LARGE SCALE PRODUCTION OF AMORPHOUS CARBON COATINGS FOR THE NEW BEAM SCREENS OF THE HL-LHC PROJECT

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Abstract

The new beam screens for the High Luminosity LHC (HL-LHC) will be coated with a low Secondary Electron Yield (SEY) amorphous carbon (a-C) thin film to suppress electron multipacting and reduce heat loads to the cryogenic system. The production will cover 40 beam screens for the new superconducting magnets of the inner triplets in LHC interaction region 1 (hosting the ATLAS experiment) and 5 (hosting the CMS experiment), as well as 24 beam screens for the drift line of the cryomodules housing the radio frequency CRAB cavities. This contribution presents the implementation of a large-scale coating facility dedicated to the deposition of a-C films on the various HL-LHC beam screens, adaptable to different geometries and lengths up to 14 meters. The rationale behind the chosen coating technology and process parameters is discussed, with emphasis on adhesion optimization, SEY minimization, and production throughput to meet the HL-LHC schedule. We report on the current status of the production campaign, including quality assurance statistics, and highlight the main challenges encountered together with the solutions adopted.

INTRODUCTION

The emission of secondary electrons from carbon thin films depends strongly on their microstructure. Films with a higher fraction of carbon atoms bonded with sp^2 hybridization exhibit lower secondary electron emission, reaching SEY values below 1, while higher fractions of sp^3 bonding may lead to SEY values above 2 [1,2]. Low-SEY amorphous carbon (a-C) coatings have been produced on a large scale by sputtering from graphite targets, usually using Ar as the discharge gas [3]. However, hydrogen contamination, originating from impurities in the discharge gas and outgassing of the coating system, promotes the formation of the sp^3 phase and consequently increases SEY values.

To overcome this issue, particularly when the coating system cannot be baked, two approaches have been investigated: the addition of a small percentage of N_2 to the Ar discharge gas [4], and the co-deposition of a getter material [5]. The latter solution was adopted to coat the new beam screens for the HL-LHC project. In addition to the gettering effect, the deposition of a titanium pre-layer enhances the adhesion of the carbon coating to the copper surface of the beam screens [5].

The beam screens are made of stainless-steel sheets, providing structural strength, with a copper cladding to reduce the resistive wall impedance [6]. Details and dimensions are given in Table 1, and Fig. 1 shows beam screens installed in the coating bench. The beam screens for the CRAB cavity cryomodules are relatively short and are coated in pairs inside a vacuum vessel. The longer beam screens for the new magnets in IR1 (ATLAS) and IR5 (CMS) are coated individually inside a vacuum chamber. They will equip the new inner triplet region magnets, composed of quadrupoles Q1, Q2a, Q2b, and Q3, a corrector package (CP), and the separation dipole magnet D1. The beam screens in the D2 dipole magnet, with two separate beam pipes, will also be coated. These beam screens, except those in D2, are shielded with tungsten blocks to protect the magnet coils from secondary particle showers originating at the interaction point and can weigh up to 300 kg.

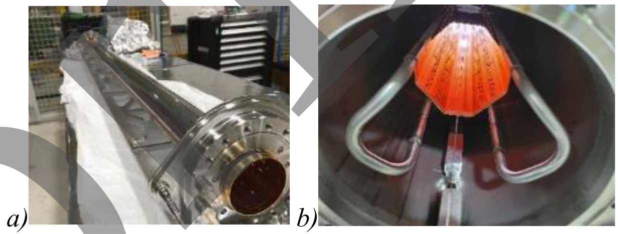
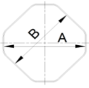


Figure 1: a) set of 2 crab cavity beam screens before coating. b) Triplet magnet beam screen before coating.

Table 1: Beamscreen Number, Dimensions and Status (4/26)

Magnet	BS type	Nb	Shape	Dim (mm)	L (mm)	aCC Status
CRAB	**DQW**	12	Circular	ID 70.1	800	done (2024)
	RFD	12			1 019	done (2024)
ITL	**Q1**	5	Octogonal	99.7 x 99.7	10 723	2/5
	Q2a	5		119.7 x 110.7	10 292	6/10
	Q2b	5				
	Q3	5			10 607	1/5
	CP	5			7 461	3/5
	D1	5			8 499	1/5
	D2	10		86 x 77	14 083	6/10

COATING PROCESS AND TECHNOLOGY

The coating is performed by magnetron sputtering and involves three main steps: surface preparation by argon ion etching, deposition of a titanium pre-layer, and deposition of the functional amorphous carbon layer. After coating, the beam screens are pumped and stored under a nitrogen atmosphere.

Coating Technology

The sputtering device is a mobile trolley, known as a “train”, composed of two targets (Fig. 2a): one graphite and one titanium. The assembly is mounted on rolling supports to keep it centred within the beam screen and to allow smooth axial displacement.

