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# Joint ATLAS/CMS ZDC upgrade project for the High Luminosity LHC

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**Abstract.** The High Luminosity LHC (HL-LHC) provides the opportunity to study heavy ion, proton-nucleus, photon-nucleus and photon-photon collisions with unprecedented luminosities at the TeV scale. The LHC heavy ion community has mapped out an extensive range of physics measurements at the HL-LHC that will push forward our understanding of both QCD, QED and even electroweak physics. The measurement of forward neutrons and photons in Zero Degree Calorimeters (ZDCs) is essential for event classification and triggering. In order to reach the required luminosities, the LHC interaction regions will be redesigned, necessitating the need to build new ZDCs that will be both narrower and much more radiation tolerant. This challenge motivated the formation of a joint project between ATLAS and CMS to build new ZDCs for Run 4, JZCaP. The ZDCs are based on radiation-hard fused silica rods that produce Cherenkov light. These rods have been developed by Heraeus Quartzglas in collaboration with JZCaP and the LHC BRAN and FLUKA groups. The Run 4 ZDCs (HL-ZDCs) are the first joint detector project between CMS and ATLAS. This talk will present the capabilities of the new ZDCs and recent R&D highlights.

## 1 Introduction

Zero Degree Calorimeters (ZDCs) played a central role in the success of the Heavy Ion (HI) physics programs of the ATLAS [1] and CMS [2] experiments during LHC Run 1 and 2. The ZDCs detect far-forward neutral particles produced in A+A and $p$+A collisions, which are mostly spectators from the interactions, enabling the possibility to distinguish between different classes of physics processes by looking at forward neutron topologies. Central and mid-central A+A collisions are characterized by the detection of several spectator neutrons in both arms of the ZDC (XnXn topology). In peripheral and ultra-peripheral (UPC) A+A collisions and $p$+A collisions, the absence of neutrons in one (Xn0n or 0nXn) or both of the ZDCs (0n0n) typically indicates that the corresponding nucleus likely did not interact hadronically and, instead, emitted a coherent photon or coherent pomeron. The measurement of the single-neutron peak is the primary tool used to calibrate the energy scale of the calorimeter (with two- and three-neutron peaks complementing the calibration). Therefore, the ability to resolve the 1n and subsequent peaks is essential for achieving a well-controlled energy scale.

In both the ATLAS (IP1) and CMS (IP5) interaction regions, the ZDC is installed in a dedicated slot in the Target Absorber for Neutrals (TAN). The TANs are radiation absorbers

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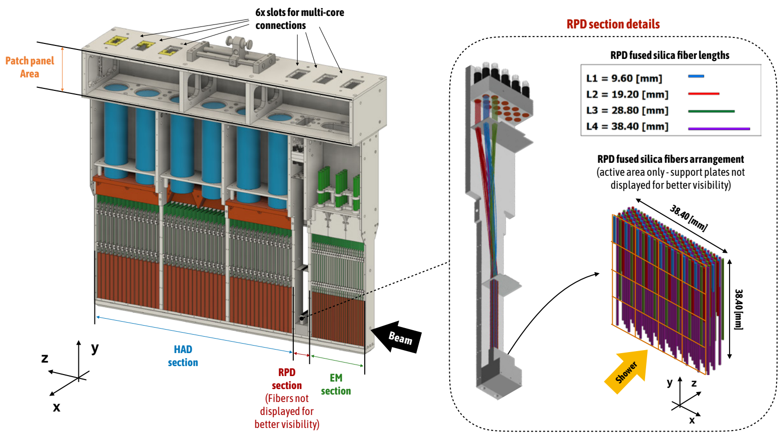

**Figure 1.** Left: HL-ZDC detector design. Right: detailed view of the RPD section.

aimed at shielding the downstream superconducting magnets from forward neutral particles emerging from the IP. The high luminosity upgrade of the LHC, HL-LHC, will necessitate substantial modifications to the LHC optics. The recombination chamber will be moved 13 m closer to IP1 and IP5 and, as a consequence, the existing TAN will be replaced by a new absorber, the TAXN [3], that will require a substantially-reduced separation between the beam pipes, resulting in only 4.6 cm available in the transverse direction for the implementation of the upgraded ZDC (HL-ZDC). The higher collision rate and the closer position to the IP will also increase the radiation levels in the TAXN. Thanks to detailed simulations provided by the CERN FLUKA group, it was possible to estimate the peak dose that will be accumulated by the HL-ZDC. Taking into account all the HI-related data taking foreseen in Run 4, a peak dose of 4.5 MGy is expected to be registered in the detector, in correspondence with the active area. Therefore, the identification of a radiation-hard Cherenkov radiator is a crucial step in the finalization of the HL-ZDC design.

