Evaluation of the radiation field in the future circular collider detector

M.I. Besana,* F. Cerutti, A. Ferrari, W. Riegler, and V. Vlachoudis

CERN, Geneva

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The radiation load on a detector at a 100 TeV proton-proton collider, that is being investigated within the Future Circular Collider (FCC) study, is presented. A peak luminosity of $30 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and a total integrated luminosity of 30 ab$^{-1}$ are assumed for these radiation studies.

A first concept of the detector foresees the presence of central and forward sub-detectors that provide acceptance up to $|\eta| = 6$ inside a magnetic field generated by the combination of a central solenoid and two forward dipoles. This layout has been modelled and relevant fluence and dose distributions have been calculated using the FLUKA Monte Carlo code.

Distributions of fluence rates are discussed separately for charged particles, neutrons and photons. Dose and 1 MeV neutron equivalent fluence, for the accumulated integrated luminosity, are presented. The peak values of these quantities in the different sub-detectors are highlighted, in order to define the radiation tolerance requirements for the choice of possible technologies. The effect of the magnetic field is also discussed.

Two shielding solutions have been conceived to minimise the backscattering from the forward calorimeters to the muon chambers and the forward tracking stations. The two tentative designs are presented and their effectiveness is discussed in terms of 1 MeV neutron equivalent fluence and particle fluence rate reduction.

I. INTRODUCTION

As part of the post-LHC high-energy program, a study is ongoing to design a new 100 km long hadron collider (FCC-hh) [1], which is expected to operate at a centre-of-mass energy of 100 TeV and to accumulate up to 30 ab$^{-1}$ at the end of data-taking, with a peak instantaneous luminosity that could reach $30 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

The radiation load at the FCC-hh will be more challenging than at the LHC, since collision energy will be more than seven times higher and the foreseen ultimate instantaneous luminosity is 30 times higher. It is important also to evaluate the long term damage, since the integrated luminosity goal exceeds by two orders of magnitude the LHC one [2] and by one order of magnitude the High Luminosity LHC (HL-LHC) one [3].

To assess the radiation load on the detector, simulations have been performed using FLUKA [4, 5], which is a Monte Carlo code benchmarked up to the TeV energy region and regularly used for beam-machine interaction studies [6], concerning in particular the LHC and its upgrade.

To optimize the computational time, only half of the detector has been implemented in FLUKA, but the contribution coming from the other half is accounted for. The impact of the backscattering from the Target Absorber Secondaries (TAS), the protection element in front of the final focus triplet, has not been included in this calculation, since, according to the current design of the interaction region [7], the absorber is expected to be outside the experimental cavern and therefore adequately shielded.

This paper is organised as follows. In section II the detector concept is discussed and its geometry is described, while the source term is characterized in section III. The obtained results for the radiation load are then presented in section IV and finally the shielding designs and their

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* Maria Ilaria Besana: maria.ilaria.besana@cern.ch
effectiveness are discussed in Section V.

II. DETECTOR DESCRIPTION

First detector concepts for a 100 TeV proton-proton collider have been established. With the 7-fold increase in center of mass energy with respect to the LHC, a similar energy increase of final state particles of hard scattering events is conservatively assumed. Therefore the tracker radius \( L \) is increased by a factor of 2 and the magnetic field \( B \) is increased by a factor 1.5 over the numbers from e.g. the CMS experiment, leading to a \( BL^2 \) increase of 6. The total thickness of the two calorimeters, electromagnetic and hadronic, has to be increased by 2 lambdas over the LHC values in order to contain the high energy particles. These considerations lead to a tracker radius of 2.4 m and total calorimeter thickness of 3.4 m and therefore an inner coil radius of about 6 m. Instead of an iron yoke for return of the magnetic flux, an active shielding coil is assumed. The volume between the central and the shielding coil is instrumented with muon chambers.

Since many interesting physics channels, specifically most of the Higgs physics, are highly forward boosted at these high energies, an increase of precision tracking and precision calorimetry from the pseudorapidity \( \eta \) range of \( \pm 2.4 \) at the LHC to an \( \eta \) range of \( \pm 4 \) for the FCC is assumed. Calorimeter acceptance has to be provided even up to possibly \( |\eta| = 6 \) value in order to be sensitive to the so called VBF jets. For this reason, two dipoles have been placed in this forward region that provide momentum spectroscopy where the solenoid becomes ineffective.