The targets are biased independently via two coaxial Kapton-insulated wires and incorporate encapsulated

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permanent magnets (SmCo, with $T_{\mathrm{Curie}} = 290°\mathrm{C}$) to provide the magnetic field required for magnetron operation without active cooling. Stainless steel cables are attached to both ends and used to displace the train. These cables and wires are wound onto four individual reels located in differentially pumped vacuum chambers at the extremities of the beam screen and are driven by stepper motors.

A central control system based on LabVIEW® controls the motors, the plasma power supplies, and the pressure gauges. It also includes laser encoders to monitor reel movement and detect cable rupture or motor stalling. The system can generate interlocks to stop the discharge and motors and send notifications in case of deviations from operating parameters. The argon pressure is controlled remotely via independent software.

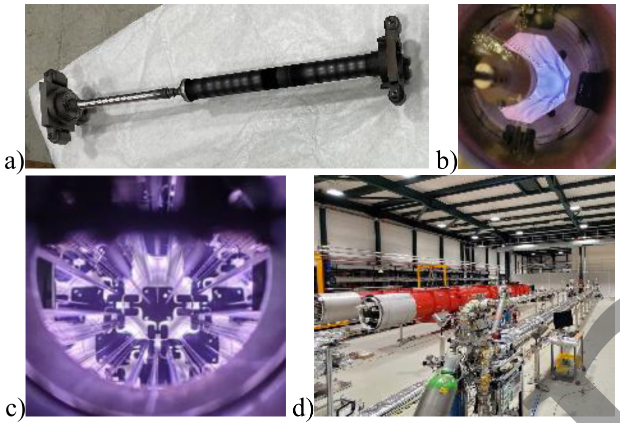

Figure 2: a) Coating train with carbon and titanium targets; b) etching ongoing with central titanium wire; c) train coating inside a beam screen with argon plasma and cables visible; d) two coating benches installed next to 2 triplet quadrupole magnets await.

Although a carbon thickness of 10 nm is sufficient to fully suppress secondary electron emission from the substrate and achieve SEY ≈ 1 [7], the nominal thickness used in production is 100 nm. This provides a safety margin against inhomogeneities related to surface roughness and large-scale processing, without affecting the HL-LHC impedance budget [8, 9].

For titanium, the thickness ranges from 80 to 500 nm to ensure adhesion, provide hydrogen gettering, and remain compatible with impedance constraints [10]. For a given beam screen geometry, the film thickness is controlled by the plasma discharge power and the speed of the train.

Surface Preparation by Argon Ion Etching

Coating adhesion is critical: interaction of the proton beam with flakes resulting from delamination can generate secondary particle showers, potentially causing magnet quenches and beam dumps, thereby affecting machine availability.

The first atoms of the deposited film bind to an oxidized copper surface. Due to thermodynamic considerations, carbon does not form strong bonds with copper oxides, whereas titanium exhibits a strong affinity for oxygen. Therefore, titanium is used as an adhesion layer.

However, the adhesion of titanium films deposited on copper surfaces exposed to ambient air for extended periods (>3 months) shows variability due to the formation of copper hydroxides. Surface analyses confirmed a correlation between reduced adhesion strength and the presence of hydroxides [5], consistent with DFT (density functional theory) calculations [11].

To address this issue, the oxide layer is reset prior to coating through argon ion bombardment, followed by controlled re-oxidation using synthetic air (80% N_2, 20% O_2). This treatment ensures stable and reproducible adhesion, even after repeated thermal cycling to 77 K [5].

Ion etching is performed by DC argon glow discharge in coaxial configuration, using the beam screen as cathode and a central titanium wire as anode. For short beam screens, the discharge operates in diode mode, while for long beam screens it is confined using a movable external solenoid, improving process control. The discharge parameters are detailed in Table 2 and the nominal ion dose applied is $\sim 2\times10^{10}$ $\mathrm{Ar^+/s/cm^2}$.

Before etching, the system is baked at 120°C for 48 h. After etching, it is cooled for 12 h before venting with synthetic air and installing the coating train.

Pre-layer of Titanium

After ion etching, the sputtering device is inserted and connected. The system is pumped and baked again for 48 h at 120°C. After cooling, a base pressure of $\sim 10^{-8}$ mbar is reached. High-purity argon (quality 60) is then introduced, and the titanium target is ignited to deposit a layer of approximately 80 nm. Coating parameters are displayed in Table 2.

Amorphous Carbon Layer

After the titanium deposition, the train is returned to its starting position, and a second pass is performed to deposit the ~100 nm carbon layer. During this step, the titanium target is intermittently activated to deposit fresh titanium, which acts as a getter for hydrogen. This titanium is immediately covered by carbon as the train progresses.

Due to the low sputtering yield of carbon, this step can take up to four days (Table 2).

