DESIGN AND PERFORMANCE OF CORONAGRAPH FOR BEAM HALO MEASUREMENTS IN THE LHC

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Abstract

The CERN Large Hadron Collider is equipped with two Beam Synchrotron Radiation systems (BSR), one per beam. These systems are used to monitor the transverse distribution of the beam, its longitudinal distribution and the abort gap population. During the 2015-2016 winter shut-down period, one of the two BSR systems was equipped with a prototype beam halo monitor, based on the Lyot coronagraph, classically used in astrophysics telescopes to observe the sun's corona. The system design, as well as part of the optics, was taken from the coronagraph used in the KEK Photon Factory, adapted in order to satisfy the LHC BSR source constraints. This project is in the framework of the HL-LHC project, for which there is the requirement to monitor the beam halo at the level of 10^{-6} of the core intensity. This first prototype has been designed as a demonstrator system aimed at resolving a halo-core contrast in the 10^{-3} to 10^{-4} range. After illustrating the design of the LHC coronagraph and its technical implementation, this contribution presents the result of the first tests with beam and the planned system upgrades for 2017.

PRINCIPLE OF THE CORONAGRAPH

The coronagraph is an instrument developed in the first half of 20th century by Bernard Lyot, a French astrophysicist, in order to observe the halo of the sun. A sketch of the Lyot coronagraph can be seen in Fig. 1.
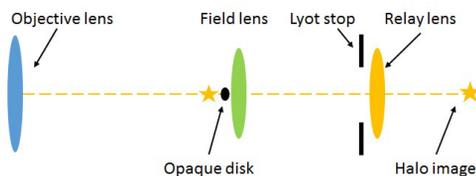

Figure 1: Sketch of the Lyot coronagraph optical layout.

A real image of the object is created by an objective lens. An opaque disk located at the image plane of this lens masks the bright core of the object in order to make the halo visible.

Such a system is however limited by the light diffracted from the limited aperture of the objective lens, which creates a diffraction pattern at the image plane, perturbing the observation of the halo.

Lyot's solution consisted of adding a field lens, which images the objective lens and thus shifts the diffraction

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fringes out of the center, as shown in Fig. 2.
By placing a well dimensioned aperture stop, the "Lyot stop", at the location where the diffraction fringes are re-imaged, the fringes are blocked and can't propagate to the final image plane, where the halo is observed. [1–4]
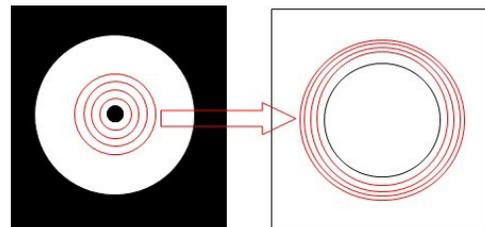A relay lens creates the final image of the beam with a magnification suitable for the camera sensor.

Figure 2: Sketch of diffraction pattern at the objective lens (left) and field lens (right) image planes.

The performance of the coronagraph is defined by its contrast, that is to say the ratio of the halo intensity with respect to the core intensity at image plane. It is limited by the background noise, which has mainly two sources: the first is the diffraction "leakage" to the image plane (i.e. diffraction fringes which are not blocked by the Lyot stop), which depends of the objective lens aperture, the mask size and the Lyot stop aperture. The second is Mie scattering, which is generated mainly by small particles on the optical elements located before the objective lens, and leads to a uniform increase of the background level. The Mie scattering depends on the size of the scattering particles and their distance to the objective lens. Mie scattering after the mask doesn't have a strong impact, since the light is by then strongly attenuated.
These limitations and the expected performance of the LHC coronagraph are quantified in the next section.

LHC HALO MONITOR DESIGN

Layout

The prototype beam halo monitor installed in the LHC during the winter shut down 2015-2016 is based on the same design and re-uses the optics of the Photon Factory coronagraph tested at KEK. Some modifications were introduced in order to fulfill the specific conditions of the LHC synchrotron light source and mechanical constraints. [5–7]
The coronagraph is designed to be used both at injection and top energy (450GeV and 7TeV respectively).