For this study, the Electromagnetic Calorimeter (EM-cal) is assumed to use liquid Argon (LAr) technology with Pb absorbers, while the Hadron Calorimeter (HAD-cal) assumes an iron-scintillator sandwich, both very similar to the ATLAS calorimeters.

Figure 1 shows the FCC-hh detector model, as it has been implemented in FLUKA, and its detailed description is provided in the following.

II.1. Detector Geometry

The FCC-hh detector is composed of a central part cylindrically symmetric and a forward part.

II.1.1. Central Region

Closest to the beam pipe is the Tracker, which will have the function of reconstructing the trajectory of the charged particles and it is designed to reach a 10% resolution on the transverse momentum \( p_T \) measurements for particles with \( p_T \) up to 10 TeV. It is composed of different silicon detectors and it extends from a radial distance from the beam axis (\( R \)) of 2.5 cm, where the first pixel layer is expected to be put, up to 2.4 m. Its length along the beam axis (\( z \)) is 16 m, centred around the interaction point. The whole system is enclosed by the barrel calorimeters: the EM-cal, which extends up \( R = 3.6 \) m and the HAD-cal, which extends up to 6 m. The solenoid coil extends from \( R = 6.25 \) m to \( R = 7.825 \) m, while the shielding solenoid is between \( R = 13 \) m and \( R = 13.475 \) m. As mentioned above, the volume between them is equipped with the barrel muon chambers.

II.1.2. End-cap Region

The calorimeter system has been designed to be hermetic up to \( |\eta| = 2.5 \). The end-cap calorimeters extend from \( z = 8 \) m to \( z = 11.5 \) m. The EM-cal has a thickness of 1.1 m, while the HAD-cal is 2.4 m thick. Muon chambers are put between 11.5 m and 14.4 m to measure the transverse momentum of muons up to \( |\eta| = 2.5 \).

II.1.3. Forward Region

The forward region is designed to catch particles up to \( |\eta| = 6 \). On each side of the central detector, a dipole is put between \( z = 14.8 \) m and \( z = 21 \) m. These dipoles have lateral coils in the horizontal plane to counteract the forces between the solenoid and each dipole. Tracking stations are foreseen before and after the dipole region, to measure the angular deviation due to the dipole magnetic field. There are not tracking stations in the dipole region, since it is easier to build and maintain detectors outside and in order to avoid occupancy from loopers. After the Forward Tracker, calorimeters (Forward EM-cal and Forward HAD-cal) are foreseen be-
tween $z = 24$ m and $z = 27.5$ m. In the present model the same material composition of the barrel calorimeters is used. Radiation calculations have shown that fluence rates are significantly higher in this region and therefore a dedicated technology for these sub-detectors will be needed. Finally a Muon Spectrometer is put after the Forward HAD-cal, up to $z = 31.5$ m.

II.2. Magnetic Field

The magnetic field is given by the superposition of a solenoid field directed along the z axis and a dipole field along the y axis. As a result, the field in the central region is directed along the z axis and it is 6 T in the tracker and below 3 T in the muon chambers. In the dipole region the field is not purely vertical and there is an up/down asymmetry: for positive $y$ the values of the field are higher, as it can be seen in Figure 2.

III. SOURCE TERM CHARACTERIZATION

Proton-proton collisions have been simulated using the DPMjet generator [10, 11], directly called from inside FLUKA. The assumed proton-proton non-elastic cross section, including inelastic scattering and single diffractive events, is 108 mbarn. The average number of particles generated in one collision is about 210. Moving away from the interaction point (IP), this multiform population evolves, even before touching the surrounding material, because of the decay of unstable particles (in particular neutral pions decaying into photon pairs). At 5 mm from the IP the average number of particles (neglecting neutrinos) is 275 and the main components are photons (almost 50%) and charged pions (37%). Neutral and charged kaons represent about the 8% of the total, while protons and neutrons are the 1.5% and 1.3% respectively. To the remaining fraction antiprotons and antineutrons (1% each) and hyperons contribute.

