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FEASIBILITY STUDY OF ChDR DIAGNOSTIC DEVICE IN THE LHC

K. Lasocha[1], T. Lefevre, N. Mounet, A. Schloegelhofer[2], M. Bergamaschi*, M. Krupa, S. Mazzoni, E. Senes, CERN, CH-1211 Geneva 23, Switzerland
D. M. Harryman, P. Karataev, JAI, Royal Holloway, University of London, Egham, Surrey, UK
A. Potylitsyn, Tomsk Polytechnic University, 634050, Lenin Ave, Tomsk, Russia
[1]also at Institute of Physics, Jagiellonian University, Krakow, Poland
[2]also at TU Wien, Vienna, Austria

Abstract

In recent years Cherenkov Diffraction Radiation (ChDR) has been reported as a phenomenon suitable for various types of particle accelerator diagnostics. As it would typically work best for highly relativistic beams, past studies and experiments have been mostly focusing on lepton machines. This contribution investigates the prospects on the utilization of ChDR as a diagnostic tool for the Large Hadron Collider (LHC). Based on theoretical considerations and simulation results we estimate the properties of the expected radiation, both in the incoherent and coherent domain, and we compare them with the requirements of the existing diagnostic systems. We also address the potential problem of the use of dielectric radiators in circular machines, where secondary electrons could potentially lead to the creation of electron clouds inside the beam pipe that may affect the radiator.

INTRODUCTION

Following the first observation of incoherent Cherenkov diffraction radiation (ChDR), using GeV electrons and positrons at Cornell [1, 2], the possibilities which ChDR brings to non-invasive beam diagnostics have been extensively investigated [3, 4]. In recent years, several accelerator facilities across the world have confirmed the feasibility of observing ChDR [5–7].

As predicted by the theory, the intensity of ChDR falls drastically if the distance between the particle and the radiator exceeds $\gamma\lambda$, where γ is the relativistic Lorentz factor and λ is the wavelength of the considered radiation. For that reason, most of the past investigations were focusing on electron or positron accelerators. The Large Hadron Collider (LHC) accelerates protons up to a velocity corresponding to $\gamma \approx 7000$, a value higher than in the case of numerous electron machines operating today. It is therefore justified to ask if ChDR diagnostics might be applied in the LHC and what are the main challenges involved.

LHC RADIATION YIELD

All the parameters, relevant for calculation of ChDR radiation yield are presented in Table 1, including the typical LHC proton and ion beam characteristics. We considered impact parameters, i.e. distance between the beam center and the surface of the radiator, corresponding to either a standard vacuum chamber dimension (31.5 mm) or to the minimum distance (1 mm) which could be obtained if the radiator would be embedded in a collimator. For simplicity and for illustrative purposes, a frequency-independent relative permittivity of 2.1 was chosen. It is close to the value for fused silica in the visible range and for Teflon for microwave regime. Emitted energy for a single particle was calculated with the Polarization Current Approach (PCA) [8, 9], under the assumption of a long (10^3 m) radiator, but the result was then scaled down to correspond to more realistic, 10 cm long radiator. This was done in order to exclude the contribution of Diffraction Radiation [10] from our estimates.

Table 1: Parameters Used for ChDR Estimation in the LHC

	p: **Inj**	p: **Flattop**	Pb^{82+}: **Flattop**
Relativistic γ factor	480	6928	2452
Number of particles	$1.15 \cdot 10^{11}$	$1.15 \cdot 10^{11}$	$7 \cdot 10^7$
Bunch length		1.2 ns	
Impact parameter		1 - 31.5 mm	
Dielectric permittivity		2.1	
Dielectric length		10 cm	

In the scope of this contribution we consider energy radiated by a single particle bunch, during a single passage along the radiator surface. Therefore, any spectrum distortions due to the repetitive character of the radiation emission in circular machines are not included. We assume that the total energy spectral distribution is a sum of incoherent signal, proportional to the number of particles, and coherent longitudinal-bunch-shape dependent signal, proportional to the number of particles squared, following the approach presented in [11].