At injection energy, the synchrotron light in the visible range is generated by an undulator magnet located 27.2m before the extraction mirror, which sends the light through a viewport to an optical table. At top energy, the visible light comes from a superconducting dipole located 26m from the mirror. The expected beam emittance is around 2um, corresponding to beam sizes varying from 1.2mm (at injection energy) to 200um (at top energy).

The coronagraph optics is composed of three sections:

The first section consists of a finely polished plano-convex objective lens of f=2000mm, located 27.5m after the dipole magnet. It creates an image of the beam with a magnification of 0.077 and 0.08 for injection and top energy respectively. A motorized rectangular slit with a 30x30mm opening is placed just before the objective lens, in order to control the aperture.The diffraction pattern of the aperture thus has a cross shape, which turns into square fringes at the Lyot stop plane.

The mask is placed at the first image plane, with a size of 5 beam sigmas required to block the beam core. In order to cover the different beam sizes, the mask is made of a 3 inch glass substrate with 12 opaque disks ranging from 100um to 650um in diameter, made by chromium deposition and etching. The mask is motorized in order to select and center the appropriate disk.

The second stage of the coronagraph is composed of the field lens, which creates an image of the objective lens with a magnification of 0.6 and the Lyot stop, located at the field lens image plane.

The field lens is an apochromat of f=816mm and 102mm diameter. The Lyot stop is a motorized rectangular slit of the same model as the one used for defining the objective lens aperture.

The third stage contains the relay lens, which is an apochromat lens of f=500mm placed just after the Lyot stop, and a telescope eyepiece of f=18mm, which is set to adjust the final image with a magnification of 30, in order to achieve a beam size on the camera of about 1.5 times the real beam size.

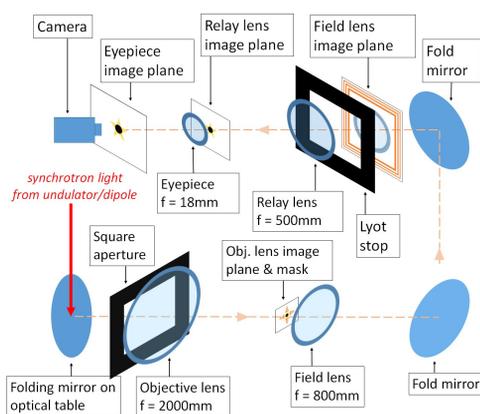The Fig. 3 shows the layout of the coronagraph.

Figure 3: Layout of the LHC coronagraph.

Expected Performance

Some analysis and simulations were performed to estimate the background coming from diffraction leakage and Mie scattering. The method and results are detailed in [1].

The diffraction leakage is estimated to be $3.7 \, 10^{-4}$, while the Mie scattering should be in the order of 10^{-4} to 10^{-5} with respect to the beam core intensity.

Considering these calculations, the contrast of the beam halo monitor in LHC is expected to be of 10^4 with respect to the beam core.

Implementation

The LHC beam halo monitor shares the light source, in-vacuum mirror and optical table with the Beam Synchrotron Radiation system (BSR), used to measure the transverse and longitudinal distribution of the beam, and the abort gap population.

The implementation of the different elements on the optical table was studied with Catia CAD software.

In order to operate the coronagraph remotely (since the LHC tunnel is not accessible while the machine is running), many of the optical components are motorized. This gives the possibility to adjust at any time the alignment, the aperture, the different focusing stages as well as the mask position and the Lyot stop size.

The whole system is enclosed in shielding boxes, in order to protect it from parasitic light and dust. In particular, the space between the objective lens to it's image plane is enclosed in a telescope tube containing baffle plates, in order to minimize the parasitic reflections and thus the background noise.

For the laboratory tests and the commissioning with beam, a simple USB CCD camera was used, with the control of the integration time used to determine the contrast. It is planned to replace the camera with an intensified scientific CMOS camera in the near future, which would allow bunch by bunch halo measurements to be performed, gating on a single bunch at any one time.