The harsh radiation environment of the HL-LHC also introduces radio-protection (RP) implications to be taken into account while designing the HL-ZDC and planning its installation. After running dedicated simulations, the CERN RP team has estimated an ambient dose equivalent rate of $\sim 800$ $\mu$Sv/h near the TAXN after a week of technical stop [4], the typical cool-down time preceding the ZDC installation. Such a high dose equivalent rate imposes a detector design that is easy to handle and connect, in order to minimize the exposure for personnel involved in the operations.

The HL-ZDC design will also include a common Reaction Plane Detector (RPD) section. By mapping the transverse profile of the neutron showers, the RPD will be capable of measuring the direction of the reaction plane on an event-by-event basis, enabling a set of collective flow measurements carried out using the same detector in both ATLAS and CMS.

## 2 HL-ZDC design

A three-dimensional view of the current design of the HL-ZDC is shown in Figure 1. Contrary to the existing ZDCs, the HL-ZDC is characterized by a single-unit structure to facilitate efficient detector handling during the installation procedure. Starting from the interaction point (IP) side and proceeding along $z$, one can identify three different sections:

- Electromagnetic (EM) section.

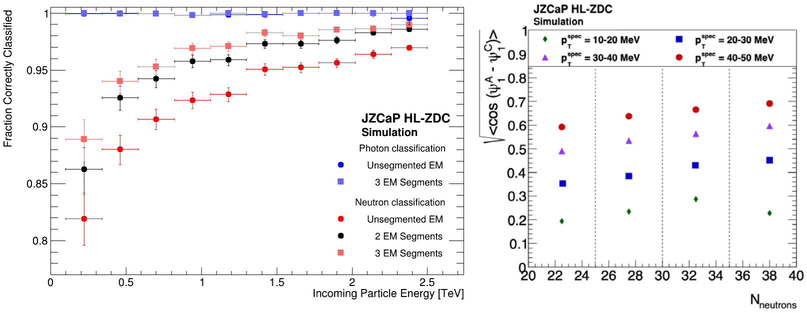

**Figure 2.** Left: HL-ZDC detector design. Right: detailed view of the RPD section.

- Reaction Plane Detector (RPD) section.
- Hadronic (HAD) section.

In all three functional components, detection is based on Cherenkov light emission in high-purity, ultra-radiation-hard fused silica material. The EM and HAD sections are calorimeters with different sampling ratios, while the RPD consists of an array of fused-silica fibers of different lengths that map the transverse profile of the shower produced within the EM module.

The EM section is the first part of the HL-ZDC encountered by particles originating in the IP. The active region consists of layers of fused silica rods (25 each of 1.5 mm diameter and 275 mm height), alternating with 4 mm thick W plates. The EM is equipped with 25 W plates, corresponding to $\sim$ 30 radiation lengths, and 1 nuclear interaction length. Above the tungsten plates, the fused silica rods are guided by stainless steel plates located atop the tungsten. The HL-ZDC EM module light signal is read out in 4 horizontal and 3 longitudinal segments. The segmentation is implemented via Winston-Cone-shaped [5] air light guides that collect and re-direct the light generated in each element toward the corresponding Photomultiplier tube (PMT). The segmentation in the longitudinal direction enhances photon-neutron discrimination, as shown in Figure 2 left panel. By contrast, the horizontal sections enable locating the beam position in the case of horizontal crossing angles.

The RPD is sandwiched between the EM and HAD section, and is characterized by a "Pan Flute" geometry (see Figure 1, right panel), proposed to optimize the light-collection mechanism and to have a detector core that is fully radiation-hard. This implementation is analogous to the ATLAS Run 3 RPD, recently constructed and tested with the beam at the CERN SPS. The RPD active region is comprised of 256 radiation-hard fused silica fibers arranged as a virtual 4×4 array of square tiles, each with an area of 9.60 mm$^2$. Since the structure of the RPD signals can be interpreted as pixels of an image, machine learning (ML) based pattern recognition techniques are planned to reconstruct the RP. The RPD will provide large data samples characterized by high dimensionality and complex dependencies between inputs and outputs. These conditions are suitable for applying deep learning techniques, such as convolutional neural network (CNN). The right panel in Figure 2 shows the RP resolution achievable by applying CNN reconstruction algorithms to the RPD signals, estimated by means of MC simulations. The RP reconstruction performance is analyzed as a function of the neutron multiplicity detected in the ZDC and of the transverse momentum kick ($p_T^{\mathrm{spec}}$) imparted to the spectators during the collision. In all the cases considered, it will be possible to achieve a meaningful measurement of the RP.