Figure 3 shows particle multiplicity as a function of pseudorapidity for 100 TeV p-p collisions compared to 14 TeV p-p collisions at 5 mm from the nominal interaction point. Due to the larger centre of mass energy, the average number of particles is expected to increase by a factor 1.8. The distribution is characterised by two symmetric peaks around $|\eta| = 1.5$ and about 80% of the particles are within the pseudorapidity coverage of the FCC detector, which is $-6 < \eta < 6$. Despite this large coverage, the majority of energy escapes from the detector. As it can be seen from Figure 4, the energy distribution for p-p collisions at 100 TeV peaks at $|\eta|$ larger than 10 and the fraction of energy inside the detector acceptance is less than 5%. The total energy increases in the detector with respect to 14 TeV collisions is about a factor 5, considering for 14 TeV the pseudorapidity coverage of present ATLAS and CMS detector ($|\eta| < 5$). In the central region ($|\eta| < 2.5$) the energy increase is instead less than 2.4.

IV. RADIATION CALCULATIONS

The load on the detector has been evaluated in terms of fluence rates, for the ultimate target instantaneous luminosity of $30 \times 10^{34}$ cm$^{-2}$s$^{-1}$, to assess the detector occupancy. The long term damage has been estimated in terms of dose and 1 MeV neutron equivalent fluence,
Figure 5. Charged particles fluence rate for an instantaneous luminosity of $30 \times 10^{34}$ cm$^{-2}$s$^{-1}$: top view. In the central region ($z < 10.5$ m) values are azimuthally averaged over 40 degrees around 0 (positive x) and $\pi$ (negative x). In the forward region an average in the vertical direction around $y = 0$ is done on a bin of 1 cm up to $|x| = 0.6$ m and on a 10 cm bin for larger $|x|$ values. The origin of the coordinate system corresponds to the nominal collision point.

Figure 6. Charged particles fluence rate for an instantaneous luminosity of $30 \times 10^{34}$ cm$^{-2}$s$^{-1}$: lateral view. In the central region ($z < 10.5$ m) values are azimuthally averaged over 20 degrees around $\frac{\pi}{2}$ (positive y) and $-\frac{\pi}{2}$ (negative y). In the forward region an average in the horizontal direction around $x = 0$ is done on a bin of 1 cm up to $|y| = 0.6$ m and on a 10 cm bin for larger $|y|$ values.

Figure 7. Charged particles fluence rate for an instantaneous luminosity of $30 \times 10^{34}$ cm$^{-2}$s$^{-1}$ as a function of the distance from the beam line, at different z positions in the detector. In the central region the values are averaged on the azimuthal angle $\Phi$ angle and they are shown as a function of the radius $R$, while in the forward region they are shown as a function of $x$ and $y$ separately. The values as a function of $x$ ($y$) are obtained with an average in the vertical (horizontal) direction on a bin of 1 cm around $y = 0$ ($x = 0$).

taking as reference the ultimate integrated luminosity of $30 \text{ ab}^{-1}$.

**IV.1. Fluence rates**

**IV.1.1. Charged particles fluence rates**

The distributions of the charged particles fluence rates are shown in Figure 5 on the z-x plane at $y = 0$ and in Figure 6 on the z-y plane at $x = 0$. The rates have a significant dependence on $R$, but a weak dependence on $z$: as expected, equi-fluence lines are substantially parallel to the $z$ axis. The distribution of charged particles is broader in the z-x plane, because of the effect of the dipole field directed along the y-axis. The latter is also visible in the z-y plane, where the higher fluence rate red line at $y > 0$ between 14 m and 17 m is due to electrons and positrons, which are captured by the magnetic field and spiralize around its lines.