In Fig. 1 a spectral density distribution is presented under an assumption of a perfectly Gaussian bunch ($4\sigma = 1.2$ ns). The strong coherent part of the spectrum ends abruptly around 1 GHz frequency, causing the measurement at higher frequencies highly challenging. In addition we see, that observation of the visible radiation would only be possible at flat top energy and when considering small impact param-

* now at Max-Planck-Institut für Physik, Munich, Germany

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eter. It is also worth noting that the energy radiated in the coherent regime (i.e. <few GHz) is lower for ions compared to protons proportionally to the square of their bunch charge, but in the incoherent regime, the energy radiated by ions becomes higher as it scales proportionally to Z.

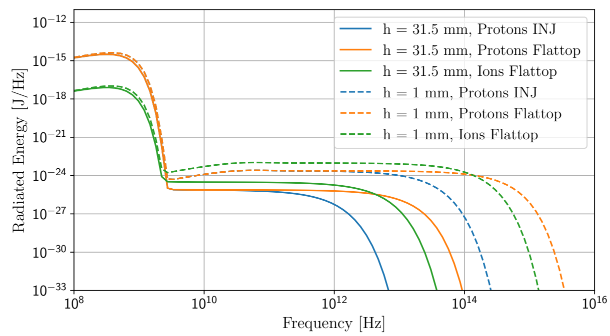

Figure 1: Energy radiated by a Gaussian bunch.

In realistic conditions, the LHC bunch profile deviates from a Gaussian shape. As a result, transition between the coherent and incoherent part of the spectrum is gradual, as reminiscences of coherence persist even for relatively high frequencies. In order to estimate to what extent this effect facilitates the measurement of ChDR in GHz range, we adopt the following non-Gaussian shape of the bunch profile:

$$\mathscr{B}(t) = N \cdot C_{norm} \cdot \left(1 - \left(\frac{2t}{\text{Bunch length}}\right)^2\right)^{\frac{5}{2}},$$

where $C_{norm} = 32/(5\pi \cdot \text{Bunch length})$.

Resulting spectral energy distributions and peak powers radiated in distinct frequency bands are summarised in Fig. 2 and Table 2 respectively. In the latter case, when a frequency is given, a frequency range $[0.96 \cdot \text{Freq}; 1.04 \cdot \text{Freq}]$ is meant, over which the total radiated power is integrated. Peak powers can be accurately measured down to the few tens of microWatts, both ions and protons bunch spectra could then be measured at least up to 10 GHz with ChDR diagnostic.

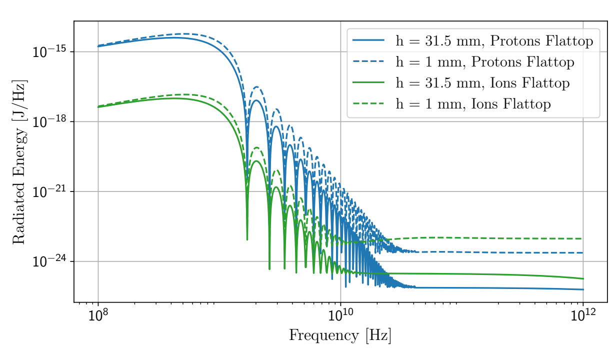

Figure 2: Energy radiated by a non-Gaussian bunch.

BEAM HALO

In high intensity rings such as LHC, outside the densely populated bunch core, a small fraction of particles acquire

