SYNCHROTRON RADIATION IN THE LHC VACUUM SYSTEM

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Abstract

CERN is currently operating the Large Hadron Collider (LHC) with 3.5 TeV per beam. At this energy level, when the protons trajectory is bent, the protons emit synchrotron radiation (SR) with a critical energy of 5.5 eV. Under operation, SR induced molecular desorption is routinely observed in the LHC arcs, long straight sections and experiments. This contribution recalls the SR parameters over the LHC ring for the present and nominal beam parameters. Vacuum observations during energy ramp, after accumulation of dose and along the LHC ring are discussed. Expected pressure profiles and long term behaviours of vacuum levels will be also addressed.

INTRODUCTION

The Large Hadron Collider (LHC), currently under operation at CERN, is designed to push further our understanding of particle physics [1]. This is the first proton storage ring which is producing a significant quantity of synchrotron radiation (SR) which affects the vacuum system. At 7 TeV per beam and with nominal beam current, the LHC photon flux will be about 3 times larger than LEP200, the previous CERN headlight machine operating with electrons and positrons. However, being a proton machine, the dissipated power by SR will be much lower than LEP200 *i.e.* 0.2 W/m against 1 kW/m. To achieve 7 TeV per beam in the 27 km circumference tunnel, the arc dipole field must equals 8.3 T. Thus, the superconducting technology is required to circulate a current of 11.85 kA in the Nb-Ti cables. These cables are cooled down to 1.9 K to increase further their performances.

The arc vacuum system is made of a cold bore held at 1.9 K housing a beam screen designed to intercept the beam induced heat load at higher temperature to minimise the cryogenic budget. Along each cell of 102 m long, the temperature of the beam screen is increasing from 5-8 K to 20 K. By design, the available cooling capacity to extract the dynamic heat load on the beam screen varies from 1.5 to 2 W/m per aperture. Under SR bombardment, desorption of hydrogen is stimulated. Consequently, the molecules are physisorbed and accumulated on the beam screen surface. In a closed system operating at 5 K, the growth of a monolayer of hydrogen leads to a saturated vapour pressure of about 10^{-4} mbar, a value by far too large for a storage ring. So, the beam screen is perforated by slots to provide pumping of the desorbed gas onto the cold bore. Figure 1 shows a picture of the LHC arc beam screen. The beam screen is made of non-magnetic copper plated stainless steel. Its transparency is ~ 4 %. Saw teeth are produced in the horizontal plane to perpendicularly intercept the SR, minimising the forward reflectivity and photoelectron yield. Shields, designed to protect the cold bore by intercepting the electron moving along the vertical dipole field lines, are clipped onto the cooling capillaries.

Figure 1: the LHC beam screen.

Due to the present interconnection design, the LHC energy is limited to 3.5 TeV per beam before upgrade to nominal after the next long shutdown.

LHC PARAMETERS

When a charged particle is accelerated longitudinally or transversally it produces a radiation. For a relativistic particle, this radiation is highly peaked in the forward direction with 1/γ opening angle. In a synchrotron, the radiation is emitted tangentially to the orbit in the horizontal plane. The energy of the emitted photons varies from infra-red to gamma rays *i.e.* from meV to MeV. The radiation spectrum is characterised by the critical energy, ε_c, energy at which the SR power spectrum is halved in two. About 90 % of the emitted photons have energy lower than the critical energy.

The SR main parameters can be computed from formulas, see *e.g.* [2]. Here, practical equations are given for protons beam at a given beam current, I and energy, E.

