EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH
CERN – SL DIVISION

CERN-SL-2002-015 BI

**The LHC 450 GeV to 7 TeV Synchrotron
Radiation Profile Monitor using a
Superconducting Undulator**

R. Jung, P. Komorowski, L. Ponce, D. Tommasini

Abstract

In LHC it will be important to measure with precision and in a non-destructive way the proton beam profiles from 450 GeV to 7 TeV. The chosen Synchrotron Radiation Monitor will make use of a two-period 5 T superconducting Undulator coupled to the D3 bending magnet in IR4. From the various variants studied, this combination is the only one which can cover the whole LHC energy range. By locating both magnets in the same cryostat, it will be possible to minimise the light source length for best precision. The undulator and telescope parameters and basic design are described. The evolution of the synchrotron radiation patterns as well as the performance with respect to sensitivity, depth of field and diffraction along the energy ramp are given.

*Presented at BIW02, 10th Beam Instrumentation Workshop
Brookhaven National Laboratory, Upton, New York
6-9 May 2002*

Geneva, Switzerland
May 2002

The LHC 450 GeV to 7 TeV Synchrotron Radiation Profile Monitor using a Superconducting Undulator

R. Jung, P. Komorowski, L. Ponce, D. Tommasini

CERN, CH1211 Geneva 23, Switzerland

Abstract. In LHC it will be important to measure with precision and in a non-destructive way the proton beam profiles from 450 GeV to 7 TeV. The chosen monitor will make use of a 5 T superconducting Undulator with two periods coupled to the D3 bending magnet built by BNL. From the various variants studied, this combination is the only one which could cover the whole LHC energy range. By locating both magnets in the same cryostat, it will be possible to minimise the light source length for best precision. The choice of the undulator parameters and its basic design will be described. The evolution of the synchrotron radiation patterns along the energy ramp will be given, as well as the performance with respect to sensitivity, depth of field and diffraction, with a description of the simulation codes used.

INTRODUCTION

There is a strong need in LHC to measure the beam profiles all along a run. The tight emittance budget asks to measure the emittance at beam injection at 450 GeV to check that the limit of 5% blow-up between the circular machines is respected. A turn-by-turn measurement during the first tens of turns will check that the matching between the accelerators is done properly [1]. A relative accuracy of the order of a few percent is requested for the measurement of the turn by turn profile oscillations that are the signature of a mismatch. The beam size evolution has then to be followed through the acceleration cycle from 450 GeV to 7 TeV where the beam size shrinks substantially but for which a normalised emittance blow-up of less than 7% is requested. Finally, the beam profile has to be measured with a relative accuracy better than a few percent to adjust the aperture controlling collimators. During all these phases, there is also a demand to measure individual bunches out of the 2808 circulating bunches, at various locations in a 72 bunches batch in order to identify beam dynamics problems.

An ideal monitor for these tasks is a non-intercepting monitor. One monitor of this kind is a Synchrotron Radiation (SR) monitor. The main candidate was a monitor close to a physics Interaction Region (IR), IR1 or IR5, using the light generated in one of the dogleg bending magnets, D2, bringing the beams back to the nominal LHC separation after the IR. This monitor was in a favourable location where the beam size increases at top energy when the beams are brought into collision optics. Unfortunately, the light production within the spectral range of available detectors,

was only sufficient above 2 TeV. From injection energy to 2 TeV, another solution had to be found. Various solutions were looked at in the RF region IR4, using room temperature or superconducting undulators to generate enough light in the neighbourhood of the visible spectrum. These solutions could cover the 450 GeV to 2 TeV region, but were useless above, generating the additional problem of changing monitors during the delicate process of the energy ramp.

An acceptable solution became possible when the IR4 layout was changed for economical reasons and a long dogleg was introduced to go from a separation of 420mm in the IR, dictated by the RF cavities, towards the 194mm in the standard LHC arc dipoles. With this layout, a superconducting Undulator could be introduced in front of the D3 separating magnet, which deflects the circulating beam from the SR generated in the Undulator. A mirror can be introduced to collect and deflect out of the vacuum chamber the SR after a drift of some 10m after D3. Above 2 TeV, the Undulator radiates again mostly outside the detector range, but this time the edge radiation of the D3 magnet will be used as SR source. Finally at top energy, the whole of D3 radiates enough SR, which has this time to be limited to a region close to the entrance edge for limiting the longitudinal acceptance of the imaging optics.