Table 2: Plasma Parameters and Coating Time

	P (W)	U (V)	p (mbar)	Thickness (nm)	t
Etching	50	~ 280	8.0E-03	~ 200	~ 5 h
Ti pre-layer	20	~ 300	8.0E-03	~ 80	~ 40 h
Ti flashes	20	~ 310	1.30E-02	~ 80	~ 4 d
C coating	75	~ 300		~ 100	

After coating, the system is cooled, vented with synthetic air, and the coating train is removed. Beam screens for CRAB cavity cryomodules are wrapped in aluminium foil and stored under nitrogen [12], while those for the inner triplet magnets are pumped and stored at 1 bar nitrogen until installation.

Quality Control

Visual inspection of the inner surfaces is performed before and after coating using a camera system. This allows evaluation of oxidation state, contamination, and coating defects.

During coating, a residual gas analyser monitors gas composition to detect hydrogen-containing species.

Witness samples placed at both ends of the beam screens allow systematic measurements of SEY and titanium thickness (via XRF). If the SEY exceeds 1.1, surface chemistry is analysed by XPS. Carbon thickness is occasionally verified by SEM/FIB, and adhesion is evaluated using the crosshatch test (ASTM D3359 / ISO 2409).

RESULTS AND DISCUSSION

The production of the 24 beam screens for CRAB cavity cryomodules was completed in 2024. Only two beam screens exhibited SEY values above 1.1 (Fig. 3a). Although slightly above specification, conditioning during beam operation is expected to reduce this SEY to below 1.1 with an electron dose less than 10^{-4} C/mm^2 [5], and these beam screens were therefore accepted.

One beam screen exhibited an excessive titanium thickness (570 nm) due to human error. Although non-conforming, it was accepted because its short length (~1 m) results in negligible impact on impedance [10]. Interestingly, this sample showed the lowest SEY value (0.83) in the production.

Production for the inner triplet magnet beam screens started in December 2024. As of April 2026, 19 beam screens have been coated. The process demonstrates excellent reproducibility, with SEY values between 0.92 and 1.02 (Fig. 3a), indicating effective hydrogen gettering. Titanium thickness ranges from 100 to 250 nm (Fig. 3b).

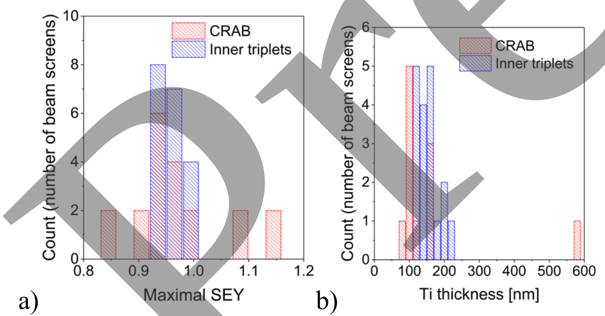

Figure 3: Histograms with the a) maximal SEY; b) Titanium thickness.

Production throughput has improved significantly over time. Early technical issues, such as electrical contact loss, mechanical failures, and actuator malfunctions, extended coating runs to four weeks. After system improvements, the duration was reduced to approximately three weeks, allowing production to match the delivery rate of beam screens.

Initial inspections revealed dust contamination and oxidation stains on some beam screens. In the most severe cases, dust levels were reduced using dedicated tooling, and ion etching parameters were adjusted to treat heavily oxidized surfaces. No delamination has been observed after coating.

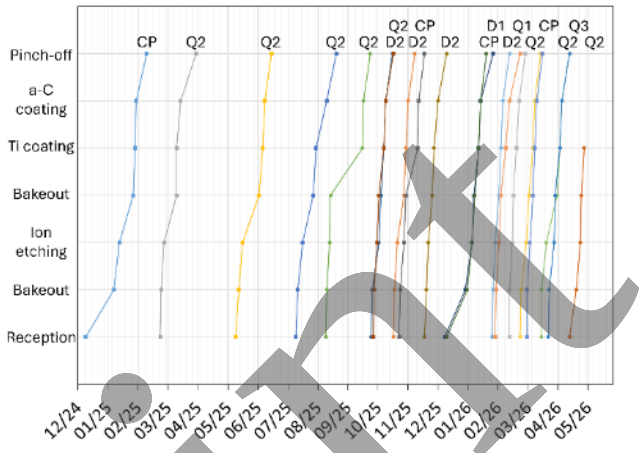

Figure 4: Dashboard showing the evolution of the coating process for the beam screens for the inner triplet magnets (As of April 2026).

CONCLUSIONS

A dedicated facility for large-scale deposition of amorphous carbon coating on HL-LHC beam screens has been successfully implemented at CERN. The combination of argon ion etching and titanium interlayer deposition ensures reliable adhesion and low SEY values.

To date, 43 out of 64 beam screens have been coated (24 for CRAB cavities and 19 for inner triplet magnets, Fig. 4), with only one non-conformity related to titanium overthickness. The process consistently achieves SEY values below 1.1 with no observed delamination.

With a production rate of approximately two beam screens per three weeks, the remaining 20 beam screens (including spares) are expected to be completed in line with the HL-LHC installation schedule.

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