The charged particles fluence rates in the Tracker are shown in Figure 7 as a function of the distance from the beam line at different longitudinal positions: inside the barrel Tracker, in a forward tracking station before the dipole, in the tracking station closer to the forward calorimeters and in the forward Muon Spectrometer. The values in the Tracker go from $2 \times 10^{10}$ cm$^{-2}$s$^{-1}$ in the first pixel layer to $10^{6}$ cm$^{-2}$s$^{-1}$ on its external side. The peaks structure visible in the distribution at $z = 4$ m reflects the position of the cylindrical tracking stations in the barrel. The fluence distribution on the vertical plane at 14 m shows a bump, due to the above mentioned capture of electrons and positrons by the magnetic field. The effect of the latter is again visible in the fact that the fluence rates in the tracking station after the dipole are higher in the horizontal plane than in the vertical one. For radii greater than 60 cm, the values in the tracking station closer to the forward calorimeters are significantly higher than the ones in the barrel (up to ten times). This is due to backscattered particles from the forward calorimeters, where the fluence rate reaches $10^{11}$ cm$^{-2}$s$^{-1}$. From there, particles populate also the external part of the HAD-calo and the Muon Spectrometer. The fluence rates are $2 \times 10^{5}$ cm$^{-2}$s$^{-1}$ and above $10^{6}$ cm$^{-2}$s$^{-1}$ in the barrel and end-cap muon chambers, respectively, more than 1000 times higher than the minimum reached in the barrel HAD-calo. These values are too high for a good muon...
IV.1.2. Neutrons and photons fluence rates

The neutron fluence rate in the muon chambers reaches $10^8 \text{cm}^{-2}\text{s}^{-1}$, causing a fake muon signal rate of $10^5 \text{cm}^{-2}\text{s}^{-1}$, assuming that neutrons would have the same efficiency as in the Resistive Plate Chambers of the ATLAS detector.

The photons fluence rate in the barrel and end-cap muon chambers is shown in Figure 8. The maximum values are $5 \times 10^6 \text{cm}^{-2}\text{s}^{-1}$ and $10^8 \text{cm}^{-2}\text{s}^{-1}$ respectively, causing a background level analogous to the one of neutrons, assuming an efficiency of 1% as in the ATLAS muon chambers. These values are too high for a good muon identification and need to be reduced. As will be shown later in the paper, this can be achieved thanks to a shielding around the forward calorimeter.

Figure 8. Photons fluence rate for an instantaneous luminosity of $30 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$: top view, zoom on barrel and end-cap muon chambers. The same scoring resolution as the one of Figure 5 has been adopted, apart for the central region ($R < 2.5 \text{ m}$ and $|z| < 8 \text{ m}$), where the considered radial resolution is 0.5 cm, instead of 1 cm.

IV.2. Long Term Damage

IV.2.1. 1 MeV neutron equivalent fluence

The distribution of the 1 MeV neutron equivalent fluence (relevant for silicon damage) is shown in Figure 9 on the z-x plane at $y=0$. As for fluence rate, a very strong dependence is observed as a function of R, while equivalence lines are to a good approximation parallel to the beam line.

Figure 10 shows the 1 MeV neutron equivalent fluence as a function of the distance from the beam axis, at the longitudinal positions already considered in Fig. 7. In the central region, at a radial distance below 50 cm, neutron fluence values exceed the ones expected at HL-LHC [12] by almost two orders of magnitude: we obtain $8 \times 10^{17} \text{cm}^{-2}$ at the first pixel layer. In the tracking stations downstream of the dipole, the fluence is above $10^{16} \text{cm}^{-2}$ even at 2 m distance from the beam line, because of backscattering from the forward calorimeters. This represents a technologic challenge, since present detectors cannot sustain these values [13]. As expected, in this distribution on the vertical plane at 14 m there is no bump, while the distributions on the horizontal and vertical plane in the last tracking station are different. This is due to the direct contribution of charged particles (accounted for in the 1 MeV neutron equivalent fluence) and to the fact that secondary neutrons, produced by charged hadrons interactions in the forward calorimeters, have a broader distribution on the horizontal plane, reflecting the dipole field effect.

Figure 11 shows the fluence in the barrel and in the end-cap calorimeters at different longitudinal positions. The fluence in the centre of the detector at the entrance of the barrel EM-calo is above $10^{15} \text{cm}^{-2}$ and it is then reduced by the calorimeters by several orders of magnitude, down to $10^{10} \text{cm}^{-2}$ on the external side of the HAD-
calo. Values increase by almost two orders of magnitude in the gap between the calorimeter and the solenoid due to particles coming from the forward calorimeters. The distribution in the barrel at \( z = 7.9 - 8 \) m is very similar to the one at the centre of the detector between \( R = 3 \) m and \( R = 5.5 \) m. For larger radii, the values are higher, because the repopulation from the forward calorimeter is more important. The fluence rate in the gap reaches \( 4 \times 10^{12} \) cm\(^{-2}\) and it is above \( 10^{13} \) cm\(^{-2}\) at the corresponding end-cap HAD-calo position. The values on the inner side of the end-caps are higher than in the barrel, in particular in the EM-calo the fluence reaches \( 10^{16} \) cm\(^{-2}\), while in the end-cap HAD-calo it is about \( 3 \times 10^{15} \) cm\(^{-2}\). The maximum on the non-IP side of the end-cap HAD-calo is lower, but here the values do not decrease significantly as a function of the radius, remaining above \( 10^{14} \) cm\(^{-2}\) up to beyond \( R = 6 \) m, because of the contribution from the forward calorimeters.