Table 2: Peak Power Emitted by a Single Non-Gaussian Bunch

Freq [GHz]	Pb/1 mm P_p [W]	Pb/31.5 mm P_p [W]	p/1 mm P_p [W]	p/31.5 mm P_p [W]
1	$8.4 \cdot 10^{-1}$	$3.9 \cdot 10^{-1}$	$3.4 \cdot 10^{2}$	$1.6 \cdot 10^{2}$
3	$3.1 \cdot 10^{-3}$	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{0}$	$2.2 \cdot 10^{-1}$
10	$1.0 \cdot 10^{-5}$	$6.2 \cdot 10^{-7}$	$1.4 \cdot 10^{-3}$	$8.6 \cdot 10^{-5}$
36	$4.7 \cdot 10^{-5}$	$1.4 \cdot 10^{-6}$	$1.3 \cdot 10^{-5}$	$4.0 \cdot 10^{-7}$
100	$1.4 \cdot 10^{-4}$	$3.9 \cdot 10^{-6}$	$3.3 \cdot 10^{-5}$	$9.8 \cdot 10^{-7}$

significantly high transverse energy, which results in the creation of the beam halo. In the context of ChDR diagnostics, estimating the impact of the halo population is especially interesting as the radiation yield strongly increases if a particle shifts closer to the radiator. Under certain conditions, the tails of the transverse bunch distribution would dominate the signal emitted at well defined wavelengths, providing thus a measurement of the tail population.

In order to study the effect of the halo on the ChDR spectral density, we take the assumption that the transverse profile of the bunch is the sum of two Gaussian distributions. The main core bunch of intensity $N = 1.15 \cdot 10^{11}$ can be characterized with a transverse standard deviation $\sigma_{core} = 0.25$ mm, while the low intensity halo Gaussian has $\sigma_{halo} = 0.5$ mm. In addition, we assume that due to the collimators no particles are present further than 1.25 mm from the bunch center. These assumptions are graphically presented in Fig. 3.

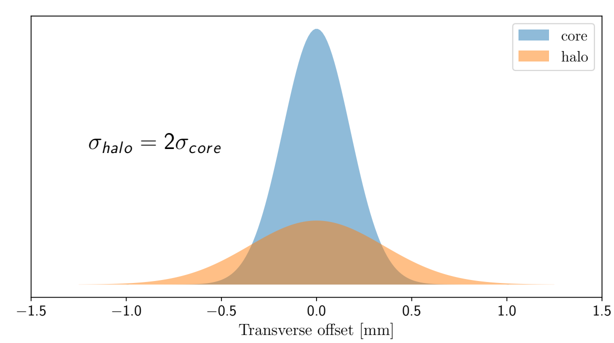

Figure 3: Schematic LHC bunch consisting of the highly populated core and low intensity halo - overscaled for illustrative purpose.

We can now observe how the ChDR intensity varies with the change of beam halo population. For that we assume that the radiator is placed 1.5 mm from the center of the beam, which can be achieved if it is embedded in a collimator. As can be seen in Fig. 4, if measuring wavelengths in 570-630 nm band, the radiation from the core dominates and the halo population has no impact on the radiation intensity, if intensity remains below 1% of the core intensity. From the shape of the radiation spectral distribution (Fig. 1) it can be deduced, that the same will hold for higher wavelengths.

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If we consider however extreme ultraviolet band, we can see that the radiation intensity becomes proportional to the halo intensity after it exceeds approximately 10^{-5} of the core population. Having in mind, that the High-Luminosity LHC upgrade Design Report [12] states a need to resolve the tails of 10^{-5} with respect to the core, ChDR diagnostics might be investigated as a potential halo measurement technique.

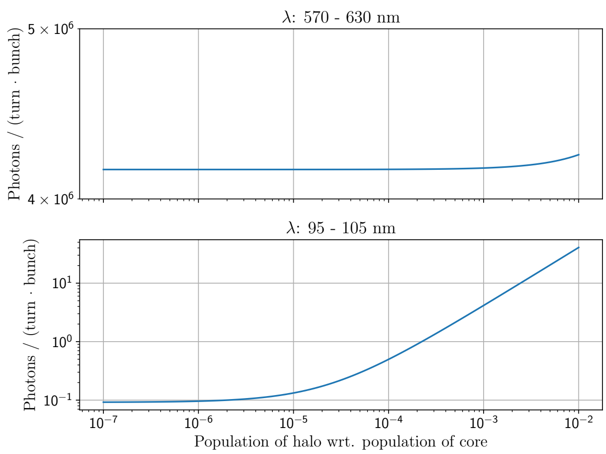

Figure 4: N° of photons emitted in orange and extreme ultraviolet frequency range, as a function of the halo population.