The critical energy is expressed by (1) with h, the plank constant, c, the speed of light, ρ, the bending radius and γ the relativistic factor.

$$\varepsilon_c = \frac{3}{2}\frac{\mathrm{hc}}{2\pi}\frac{\gamma^3}{\rho} = 3.8535\,10^{-7}\,\frac{\mathrm{E}[GeV]^3}{\rho[m]} \quad (1)$$

The average power emitted by the beam per unit of length is given by (2) with e the elementary charge ε_o the vacuum permittivity and m_o the proton classical radius.

$$\mathrm{P_0\,[W/m]} = \frac{\mathrm{e}}{3\varepsilon_0\left(\mathrm{m_0c^2}\right)^4}\frac{\mathrm{E}^4}{2\pi\rho^2}\mathrm{I} = 7.79\,10^{-12}\,\frac{\mathrm{E}[GeV]^4}{2\pi\rho[m]}\mathrm{I}[mA] \quad (2)$$

The photon flux, $\dot{\Gamma}$, is expressed by (3).

$$\dot{\Gamma} = \frac{5\sqrt{3}\mathrm{e}}{12\,\mathrm{h}\,\varepsilon_0\mathrm{c}}\frac{\gamma}{\rho}\mathrm{I} = 7.017\,10^{13}\,\frac{\mathrm{E}[GeV]}{\rho[m]}\mathrm{I}[mA] \quad (3)$$

Arc Magnets

The LHC arc lattice is of FODO type. The beams are circulating in two beam lines separated by 194 mm. Each of the dipole emits SR along its magnetic length (14.3 m).

Given the bending radius of 2803.95 m, the incidence angle of the SR is 5.1 mrad. Only 2.9 m of arc irradiates the same magnet, the remainder (11.4 m) goes into the next magnet or the straight section. Table 1 shows the SR main parameters of the arc dipoles when operating the LHC with nominal beam current (584 mA). In the last column, the annual photon dose is computed assuming continuous operation during 150 days.

Table 1: SR main parameters of the arc dipoles

Energy [TeV]	ε_c [eV]	P [mW/m]	$\dot{\Gamma}$ [ph/m/s]	Dose [ph/m]
3.5	5.5	14	$5\ 10^{16}$	$7\ 10^{23}$
7	43.9	222	$1\ 10^{17}$	$1\ 10^{24}$

In Figure 2 is shown the 3.5 TeV LHC photon flux distribution in the vertical angle. Photons whose energies are above 3 eV are vertically confined to less than 0.3 mrad. At 7 TeV, the flux of high energy photon is more intense and more focussed vertically. The height of the SR fan on the beam screen wall is ~ 5 mm.

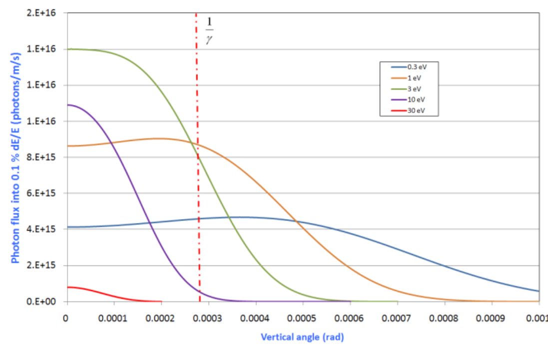

Figure 2: Photon flux distribution in the vertical angle at 3.5 TeV.

Figure 3 shows LHC spectra at injection energy (450 GeV), 2.5, 3.5 and 7 TeV. The LHC emits in the VUV range. At injection, the energy of photons is in the meV range. Above, ~ 2.5 TeV a significant fraction of the photon spectrum have energies in the eV range.

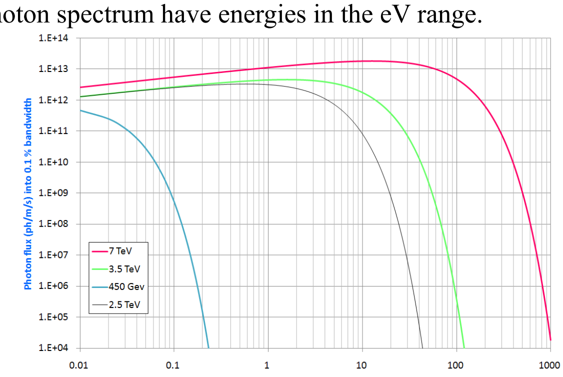

Figure 3: LHC synchrotron radiation spectra.

