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TOWARDS THE IMPLEMENTATION OF LASER ENGINEERED SURFACE STRUCTURES FOR ELECTRON CLOUD MITIGATION

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Abstract

The LHC operation has proven that the electron cloud could be a significant limiting factor in machine performance, in particular for future High Luminosity LHC (HL-LHC) beams. Electron clouds, generated by electron multipacting in the beam pipes, lead to beam-induced heat load in cryogenic systems. Laser Engineered Surface Structures (LESS) is a novel surface treatment, which changes the morphology of the internal surfaces of vacuum chambers. The surface modification results in a reduced secondary electron yield (SEY) and, consequently, in the reduction or eradication of the electron multipacting effects. Low SEY values of the treated surfaces and flexibility in choosing the laser parameters make LESS a promising treatment for future accelerators. LESS can be applied both in new and existing accelerators owing to the possibility of automated in-situ treatment. This approach has been developed and optimised for selected LHC beam screens in which the electron cloud has to be mitigated before the HL-LHC upgrade. We will present the latest steps towards the implementation of LESS.

LHC VACUUM SYSTEM AND ELECTRON CLOUD PHENOMENON

The whole accelerator complex of CERN hosts the longest accelerator vacuum system in the world, with over 124 km of vacuum lines [1]. Half of it belongs to the LHC beam vacuum system with two beam lines 27-km long each, evacuated down to $10^{-10} \div 10^{-11}$ mbar. The most crucial components of this system are the beam screens that are located inside the beam pipe in the cold sections of the LHC. The main role of the LHC beam screens is to shield the beam pipes, at an operational temperature of 1.9 K, by intercepting the heat loads generated by the beam such as synchrotron light, energy loss by nuclear scattering, image currents and electron clouds, ensuring the vacuum stability.

The beam screens are made of 1-mm thick sheet of special grade of stainless steel with very low magnetic permeability, which is then co-laminated with a 75-µm thick high purity copper sheet in order to reduce impedance and improve thermal properties. The beam screens are actively cooled (operational temperature 5 ÷ 20 K) by two capillaries that are directly welded to their walls. This imposes a racetrack shape for the beam screens, optimized to fit into the circular beam pipes (Fig. 1). Since the beam pipes sizes vary along the LHC, also the beam screens have different dimensions depending on their position in the vacuum system along the accelerator.

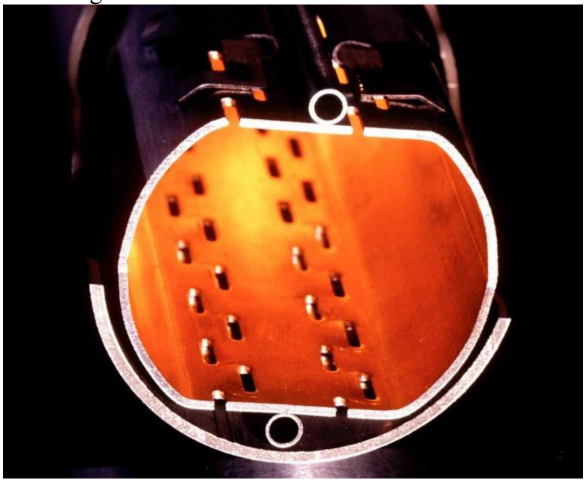

Figure 1: The LHC beam screen.

The mechanism of liberating multipacting electrons from the beam vacuum chamber surface, which is at the origin of the electron-cloud build up, is known and observed in many accelerators worldwide. With increasing beam intensity of modern machines, it has become a limiting factor in the operational performance of high energy accelerators, causing instabilities of the beams, increase of pressure in the vacuum chambers and excessive heat loads [2].

The electron multipacting can be reduced or eradicated by reducing the secondary electron yield (SEY) of the surfaces exposed to the beam. The SEY is the ratio of the number of electrons emitted from the surface (secondary electrons) to the number of incident electrons (primary electrons) and is a surface property that depends on surface state (oxidation, contamination), but also on the energy of primary electrons. In order to eliminate the electron multipacting and avoid the electron cloud formation, one should maintain all surfaces facing the beam in such a state that the SEY stays low, ideally not exceeding a unity value of 1.

There are several solutions that have been developed, tested and successfully applied to deal with electron clouds such as conditioning the surface by electron bombardment (scrubbing), depositing on the surface of a material with a low SEY or increasing of surface roughness [3]. For example, the Super Proton Synchrotron (SPS) vacuum system at

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CERN is being upgraded in order to inject 25 ns bunch spaced beams of higher intensity in the LHC by using amorphous carbon coating [4] of the inner surface of critical beam pipes. Vacuum chambers in selected magnets are treated in-situ by inserting a train of segmented graphite hollow cathodes. In addition for the LHC accelerator the beam screen scrubbing process became a standard procedure to condition the vacuum system at the beginning of each yearly operational run.