The values in the forward calorimeters are naturally even higher: the maximum fluence is \( 7 \times 10^{18} \) cm\(^{-2}\) and above \( 4 \times 10^{18} \) cm\(^{-2}\) in the EM-calo and HAD-calo, respectively.

Finally, the fluence in the muon chambers reaches \( 10^{14} \) cm\(^{-2}\) in the barrel and \( 3 \times 10^{15} \) cm\(^{-2}\) in the end-cap, but they can be mitigated with the shielding discussed in section V.

**IV.2.2. Dose**

Figure 12 shows the dose distribution in the z-y plane. As for the charged particles fluence rate, the effect of the magnetic field is visible in the dipole region. The higher dose line in the \( y > 0 \) half-plane between 14 m and 17 m is due to electrons and positrons, which spiralize along the magnetic field lines. An analogous capture effect causes the higher dose line in the \( y < 0 \) half-plane between 20 m and 24 m, consistently with what can be observed in Figure 6. The dose in the first pixel layer is 600 MGy, almost two orders of magnitude higher than what is expected at the HL-LHC [12]. It is reduced to 80 kGy at the entrance of the barrel EM-calo at \( \eta = 0 \) and it reaches a maximum of 120 kGy in this sub-detector. The dose at the entrance of the HAD-calo is 4 kGy and it reaches a minimum of 0.01 kGy. The values in the HAD-calo for \( z > 10 \) m are a little bit higher, above 0.05 kGy, due to the contribution from particles coming from the forward calorimeter, where the dose values reach 10 GGy. While the values in the barrel HAD-calo can be sustained by a scintillator detector, the maximum value in the end-cap hadronic calorimeter is 0.4 MGy, which is excessive for this technology. Since the dose in the end-cap at a radial distance grater than \( 3.6 \) m is 2 kGy, a possible solution is to have an extended barrel HAD-calo based on scintillator technology up to \( z = 11.5 \) m with a radius larger than \( 3.6 \) m. The dose in this area is below few kGy, apart for the non-IP face of the HAD-calo, where at \( 3.6 \) m it reaches 10 kGy. However this hot spot can be mitigated with a shielding. A different type of hadronic calorimeter, using for example Liquid Argon technology, is needed to cover the end-cap HAD-calo region for \( R < 3.6 \) m.

**V. SHIELDING DESIGN AND EFFECTIVENESS**

In order to protect the forward tracking stations and the muon chambers in the barrel and in the end-cap from back-scattering from the forward calorimeter, two shielding solutions have been designed to be put in front and around the forward calorimeters.

**V.1. Shielding in front of the forward calorimeters**

This shielding has been designed to protect the Forward Tracker. It is made by 5 cm of lithiated polyethylene, with a 2 mm thick cover of aluminium on the two sides. The material choice aims at the neutron capture without gamma emission, thanks to lithium. The effect
Figure 13. 1 MeV neutron equivalent fluence as a function of x with (square) and without (triangle) shielding, at different z positions in the detector. The values are obtained with an average in the vertical direction on a bin of 1 cm around y = 0.

of the shielding is clearly visible looking at the 1 MeV neutron equivalent fluence distribution as a function of distance from the beam line in three tracking stations in front of the forward calorimeters, shown in Figure 13. On the two tracking layers closer to the calorimeters the fluence is reduced by up to a factor of three, while the impact on the tracking station upstream the dipole is less important, but still visible. Despite its limited thickness, the shielding is effective. However these values remain a technology challenge for silicon detectors.