SR CHARACTERISTICS OF THE UNDULATOR

An Undulator is a periodic magnetic structure that concentrates the SR through interference in a cone in the forward direction along the beam path [2]. It is characterised by a factor K, with $K < 1$ for an Undulator:

$$K = \lambda_u B_0 \frac{e}{2\pi m_p c} \quad (1)$$

where λ_u is the Undulator period and B_0 the peak magnetic field on the beam axis.

The coherence condition relates the emitted SR wavelength λ_c to a given direction θ with respect to the beam axis and the Undulator characteristics by:

$$\lambda_c = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) \approx \frac{\lambda_u}{2\gamma^2} (1 + \gamma^2 \theta^2) \quad (2)$$

The angular spectral energy density in the deflection plane of the Undulator is given in equation (3), with the usual notations, k being a constant and N_u the number of Undulator periods. From this equation, it is clear that the light production will increase as B_0^2 . It can also be seen that the light production decreases when going away from the beam axis and that the light spectrum narrows around λ_c when the number of Undulator periods N_u increases:

$$\frac{d^2 W}{d\Omega d\lambda} \approx k B_0^2 \left[\frac{\gamma}{1 + \gamma^2 \theta^2} \right]^6 [1 - \gamma^2 \theta^2]^2 \left[N_u \frac{\lambda_c}{\lambda} \right]^2 \left[\frac{\sin\left(\frac{\lambda_c}{\lambda} - 1\right) \pi N_u}{\left(\frac{\lambda_c}{\lambda} - 1\right) \pi N_u} \right]^2 \quad (3)$$

Based on these considerations, a two period superconducting Undulator, of 28cm period, and with a peak field of 5T was chosen. The relevant parameters of this

Undulator are: $K = 0.07$ and $\lambda_{co} = 608 \text{ nm}$ at 450 GeV and already down to $\lambda_{co} = 55 \text{ nm}$ at 1.5 TeV on the beam axis. It is only because of the spectral width due to the small number of magnetic periods and to the angular acceptance of $-0.5/+1.5 \text{ mrad}$, that there will be a reasonable amount of energy available in the spectral range of the detectors.

The evolution of λ_c as a function of beam energy and observation angle is given in figure 1. This situation is acceptable at high energy because the edge of the D3 magnet starts to produce enough SR from 1 TeV onwards.

FIGURE 1. Coherence wavelength versus angle to the beam direction as a function of beam energy, with the spectral sensitivity bands of a back-illuminated CCD and a MCP with a SS25 photocathode.

SR EMITTED BY THE D3 BENDING MAGNET

Starting at 750 GeV, the edge of D3 will emit light in the range of interest.

FIGURE 2. Angular light pattern resulting from the combination of the SR from the Undulator (ring pattern with central peak) and of the D3 bending magnet input edge (at the centre of the Undulator pattern) and exit edge (peak at the left) at 1 TeV.

The light is emitted by the entrance edge along the same direction as the Undulator SR, and can hence be extracted under the same conditions. This light will interfere with the light produced by the Undulator. A typical angular light pattern for the intermediate energies is given in figure 2.

Once the energy increases beyond 2 TeV, the whole core of D3 will produce SR.

THE LHC SR PROFILE MONITOR

The principle of implementation of the monitor is given in figure 3. The proton beam leaving Interaction Point 4 at the top right of the figure, enters the Undulator before being deflected by 1.6 mrad by the D3 magnet towards D4.

FIGURE 3. Schematic view of the Undulator/D3 SR monitor in IR4 of LHC.

The Undulator and D3 are located in the same cryostat to minimise the distance between them, in order to reduce the extent of the light source. The light generated in the Undulator and at the edge of D3 travels a distance of 24m before an extraction mirror can be inserted at an acceptable distance from the beam, typically $15 \sigma_H$. The beam and the light will travel in an enlarged vacuum chamber with tapered transitions at both ends in order to reduce the perturbation to the beam.