The majority of the HL-ZDC length ($\sim$ 530 mm) is dedicated to the HAD section, comprised of a total of 4.5 nuclear interaction lengths divided into three sub-modules. Each sub-module consists of 15 layers of 1.5 mm diameter fused silica rods sandwiched between

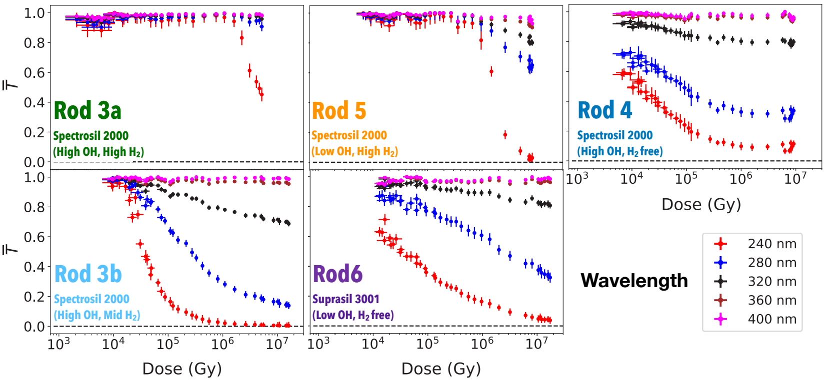

**Figure 3.** Optical transmission of different fused silica materials as a function of dose received in the TAN. Each panel corresponds to a fused silica material characterized by different levels of OH and $H_2$ dopants. Results are displayed from 240 nm (lower limit of the measurement) to 400 nm. As one can note, negligible losses in transmittance are observed for all the materials when approaching this wavelength. For this reason, results from 400 nm to 1500 nm (upper limit of the measurement) are not included at this point. Rod 3a, characterized by high concentrations of OH and $H_2$ dopants, exhibits a mostly perfect optical transmission up to the MGy scale.

10 mm tungsten plates. The fused silica rods terminate at trapezoidal air light guides that direct the Cherenkov photons to the closest PMT. Each HAD sub-module is equipped with two light guides and two PMTs, resulting in a total of six PMT channels to be read out. Thanks to the greater depth compared to the existing detectors (5.5 vs 4.5 $\lambda_{\mathrm{int}}$), the energy resolution of the HL-ZDC is expected to be better than those characterizing the Run 3 detectors [3], despite the narrower transverse dimensions.

## 3 R&D highlights

The unprecedented collision rate that will be reached by the HL-LHC poses radiation hardness challenges that are common for all forward detectors installed in the TAXN, such as the ZDC and the BRAN luminosity monitor [6]. For this reason, JZCaP has started an R&D effort with the CERN BRAN and FLUKA teams to carry out radiation hardness studies on fused silica materials irradiated in the LHC. The first irradiation campaign took place in Run 2, when seven 40 cm long fused-silica rods, characterized by different material compositions, were inserted in a Run 4 BRAN prototype installed in the TAN. Thanks to detailed FLUKA simulations transporting collision products from the center of the ATLAS detector hosted in the experimental cavern up to the TAN [7], it was possible to estimate the dose accumulated in the BRAN rods, which spans over four orders of magnitude. Therefore, by cutting the rods into 1 cm segments, it was possible to form sub-sets of 40 samples, each characterized by the same material composition and different irradiation levels. Figure 3 shows preliminary results of this analysis which correlate transmittance over a wide wavelength range with the dose accumulated in each sample. The results, currently being drafted for publication, already informed the choice of material for the ATLAS Run 3 ZDC refurbishing. For the sake of the same refurbishing campaign, a dedicated polishing procedure was developed to improve the transmission of light from the rods to the light guide, see [8] for more details. The refurbished ATLAS ZDC was operated successfully for the first time during the 2021 pilot run [9].

## Acknowledgements

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