DIAGNOSTIC WITH SYNCHROTRON RADIATION OF THE LHC PROTON BEAMS.

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Abstract

Proton beam diagnostics at LHC will be done with a synchrotron radiation monitor that will provide 2D images of the beams, from which the transverse profiles and related emittances will be obtained. In order to optimize the monitor performances over the whole LHC energy range, a survey of different types of light sources has been performed. Based on numerical and analytical methods, the comparison of photon fluxes and spectra has shown the necessity of a dedicated design, namely a superconducting undulator combined with a deflection dipole in the IR4 straight section of LHC.

1 INTRODUCTION

The measurement of the beam profiles over the whole proton beam energy range of LHC is of prime importance. The requested relative accuracy is of a few percents of beam sizes, all the way through the acceleration cycle from 450 GeV to 7 TeV. Turn by turn as well as individual bunch measurements are also required with a view to identifying beam dynamics problems. A synchrotron radiation (SR) monitor is one of the retained candidates to perform the task.

However SR has to cope with detrimental conditions such as low injection energy (450 GeV), low intensity, or small bunch spacing, for instance during commissioning, which imposes extensive work on the SR source optimization. Several possible configurations have been studied and compared in this framework to converge to the proposed solution of a superconducting undulator combined with a dipole of the D3 type in the IR4 straight section (RF cavity region).
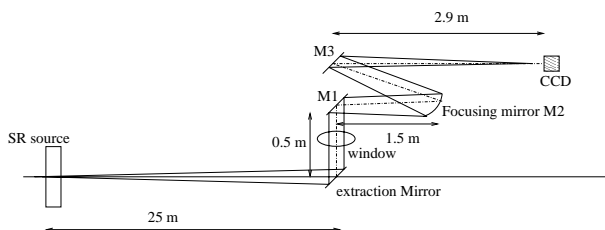
2 PRINCIPLE

Figure 1: SR monitor principle.

Protons emit SR in a small cone centered on the particle

trajectory when traveling in a magnetic bending field. For the profile measurement, the light emitted by the beam in the wavelength range 350-1100 nm is imaged onto a CCD detector by means of folding and focusing mirrors (Fig. 1). The image is the convolution of the beam transverse profile by the SR Point Spread Function (PSF) and the total intensity in the image is proportional to the number of particles in the beam.

In order not to restrict the machine aperture, the mirror edge has to be located 15 rms beam sizes away from the beam axis, making it necessary to have a beam deflection between the SR source and the extraction mirror, which imposes various geometric constraints in the diverse configurations studied.

3 CHOICE OF THE SOURCES

By tailoring the magnetic structure of the source, it is possible to optimize the spectral angular energy density for a given machine geometry and observation frequency range. This is what has been worked out for the LHC SR monitor in order to propose a layout suitable for diagnostics over the whole acceleration cycle.

3.1 D2 Dipole

Based on the LEP experience, the most natural source to consider is a main dipole in the machine, yet light extraction problems due to the cryostats preclude using the arc dipole. A possible solution is a D2 type separation dipole, 9.45 m long with a magnetic field of 2.65 T at 7 TeV, and with a constant deflection angle $\alpha = 1.07$ mrad over the whole acceleration cycle.

At 450 GeV the light cone opening is $1/\gamma = 2$ mrad. As a consequence, the cones emitted by both edges of the dipole are superposed and interfere.

As the proton energy increases, α stays constant whereas the SR opening angle shrinks as $1/\gamma$ to reach 0.5 mrad at 2 TeV. At that energy, the light cones are angularly separated and the radiation emitted by the core of the dipole is observable. It then becomes possible to collect the light from the core and to filter out possible parasitic sources located upstream of the dipole.

As no suitable analytical model is available to describe the SR emitted by D2, the energy intercepted by the optics when the horizontal angular acceptance is limited with a slit in the focal plane [1], presented in Table 1, was simulated with the code Zgoubi [2]. It has been evaluated that to perform a beam profile measurement with a 5% precision, the energy required in the turn by turn mode, with the nominal bunch (10^{11} protons) and with the chosen optical elements is 10^{-23} J for one proton. The simulations show

Table 1: Energy collected (350-1100 nm) with a slit in the focal plane limiting the angular acceptance to 0.25 mrad.