Fig. 4 shows a 3D drawing of the BSR optical table with the coronagraph installed, but without the light shielding boxes.

LHC HALO MONITOR TEST BENCH

Before the installation of the halo monitor in the LHC, a test of the complete instrument was conducted in order to check mechanical aspects (assembly, motors, etc.) and measure its performance.

In order to reproduce as accurately as possible the LHC conditions, the test included a 27m long drift line, mimicking the distance between LHC light source and the in-vacuum extraction mirror. A spare of the in-vacuum mirror was used to reproduce its contribution to the Mie scattering.

A 200um pinhole illuminated by a broadband fiber lamp was used as a light source. A piece of transparent plastic could be inserted in front of the pinhole in order to create an artificial halo.
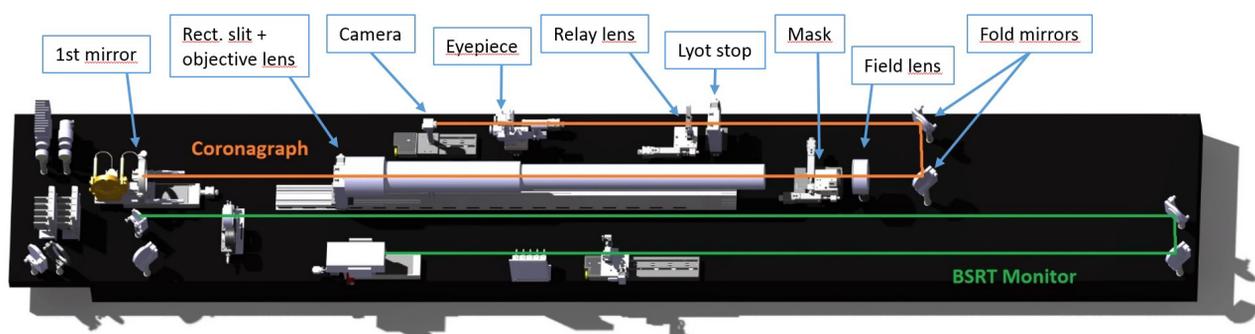
Figure 4: 3D drawing of the LHC halo monitor.

The first step of the test consisted of precisely locating the objective lens image plane in order to place the mask.

The second step was then to adjust the objective lens aperture and the Lyot stop. The diffraction pattern at the Lyot stop location depends on the objective lens aperture and the mask size, but it has to be considered that a small objective lens and Lyot stop aperture deteriorates the image resolution by increasing the point spread function. An objective lens aperture of 20x20mm was finally selected with the Lyot stop adjusted by optimizing the final image.

The contrast was measured with the following procedure. Images of the object without the mask were acquired, adjusting the camera exposure time in order to reach a maximum intensity value at the light core near (but below) saturation. The mask was then inserted and the exposure time increased until a maximum halo intensity of the same value as that of the core without mask was achieved. The ratio between the halo exposure time and the core exposure time gives the contrast.

Fig. 5 shows images obtained with a 800um mask. It was possible to observe light with a contrast of 10^7. The results on the test bench were promising: the surface quality of the in-vacuum mirror appears to be sufficient to allow the halo observation.
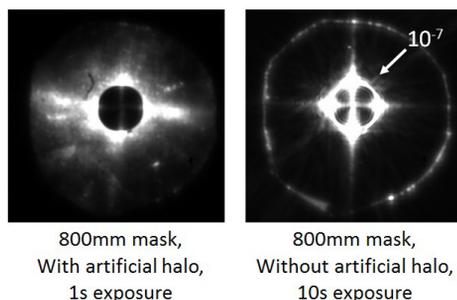
LHC HALO MONITOR COMMISSIONING

The beam-halo monitor was installed in the LHC during the winter shutdown 2015-2016, and commissioned in April 2016, at the 2016 LHC top energy of 6.5TeV.

The same procedure as the one described in the test bench section of this paper was carried out for finding the objective lens image plane and setting the aperture.