The SR monitor's performance and calibration will be checked at low proton beam intensity with H and V Wire Scanners located at the exit of D3.

Undulator Magnet

The undulator consists of 8 superconducting coils assembled around ferromagnetic iron poles to produce two periods of magnetic field with a sinusoidal shape: figure 4.

To block the conductors during magnet excitation, the coils will be clamped under pre-stress. Vertical clamping will be provided by splitting the magnet into a lower and an upper part, and by closing the structure with spacers between the upper and lower coils outside the beam tube. Horizontal clamping will be provided by retaining blocks fixed by copper/beryllium tie bolts.

The main parameters of the Undulator are listed in Table 1.

TABLE 1. Undulator: main parameters.

Period length	280 mm
Number of periods	2
Iron yoke length	710 mm
Gap	60 mm
Beam tube size	50/53 mm ID/OD
Maximum magnetic field in the gap	5 T
Maximum field error within ± 10 mm from axis	0.25%
Supply current	250 A
Total energy stored at 250 A	150 kJ
Magnet inductance	4.8 H
Coil cross section	36.5 x 42.5 mm ²
Cable size	1.25 x 0.73 mm ²
Overall coil size	140 x 223 x 36.5 mm ³
Operating temperature	4.2 K
Margin to quench on load line	20 %
Main field/peak field ratio	0.83
Hot spot temperature in case of a quench at 5 T	120 K

FIGURE 4. Perspective view of the 2 period Undulator with Pole pieces extending beyond the coils (total length 71cm) and Vertical Magnetic Field component along the beam axis.

Telescope

It is intended to re-use the LEP SR telescopes [3] with some modifications. The telescope uses primarily mirrors for folding and focusing. The detectors will be back-illuminated CCDs for highest sensitivity and ordinary CCDs coupled to Multi Channel Plate (MCP) intensifiers for single bunch or single batch, down to turn-to-turn, observations. This telescope has to adapt to changing conditions over a run. At injection energy at 450 GeV, the Undulator is used. The beams are large, $\sigma \sim 1.2$ mm, and emit little light. At the top energy of 7 TeV, the D3 magnet is used, whilst the Undulator emits in the UV at large angles which can reach the detectors. At that

energy the beams are also small, $\sigma \sim 300 \mu\text{m}$, and D3 emits a large amount of light. For that reason, two detector set-ups are foreseen. As there is enough light available at high energy, a bandpass filter will be used together with a magnifying lens which will image the beam from the first image plane onto the second detector set. This set-up can also take into account the longitudinal separation of the Undulator and the D3 edge, which has to be kept below 80cm. Chromatic, linear density and polarisation filters are installed as well as a slit in the focal plane to restrict the acceptance in D3.

The magnification is determined by the 4m focal length spherical mirror and the $23 \times 23 \mu\text{m}^2$ pixel size. It has been set to $G=0.2$ in order to have 3 pixels per sigma at 7 TeV, which gives then 13 pixels per sigma at injection. One of the limitations of the performance is the distance by which the light extraction mirror has to be retracted from the beam. For the moment, a distance of $15\sigma_H$ has been asked for. It is hoped that with operational experience, this distance can be decreased to come closer to the machine aperture set by the collimators closed to $\pm 7\sigma$. In any case, the extraction mirror will be movable, so that it can follow the $15\sigma_H$ limit to improve the performance at high energy.

Due to the long distance to travel and the small opening of the light cone, proper alignment has to be provided. A set-up using a folding mirror and a laser located close to the SR telescope will be used: see figure 5. A similar set-up has been used in LEP and has proven to be extremely useful. The Undulator itself has to be aligned on the entrance magnetic axis of D3 to a tolerance of the order of $\pm 5 \text{ mrad}$.

FIGURE 5. Monitor layout with alignment set-up of the optical elements of the SR telescope.