The High Luminosity LHC (HL-LHC) is a novel configuration of the Large Hadron Collider, aiming at increasing the luminosity by a factor five, or more, above the nominal LHC design. The integrated luminosity, in the experiments ATLAS and CMS will increase from the 300 fb^{-1}, of the LHC original design, up to 3000 fb^{-1} or more [5]. In order to achieve this goal, an upgraded version of the focusing quadrupoles will be installed in the insertion region around ATLAS and CMS. The new magnets around ATLAS and CMS will be equipped with vacuum chambers designed and optimized for high intensity beams, with the appropriate electron cloud mitigating treatment already implemented ex-situ (currently amorphous carbon coating as a baseline solution). However, no changes will be made for the magnets around the ALICE and LHCb experiments, which means that all the systems in these regions, including vacuum and cryogenics, will face much higher beam intensities than they were initially designed for. It is therefore essential for the HL-LHC upgrade to supress the electron clouds, which are nowadays the major contributors to the heat loads in the LHC. The magnets around ALICE and LHCb must be treated in-situ, for minimal disruption of the configuration and for scheduling reasons.

LASER ENGINEERED SURFACE STRUCTURES (LESS) TREATMENT

LESS supresses the electron clouds by taking advantage of morphological modifications of the surface [6-7]. The micro-structures, created by laser ablation, trap emitted electrons and mitigate the multiplication effect. There are several patterns of treatment possible, however for practical application the most convenient ones are with parallel grooves for flat samples (Fig. 2) and spiral patterns for tubes. Feasibility studies have been done to demonstrate the benefits of LESS treatments in prototype liners [8] and in a beam screen, installed at the SPS in the COLDEX facility [9], with very encouraging results.

The LESS treatment of copper flat samples used for surface characterization and for the accelerator tests is done by a linearly polarized 10 ps pulsed laser beam with a wave-length of 532 nm, at a repetition rate of 200 kHz and a maximum average power of 25W.

The mitigation based on LESS can be more easily implemented in long beam pipes by optical fibre transmission and dedicated optical focusing. The big advantage of LESS structuring is the possibility to perform it in air or inert gas. It significantly simplifies the procedure when doing in-situ treatments inside existing accelerator vacuum chambers. Additionally, by controlling laser powering, a selective treatment is possible of complex elements with treatment-sensitive components, such as electrodes in beam position monitors.

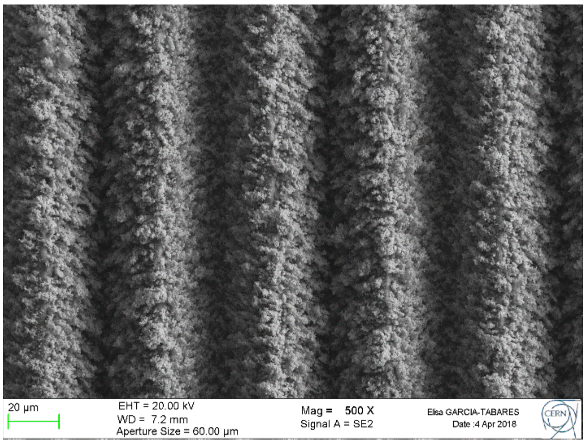

Figure 2: Top view of LESS treated surface.

CHALLENGES OF THE LHC BEAM SCREENS IN-SITU TREATMENT

Beam Screen Shape

The first challenge of the LHC beam screen LESS treatment is its racetrack shape. The treatment of the COLDEX beam screen, with a circular cross section, simply required to choose the optical parameters in such a way that the laser beam was focused on the internal surface of the beam screen. In the case of the LHC beam screens, the distance between the surface and the treatment head varies on the flat part of the surface and must be compensated by choosing correct laser parameters.

Given the effective internal radius of the beam screen was variable, it was essential to select an optical configuration, which would allow minimal variation in the treatment at each surface location. This was accomplished by selecting optical equipment and parameters which would result in as large a spot size as possible in order to have as long a Rayleigh range as possible (the distance from the beam waist at which the cross sectional area is doubled). This range is in turn limited by the minimum fluence (laser power per unit surface) which will allow effective laser treatment of the copper surface. In other words, whilst a larger beam waist will provide a greater Rayleigh range, it will also require more average laser power (this requirement grows with the waist radius squared) to realise the equivalent fluence at the copper surface, which is limited primarily by the maximum average power (currently 25W) of the laser source used.

Treatment depth

Taking into account the thickness of the copper layer on the internal surface of the LHC beam screen (75 µm), the depth of the LESS treatment becomes an important parameter (Fig. 3). In order not to affect the required electrical and thermal properties of the beam screen, the maximum allowed depth of the treatment is 25 µm. The

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treatment depth depends directly on the chosen laser fluence and number of pulses per spot. However, lowering of the laser fluence results in a smaller area to be effectively covered by the micro-structures and this can produce an increased SEY. The solution is to compensate this effect by varying the hatch distance. For each chosen fluence, there exists an optimal distance between the grooves. A too small hatch distance causes partial reflection of the laser beam by the already-treated surface that reduces the effective power deposited on the surface, whereas a too large hatch distance results in untreated areas in between the grooves that increases the SEY. Optimization of the process for the ALICE and LHCb beam screens is currently ongoing.