Insertion Magnets

In the long straight sections (LSS), separation dipoles are introduced to bring the beams in a single beam pipe to allow collisions or to increase the beam separation to 224 and 420 mm for the insertion of collimators and RF cavities. Table 2 shows the main parameters for the LHC separation dipoles of the experimental insertions when operating at nominal current. In LSS 1 and 5 (*i.e.* ATLAS and CMS), D1, the separation dipole located in front of the triplet quadrupoles, is operating at room temperature (RT). In LSS 2 and 8 (*i.e.* ALICE and LHC-B), D1 is operating at 4.5 K. In all experimental insertion, D2 is the superconducting dipole which brings the two beams in a single beam pipe. As compared to the arc, the photon flux and the critical energy are a factor 2 to 7 lower.

Table 2: SR main parameters of the separation dipoles of the LHC experimental insertions

Name	Energy [TeV]	ε_c [eV]	$\dot{\Gamma}$ [ph/m/s]	Dose [ph/m]
D1 at RT	3.5	0.8	$8\ 10^{15}$	$1\ 10^{23}$
	7	6.5	$2\ 10^{16}$	$2\ 10^{23}$
D1 and D2 at 4.5 K	3.5	2.5	$2\ 10^{16}$	$2\ 10^{23}$
	7	20	$5\ 10^{16}$	$6\ 10^{23}$

It can be shown that 25 m after the arc extremity, the remaining photon flux from the last dipole relative to the arc is about 10 %. At D2 level, this value drops to 1 %. Therefore the main contributors of SR inside the experimental insertion are D1 and D2 magnets.

Due to the large bending radius of 6.1 and 18.2 km for the 4.5 K and RT dipoles respectively, the SR light travels 15 and 30 m before impinging the vacuum chamber at and angle of 1.5 and 0.2 mrad respectively. Moreover, since the Cu plated beam screen of the triplet quadrupoles is highly reflective at these photon energy (close to 100 %), the entire experimental beam pipe is irradiated by the SR.

LHC OBSERVATIONS

The first signs of SR were observed at the arc extremities during summer 2010. At that time, it was clearly identified that at flat top, one beam pipe showed a pressure increase in the range of a few 10^{-10} mbar for some mA while the other one, at the same location, did not show any. In all cases, the pressure rise was correlated with the proton beam which was coming out of the arc. Since then, the beam current has increased to 320 mA (fill 2040) with a pressure increase at the arc extremity of 10^{-9} mbar. The 22nd of August 2011, the accumulated photon dose in the arc reached $6\ 10^{22}$ ph/m.

Figure 4 shows the dynamic pressure increase in mbar/A measured at the arc extremity as a function of the integrated dose, Γ. The dynamic pressure decreases with the dose. The molecular desorption yield, η, proportional to the dynamic pressure, is reduced according to (4). α is equals to 0.8 which is very closed to values observed in other machines [3].

$$\eta \propto \Gamma^{-\alpha} \tag{4}$$

During the course of the year, a scrubbing run was held while $3\ 10^{21}$ ph/m were accumulated. The objective of this run was to reduce the electron cloud activity while conditioning the vacuum chamber wall under electron bombardment [4]. As seen from Figure 4, no net gain on the conditioning rate was achieved. Indeed, due to their geometric properties, SR induces desorption from the side wall of a vacuum chamber, while the electron cloud in field regions induces desorption from the top and bottom side of a vacuum chamber in a way that the two independent contributions add up.

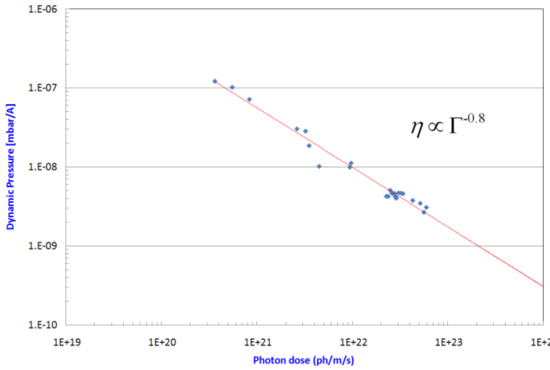

Figure 4: Reduction of the dynamic pressure measured at the arc extremity versus the photon dose.