PERFORMANCE ANALYSIS

The photon production has been computed with the ray-tracing code Zgoubi [4]. With the optics set-up described there will be a maximum of 200 photons per pixel (px) at injection and $80 \cdot 10^3$ photons/px at top energy for a pilot pulse of $5 \cdot 10^9$ protons in single turn mode. This will be sufficient to observe the beam behaviour in LHC before injecting and accelerating a nominal bunch. It should also be sufficient to check if there are sizeable matching errors. For a nominal bunch of $1.1 \cdot 10^{11}$ protons, there will be $4 \cdot 10^3$ photons/px at injection and up to $2 \cdot 10^6$ photons/px at top energy. This will permit high precision measurements from a statistical point of view. But the

imperfections of the LHC monitor are due, to a large amount, to the source length, the interference between the two sources and the diffraction of the SR light cone due to the small opening angle at high energy and the limited acceptance of the extraction mirror. At 450 GeV, the emission pattern is a gaussian like cone with an opening of $\sim 0.8\text{ mrad}$ FWHM, within the acceptance of the extraction mirror. At 1 TeV, see figure 2, the light pattern is the superposition of two sources, which will generate a beam broadening through interference and diffraction. Finally, at 7 TeV, where mainly D3 will produce light in the useful spectrum, there is a classical bending magnet SR pattern, with clearly visible edges, cut by the extraction mirror.

The influence of the source characteristics on the performance was evaluated with the program SRW [5]. SRW is a numerical code dedicated to the derivation of SR features generated by an arbitrary magnetic field pattern followed by a propagation through an optical chain producing a display of the Point Spread Function (PSF). SRW provides the SR intensity distribution for a "filament" electron beam, i.e. with zero emittance. The electric field in the frequency domain is derived from the Fourier Transform of the retarded potentials, allowing to perform the computing in the far field, as well as in the near field SR approximations. The SR propagation from a transverse plane to another one is implemented using the Fourier optics approach, assuming small angles and large distances compared to the wavelengths. The electric field in a transverse plane after an optical element is derived by applying an operator describing the optical element. The program parameters have been modified to take into account protons and the results have been cross-checked with Zgoubi.

The beam image at the detector will be the convolution of the density distribution of the beam and of the PSF of the optical system.

The images of the filament beam in the detector plane, together with a cut through the horizontal beam axis are given in Fig 6 to 8 for 450 GeV, 1 TeV and 7 TeV. The results for the horizontal polarisation component of the SR are summarised in Table 2.

TABLE 2. Undulator SR profile monitor performance.

Energy / Sizes [μm]	Beam		PSF		Beam Image			
	σ_H	σ_V	σ_H	σ_V	σ_H	σ_V	$\delta\sigma_H/\sigma_H$	$\delta\sigma_V/\sigma_V$
450 GeV	960	1323	159	141	973	1330	1.1%	0.6%
1 TeV	644	888	198	120	674	896	4.6%	0.9%
7 TeV	244	335	156	194	290	387	18%	15%

FIGURE 6. 2 D and Horizontal cut of the Point Spread Function of the SR monitor at 450 GeV.

FIGURE 7. 2 D and Horizontal cut of the Point Spread Function of the SR monitor at 1 TeV.

FIGURE 8. 2 D and Horizontal cut of the Point Spread Function of the SR monitor at 7 TeV.

The image broadening introduced by the PSF is small enough to extract the real beam size to the expected accuracy by a simple quadratic subtraction. The broadening will be independent of the beam intensity and will be stable for a given light pattern, i.e. beam energy. The corrections can hence be calibrated with the Wire Scanners.

It would nevertheless be advantageous for the precision of the measurement that the machine optics provides higher β s.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help and fruitful discussions with J. Bosser, O. Chubar (ESRF), P. Elleaume (ESRF), A. Hofmann, F. Méot (CEA/Saclay), S. Russenschuck and M. Sassowsky.

REFERENCES

1. C.Bovet, R. Jung, EPAC 1996, Sitgès, June 1996, pp. 1597-1599
2. A. Hofmann, CAS, Grenoble, April 1996, CERN 98-04, August 1998, pp. 1-44
3. G. Burtin et al, CERN SL-99-049 BI, August 1999
4. F. Méot, S. Valero, CEA-Saclay, DSM/DAPNIA/SEA-97-13, 1997
5. O. Chubar, P. Elleaume, EPAC 1998, Stockholm, June 1998, pp. 1177-1179