A test to quantify the diffraction leakage was then performed. At top energy, the aperture available for beam imposed by the collimation system is 3.5x4.5mm. This implies that at the objective lens image plane, where the magnification is 0.08, the light produced by the beam should be confined in a 280x360um area. Thus, with the biggest size of mask (650um) placed in front of the core, all observable light on the image can be considered as diffraction leakage and Mie scattering. The Fig. 6 shows an image obtained during this test. A light spot of intensity 10^{-4} with respect to the beam core is clearly visible on the right side of the mask only, whose origin appears to be independent of the objective lens and Lyot stop size apertures. Its intensity makes the observation of the beam halo impossible in the present state.
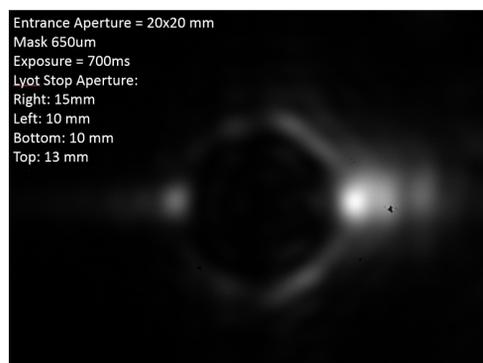

Figure 6: Image acquired with the LHC beam halo monitor in the frame of quantifying the diffraction leakage.

800mm mask,
With artificial halo,
1s exposure

800mm mask,
Without artificial halo,
10s exposure

Figure 5: Images acquired with different camera exposure time.

This parasitic light spot, which was never observed during the lab tests, might therefore be explained by the source of the LHC synchrotron light. Indeed, the in-vacuum mirror will reflect the light produced by the dipole magnet from its edge up to 3.3m inside [7].

The edge of the in-vacuum mirror might therefore diffract some of this light and act as a secondary light source.

A way to block this parasitic light before the image plane would be to place another motorized rectangular aperture at the plane where the in-vacuum mirror is imaged by the field lens (i.e after 1m), so doing hiding the edge of the mirror from the subsequent optics.

To test this hypothesis, one can make a comparison of this parasitic light spot at injection and top energy. At injection, the light emitted by the undulator covers all the in-vacuum mirror. Since the shape of the source is not the same as at top energy, it is to be expected that the shape of the parasitic spot will be different. If this is not the case, it would suggest that this light spot has another origin, such as internal reflections. This test is yet to be carried out.

Fig. 7 shows the power of synchrotron light on the extraction mirror at injection and top energy.
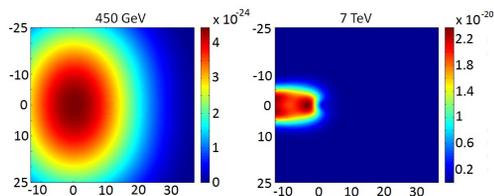

Figure 7: Simulation of the LHC SR power (in units of $W \cdot mm^{-2}$ per proton) at the extraction mirror at injection (left) and top energy (right).

CONCLUSION AND PERSPECTIVES

Successful tests of the LHC beam halo monitor were conducted on a test stand and allowed the optical and mechanical design of the system to be validated.

The system was able to distinguish the halo from the core for a test lamp with a contrast of 10^7, well above the 10^4 contrast expected for this prototype with beam, for which the main limitation is expected to come from diffraction. [1] Tests of the real system performed with the LHC proton beam at 6.5TeV, showed a parasitic spot with an intensity of 10^{-4} with respect to the beam core, above the level of the halo expected to be observed.

A potential cause of this parasitic light is the diffraction of the synchrotron light on the edge of the in-vacuum mirror, which then effectively acts as a secondary light source.

A way to avoid the propagation of this light to the image plane would be to add a second adjustable Lyot stop at the image plane of the mirror created by the field lens. Tests are foreseen to be carried out at injection energy, in order to verify this hypothesis, which would then allow mitigation measures to be put in place for further testing of the coronagraph for beam halo measurements in late 2016.

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