RADIATOR COATING

One of the limiting factors in the performance of the LHC, potentially leading to instability arising and excessive heat load, is the creation of electron clouds inside the beam pipe [13]. One of the ways to mitigate this effect is to coat the inner walls of the beam pipe with an amorphous carbon (a-C) layer [14]. Such a coating characterizes with a low secondary electron yield, therefore decreases the probability of the electron cloud build-up.

When using Cherenkov diffraction radiator, the presence of secondary electrons at the surface of the dielectric would be a risk both to build-up e-cloud but also to charge up the dielectric. It is therefore important to know if low resistivity coatings can be used to mitigate this effect without reducing significantly the radiation power.

Such an analysis cannot be performed with the PCA model, as it describes only one-layer structures. An alternative approach was proposed in [15], where the ChDR was modelled for infinitely long multi-layer cylindrical or flat geometries. Using this method we calculate the ChDR radiation suppression due to the presence of a thin 0.5 μm a-C layer on top of the dielectric placed within the beam pipe in the case of protons at flat top energy. As for adhesion purposes a-C is sometimes coated on an intermediate 100 nm titanium layer, we simulate this case as well. Thickness and electrical properties of the layers follow the ones reported in [16].

As can be seen in Fig. 5, in sub-THz range the sole presence of a-C coating does not lead to signal suppression stronger than 10%. Adding an intermediate layer of titanium has a significant impact and reduces the radiation yield down to 1.5% of the original value. Experimental validations of such an effect are foreseen to validate what coating to choose.

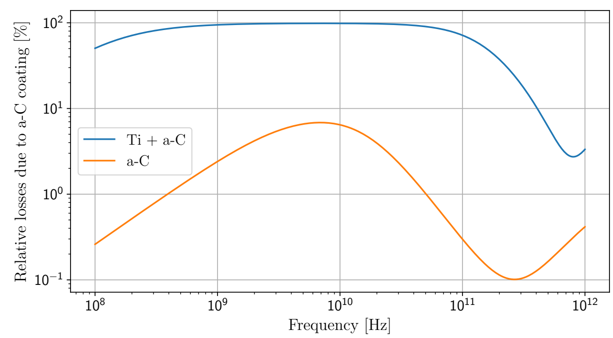

Figure 5: Signal reduction due to the presence of a-C coating.

CONCLUSIONS AND PROSPECTS

In this contribution we have presented preliminary studies on the possibility of the ChDR diagnostics in the LHC. The results of these calculations support the feasibility of measuring ChDR in the microwave frequency range for longitudinal bunch spectrum characterisation up to high frequency (10 GHz). In addition, it was estimated that the presence of halo particles has a negligible impact on the measured signal in the frequency bands most relevant for the diagnostic purposes, but observation of ChDR in extreme violet might provide some information on the halo population. Finally, covering the radiator with a-C coating was shown not to have a significant impact on the output signal.

To highlight future work, Fig. 6 presents the experimental setup which is being prepared for the first measurements of ChDR emitted by protons. The tests are planned to be carried out at HiRadMat facility [17] at CERN. The shown dielectric buttons are made out of brazed alumina on stainless steel. Tests with coated versions of the buttons are also foreseen to happen later on.

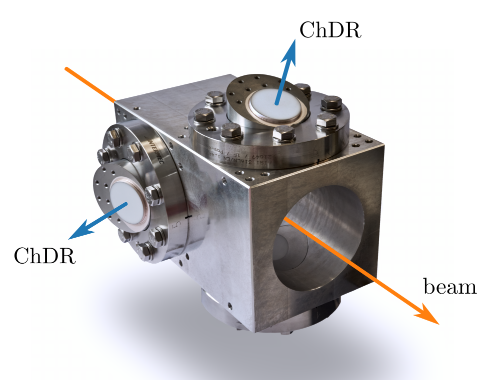

Figure 6: Schematic of ChDR pick-up using alumina rods.

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