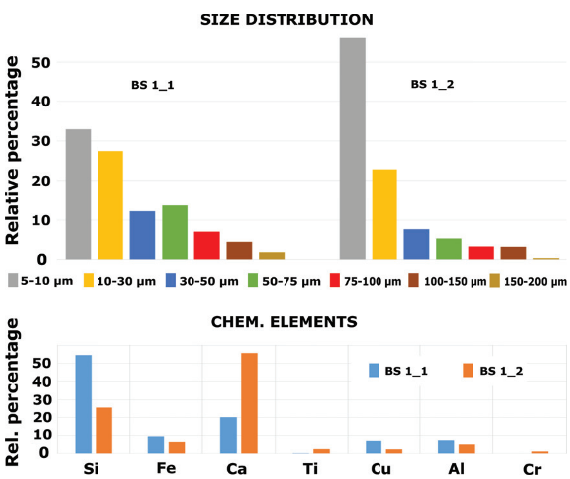

Figure 6: (BS) The size distribution of the dust is shown in the upper part and differs between the two pieces of BS1. The EDX spectra revealed similar elemental composition for the dust found in BS1_1 and BS1_2, but the peaks in Si and Ca seem complementary.

Results for the Cold Bore (CB)

The challenge of cleaning a 16 m long pipe with a radius of 5 cm was overcome by the use of electrostatic dusters as used in household cleaning. A train of three clean dusters was pulled through the pipe and subsequently packed for particle extraction. One of the magnet bores had been opened and measurements were performed involving a chariot being run through the pipe. The impact of such an intervention can be estimated from the comparison of the two apertures.[2]

The elemental composition shown in Fig. 7 contains the same species of particles, but their relative numbers differ between the apertures. This is consistent with the fact that V2 was already opened for magnetic measurements and a tool had been pulled through the pipe bringing in additional contamination. The respective size distributions for the particulate contamination collected from the two vacuum pipes seem very similar over the course of the three dusters, independent of the intervention on vacuum line V2. This indicates that the external contamination brought in by the measurement procedure is comparable with the one already present inside the cold bore.

[2] Due to the short time available, the dusters had been still slightly wet from the cleaning and during storage time the internal steel rod had oxidized and contaminated the samples with rust, hence the iron content of the samples was neglected in the interpretation of the results.

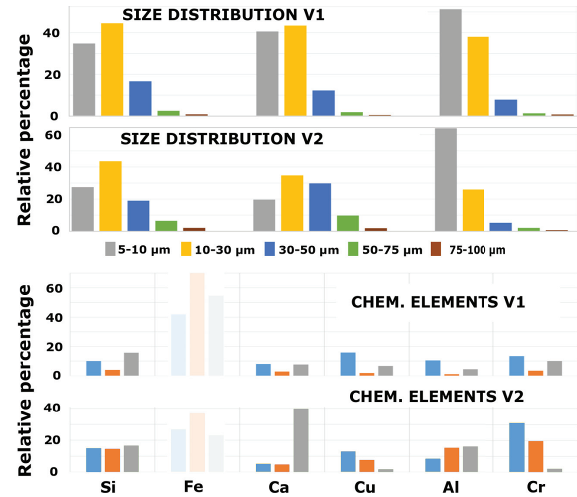

Figure 7: (CB) The top part shows the size distribution for V1 and V2. The results for each of the 3 dusters are grouped into one column. Iron is excluded. The lower part shows the percentage of the most abundant elements and shows the probable contaminants introduced by the measurement in V2.

CONCLUSION

Dust samples were collected from various LHC vacuum components (cold bore, beam screen, plug-in modules) and analyzed by scanning electron microscopy. The particulate contamination is known to cause beam losses leading to beam dumps and magnet quenches and the analysis results will improve existing models to find operational settings that minimize the impact on beam operation. The particulate contamination within the LHC vacuum system mostly consists of small sized macro-particles. At LHC, such macro-particles are quickly ionized and result in rather small beam losses. For FCC, simulations are required to understand if such small macro-particles could cause unacceptable beam losses. The chemical composition of the dust samples varies over the components. This could be related to the different manufacturing processes and materials used. For the plug-in modules also wear and tear could explain the relatively high amount of indium macro-particles. The Ca-, Al- and Si-based contaminants were present in all samples and could be originating from the concrete dust inside the tunnel or the manufacturing environments, since the LHC was not assembled under clean-room conditions.

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