V.2. Shielding around the forward calorimeters

A massive shielding has been designed to be put around the forward calorimeter up to the cavern wall, in order to protect the barrel and end-cap muon chambers from backscattered particles. The shielding is visible in Figure 14 and it is composed by a 2 m thick iron wall to remove high energy particles. A 5 cm thick layer of lithiated polyethylene is put externally to further slow down and capture neutrons. Finally a 1 cm thick layer of lead is added as outer boundary, in order to absorb the capture photons, already made rare by the lithium presence.

Figure 14 shows the effect of the shielding on the neutron fluence rate, which is reduced by about four orders of magnitude in the relevant locations. Some neutron leakage can be seen at z = 25 m, at the level of the entrance of the electromagnetic forward calorimeter. In the barrel and end-cap muon chambers one obtains about $10^3 \text{ cm}^{-2}\text{s}^{-1}$ and $10^4 \text{ cm}^{-2}\text{s}^{-1}$, respectively, causing a maximum fake muon signal of $10^3 \text{ cm}^{-2}\text{s}^{-1}$. Figure 15 shows the photons fluence rate in the muon chambers on the z-x plane. The average on the $\Phi$ angle in the central region and on y in the forward region has been done on larger intervals with respect to previous plots, to improve statistics. From the comparison with

Figure 8, the rate is reduced also in this case by four orders of magnitude and it reaches $10^5 \text{ cm}^{-2}\text{s}^{-1}$ in the end-cap, yielding a fake muon signal again of the order of $10^3 \text{ cm}^{-2}\text{s}^{-1}$. These values are comparable to the rates that can be afforded with present technologies and are currently observed in LHC experiments muon chambers.

Figure 14. Neutrons fluence rate for an instantaneous luminosity of $30 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in the presence of the shielding described in the text: top view. The same scoring resolution as the one of Figure 9 has been adopted, except for the end-cap muon chamber region, where the average on y has been done on a bin of about 1.3 m for $|x| > 0.6$ m.

Figure 15. Photons fluence rate for an instantaneous luminosity of $30 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in the presence of the shielding described in the text: top view, zoom on the muon chambers. In the central region ($z < 10.5$ m) values are azimuthally averaged over 120 degrees around 0. In the forward region an average in the vertical direction around $y=0$ is done on a bin of about 4.1 m for $|x| > 0.6$ m.
VI. CONCLUSION

A first concept of the detector has been implemented in FLUKA and the radiation load has been assessed in terms of fluence rates and long term damage relevant quantities. The 1 MeV neutron equivalent fluence values in the tracker are significantly higher than what is foreseen for HL-LHC, up to about two orders of magnitude. In particular, the values in the forward tracking stations are above $10^{16}$ cm$^{-2}$ even in their external part (up to 2.5 m for the one closer to the calorimeter), because of the impact of the particles backscattered by the forward calorimeters. There are no technological solutions which can sustain such values, representing a clear challenge.

The estimated particle fluence rates, 1 MeV neutron equivalent fluence and dose values in the barrel are compatible with the choice of a LAr based EM-calo and a tile HAD-calo, while the scintillator technology could not sustain the dose values foreseen in the end-cap. A possible solution is to have an extended HAD-calo barrel based on scintillator technology up to $z = 11.5$ m with a radius larger than 3.6 m and to use LAr technology for smaller radii. Finally, the obtained fluence rate values in the muon chambers in the barrel and in the end-cap are too high for a good muon identification, because of particles backscattered from the forward calorimeters.

Based on these results, two different shielding systems have been conceived around and in front of the forward calorimeters to protect muon chambers and forward tracking stations. The resulting mitigation in the muon chambers is effective, reducing the neutrons and photons fluence rates by about four orders of magnitude, down to manageable levels. For what concerns the forward tracking stations, the 1 MeV neutron equivalent fluence is reduced by up to a factor of three. Given the very limited amount of material (5 cm), the shielding is quite effective even if values remain challenging for present technologies.

In the future, the detector design is going to be further optimised to find the best compromise between cost and performance. Alternative options are under study, which for example don’t foresee the presence of forward dipoles. It will be interesting to repeat the calculation for the new configurations to highlight the effect of their variations in terms of radiation load.

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[8] Pseudorapidity $\eta \equiv -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$, where $\theta$ is the angle between the particle three-momentum $p$ and the positive direction of the beam axis.