Proton	Energy collected (J) for 1 proton	
Energy(TeV)	D2 center	D2 edge
0.45	2.3×10^{-28}	1.9×10^{-28}
1	1.1×10^{-26}	4.5×10^{-26}
2	4.6×10^{-24}	8.4×10^{-24}
7	9×10^{-22}	3.6×10^{-22}

that on top of interference issues at injection energy, below 1 TeV, the signal is too weak for profile measurements. To cover all the energy range, others sources have hence to be considered.

3.2 Miniwiggler

Starting from the possibility to use the 1 m long proto-type coils of the LHC superconducting dipoles, a miniwiggler has been studied for the beam energy below 2 TeV, in complement to the D2 dipole for the high energies. The miniwiggler is comprised of four 1 m long dipoles, with the magnetic field increased with the proton energy in order to have constant and self-compensated orbit bump. With a maximum magnetic field of 6 T, the dipole deflection α is 0.86 mrad. The observation is taken in the direction of the beam between the first two dipoles in order to maximize the separation between proton beam and SR (Fig. 2). At
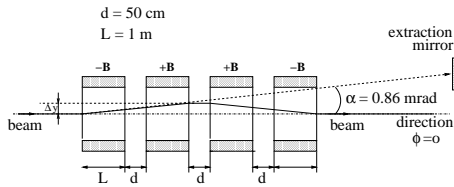
Figure 2: Miniwiggler configuration. ϕ is the angle in the horizontal plane between the observation direction and the miniwiggler axis.

450 GeV, the SR opening angle is $1/\gamma = 2$ mrad and again the magnet deflection is too small to separate the radiation cones from the dipoles emitting in the direction $\phi = \alpha/2$ for the first two and in the direction $\phi = -\alpha/2$ for the last two. The dipoles therefore interfere, and the maximum intensity is in the direction of the proton beam, so that only part of the light cone is collected by the extraction mirror.

To increase the light production at injection energy, another solution, called "double extraction", has been considered. It uses the miniwiggler with the same magnetic fields for the whole energy ramp, with already B=6 T at injection. The deflection angle of the dipole is then 4 mrad, requiring another closer extraction mirror.

3.3 The Undulator

An undulator is a periodic structure with a sinusoidal magnetic field $B(z) = B_0 cos(k_u z)$ with $k_u = 2\pi/\lambda_u$ and

λ_u being the spatial periodicity of the structure (Fig. 3). A proton beam in such an undulator will wiggle with
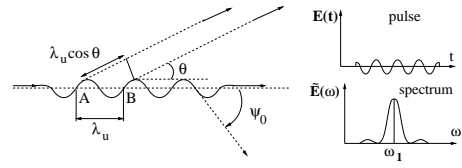

Figure 3: Planar sinusoidal undulator

a coherent temporal structure thus producing a quasi-monochromatic radiation, according to the constructive interference condition between λ_u, the observation direction θ and the deflection parameter $K = \psi_o/\gamma$:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \qquad (1)$$

where ψ_o is the maximum trajectory deflection. The angular distribution of the emitted light depends on the emitted frequency, the beam energy and the undulator characteristics by:

$$\frac{d^2W}{d\Omega d\omega} \propto B_0^2 \lambda_u \gamma^4 f(\theta,\varphi)\frac{N^2}{\omega_u}\left(\frac{sin(\frac{(\omega-\omega_u)\pi N}{\omega_u})}{\frac{(\omega-\omega_u)\pi N}{\omega_u}}\right)^2 \qquad (2)$$

wherein $\omega_u = \frac{4\pi\gamma^2 c}{\lambda_u(1+\gamma^2\theta^2)}$ is the critical pulsation and $f(\theta,\varphi) = \frac{(1-\gamma^2\theta^2\cos(2\varphi))^2+(\gamma^2\theta^2\sin(2\varphi))^2}{(1+\gamma^2\theta^2)^5}$ describes the spatial distribution, φ being the azimuthal angle around the θ axis.

The frequency spread around ω_u of the SR spectral distribution is shrinking with an increasing number of periods N and the emitted wavelength for a given observation angle decreases with increasing beam energy. Optimization of the intensity collected within the observation wavelength range, over the large LHC energy span and accounting for the limited observable light cone angle (about 2 mrad, due to the vacuum chamber size), leads to a 28 cm two periods undulator with about 6 T peak magnetic field.

Given these parameters, the wavelengths received on the mirror (with an angular acceptance between 0 and 1.5 mrad) stay in the observation wavelengths range (200-900 nm) when the beam energy increases up to 7 TeV.

A pre-design of the undulator has been performed with OPERA3D [3] and has provided a simulated magnetic field which has been used for the simulations with Zgoubi, presented in the following paragraph.