The variation of the dynamic pressure at the arc extremity was also measured while the LHC beam energy was ramped from 450 GeV to 3.5 TeV. During this phase, the LHC spectrum is modified according to Figure 3. In the same time, the photon flux is also increased linearly. As shown in Figure 5, when the beam energy is above 2.5 TeV, the pressures increase by about one order in magnitude. This beam energy corresponds to a critical energy of 2 eV.

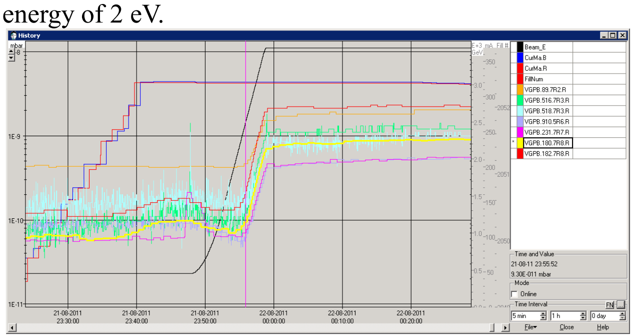
Figure 5: Pressure observed during a ramp (fill 2040-21/8/2011)

Figure 6 shows the computed dynamic pressure in mA/TeV proportional to the molecular desorption yield as a function of the critical energy. Each curve can be fit to (5) with β equals 2.5.

$$\eta \propto \varepsilon_c^{\beta} \qquad (5)$$

Pressure increases due to synchrotron radiation were also observed in the LHC experiments. For instance, during fill 2040, the recorded pressure at the level of the entrance of the triplet quadrupole (Q1) and inside the high luminosity experiments at 18 m from the interaction point were 5 10^{-10} and 2 10^{-11} mbar respectively.

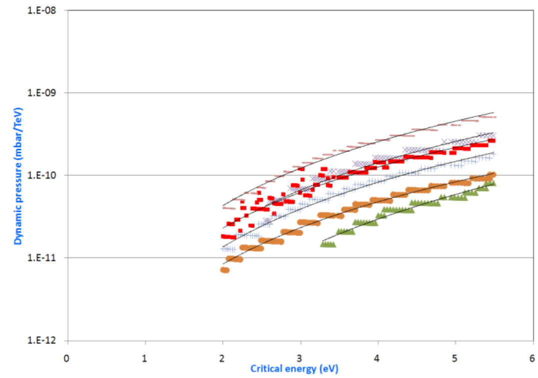

Figure 6: Dynamic pressure observed during the ramp (fill 2040-21/8/2011)

FUTURE PERFORMANCES

Based on the previous observations, the future performances of the LHC vacuum system can be extrapolated. We assume that the vacuum system is conditionned to neglect the electron cloud contribution and that LHC operates below the electron cloud threshold. The LHC will operate at 3.5 TeV till the consolidation of the interconnection during the next long shutdown after which 7 TeV per beam will be reached. LHC is currently operating with 50 ns bunch spacing. However, the bunch spacing could be reduced to 25 ns in the coming months opening the possibility to reach the nominal beam current. In this case, the accumulated photon dose in the arc would be ~ 7 10^{23} ph/m *i.e.* one order of magnitude larger than at present. The achieved pressure at the arc extremity would be a few 10^{-10} mbar before the next long shutdown. After consolidation for 7 TeV operation, the arc extremity pressure will be a few 10^{-8} mbar. Due to the larger pumping speed and lower desorption yields, the pressure inside the arc will be at least one order of magnitude lower *i.e.* the vacuum beam life time will be larger than 100 h.

CONCLUSIONS

For the first time, a vacuum system was designed to be subjected to SR from a proton beam. In this contribution, the main SR parameters of the LHC have been presented. During the commissioning of the LHC, dynamic pressures due to SR were observed in several areas of the ring despite the present operation with reduced beam energy. Extrapolation of present performances to design values indicates that the target vacuum beam life time of 100 h will be reached.

REFERENCES

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