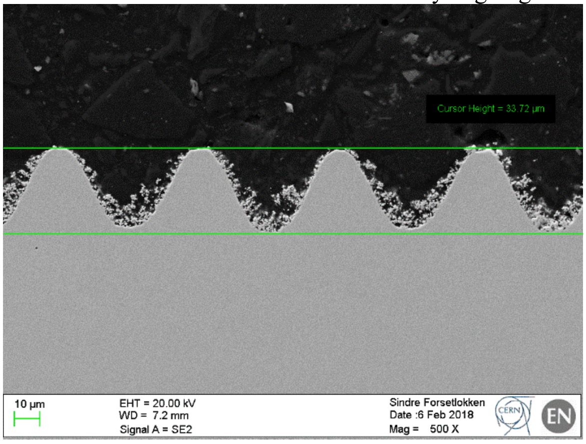

Figure 3: Cross-section of LESS treated surface.

In-situ Treatment

Finally yet importantly, the in-situ treatment must be carried out in relatively long (up to 15 meters) and narrow pipes, which means that the laser light must be delivered over long distances in a very limited space. For the in-situ treatment of the LHC magnets, the access to the beam screens is limited to a 15-cm long entry slot created by dismantling part of removable interconnection unit called plug-in module. Additionally, the chosen pattern of grooves requires high precision in treatment head movement. All these requirements led to a sophisticated hardware and software development, namely the optical fibre with the beam delivery system, the robot that carries the fibre and provides the treatment inside the beam screen and the control system that manages the whole process.

The optical fibre selected for a first-trial basis was a 6m-long photonic crystal fibre with a mode-field diameter of 14µm. The fibre loss at 532 nm wavelength is 250 dB/km. The laser beam was coupled into the fibre at approximately 80% transmission efficiency via a bespoke Beam Delivery System (BDS) which allowed for the evacuation of the entire fibre in order to reduce transmission instabilities and optical nonlinearities. The fibre was terminated with a bespoke lens which allowed for a fully collimated beam to be utilised within the robot. This collimation lens, situated at the focal length from the fibre tip, was encased in a bespoke fibre head, designed to be installed within the robot.

The LESS treatment robot is a novel solution designed and manufactured by an industrial contractor for the in-situ treatment of the LHC beam screens (Fig. 4). The dimensions of the robot are limited longitudinally by the interconnection entry slot and by the beam screen cross-section shape. The robot moves along the beam screen using the inchworm movement principle, by means of a pneumatically-driven clamping system. The robot movement along the beam screen is disentangled from the treatment head movement that is carried out by an electrical motor coupled with a precision driving screw. During LESS structuring the robot remains rigidly clamped to the beam screen and only the rotating treatment head moves longitudinally engraving the spiral pattern in the beam screen.

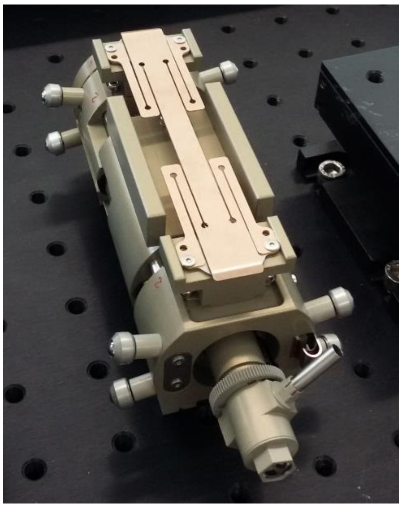

Figure 4: The LESS treatment robot.

IN-SITU TREATMENT SET-UP

The in-situ LESS set-up is composed of the laser, the BDS, the optical fibre and the robot. An integrated control system allows the enabling of the laser when the robot is clamped in stable position and provides the interlock matrix to catch anomalies and avoid damages.

The whole LESS treatment system was commissioned at the University of Dundee and a first trial treatment was performed in the biggest of LHC beam screens, so called Type 74, with the diameter of round parts of 70.65 mm and distance between the flat parts of 60.95 mm (Fig. 5).

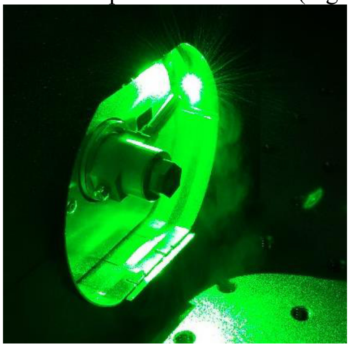

Figure 5: The first treatment of the LHC beam screen.

CONCLUSION

In addition to the evident benefit for the HL-LHC upgrade, the LESS solution would be useful for any other accelerator suffering from electron cloud phenomena, in particular the LHC injection chain at CERN, but also for other existing and future accelerator facilities in the world. In the future, it could be considered as a standard treatment for multipacting suppression.

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