3.4 Comparison of the sources at 450 GeV.

Several sources and configurations have been computed, taking into account the geometrical constraints of an implementation in the LHC ring and of the light extraction. The most interesting configurations, presented before, are compared in Table 2 in terms of energy production per proton, in the observation wavelengths range, at injection energy.

Table 2: Comparison of the intensity collected by the different set-ups for a proton energy of 450 GeV. The simulations have been done with Zgoubi for the frequency range 350-1100 nm.

Layout name	B (T)	total length	Energy on mirror (J) (1 part., 1 turn)
miniwiggler	1.3	5.5 m	5.6×10^{-26}
double extraction	6	5.5 m	1.6×10^{-24}
undulator	6	56 cm	1.04×10^{-23}

4 THE CHOSEN SR SOURCE FOR LHC

4.1 Layout

The superconducting undulator is the source which optimizes the light production at injection energy in the wavelength range of concern. As the SR is emitted in the beam direction, the beam must therefore be deflected between the undulator and the extraction mirror. The undulator will be installed in front of an existing 9.45 m long D3 type dipole with a magnetic field of 4.5 T at 7 TeV (Fig. 4). As
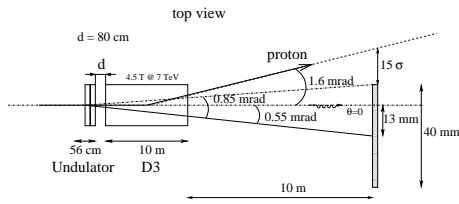

Figure 4: Undulator layout at IP4.

a consequence, the actual SR source is comprised of the undulator from 450 GeV to about 1 TeV, both the undulator and the D3 edge between 1 and 2 TeV, and the input edge above 2 TeV. The angular energy density emitted by the undulator and D3 together is simulated for 450 GeV in Fig. 5 (left) and for 1 TeV in Fig. 5 (right). At 1 TeV,
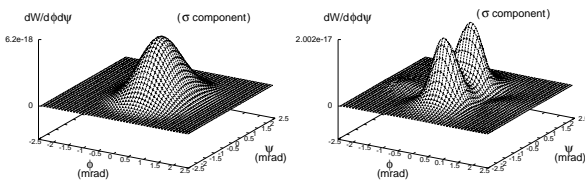

Figure 5: Angular energy density $\frac{dW}{d\phi d\psi}$ (horizontal or σ component) emitted in the source by a proton of 450 GeV (left) and of 1 TeV (right) in the range 200-900 nm. The ϕ (resp. ψ) angle defines the observation direction w.r.t the horizontal (resp. vertical) plane.

the undulator is out of tune so that the useful wavelengths are emitted at higher θ values : the central lobe visible at 450 GeV changes into an annular density pattern centered

on θ=1.5 mrad, corresponding to the emission direction of the visible wavelength, and modulated by the asymmetric spatial distribution factor f(θ,φ).

4.2 Performance

Table 3 summarizes the collected energy per proton and per turn on the extraction mirror for different wavelength ranges corresponding to different sensitivity regions of the CCDs. It shows that it is now possible to measure beam profiles over all the acceleration cycle with this source.

Table 3: Energy received on the mirror, emitted by undulator and D3 together, for different wavelength ranges.

Proton Energy (TeV)	Energy on the mirror (J) (1 part, 1 turn)		
	200-900 nm	400-600 nm	600-900 nm
0.45	1.51×10^{-23}	4.05×10^{-24}	1.10×10^{-23}
1	3.30×10^{-23}	2.86×10^{-24}	8.52×10^{-25}
2	5.47×10^{-23}	1.69×10^{-23}	2.42×10^{-23}
7	2.21×10^{-21}	4.92×10^{-22}	3.04×10^{-22}

5 CONCLUSION

The light source performance is fundamental for the selection of a SR profile monitor. The study undertaken for LHC has shown that a dedicated source is necessary to meet the requirements of the users. The proposed solution is the combination of a 2-period superconducting undulator with the fringe field of a separation dipole D3, which will be implemented in the IR4 region. The simulation has shown that the light produced is sufficient for beam profile measurements with a single bunch down to a turn by turn mode.

Detailed studies taking into account the effects of diffraction and depth of field on the image size have been made. First simulations with the ESRF code SRW have shown that the induced image broadening is less than 1 % at injection and about 18% of the beam size at collision energy (where the beam has the smallest dimensions).

6 ACKNOWLEDGMENTS

7 REFERENCES

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