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Functional Specification

D R A F T

MEASUREMENT OF THE TRANSVERSE BEAM DISTRIBUTION IN THE LHC RINGS

Abstract

This document presents an analysis of the expected use of the transverse beam profile for machine operations and studies. The beam parameters to be derived from the transverse profile are identified and their required accuracy estimated. These requirements are converted into functional specifications for the beam diagnostics instruments. The whole spectrum of possible beams is considered as well as design constraints.

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History of Changes

Rev. No.	***Date***	***Pages***	***Description of Changes***
1.0	11/11/2001		Initial Submission

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1. SCOPE

The present specification provides the functional requirements for the monitors that will measure the transverse distribution of the beams in the LHC rings and dump lines.

The beam diagnostics instruments to be installed in the injection lines are covered in a separate specification [1]. The transverse profile monitors foreseen at the junction of the injection lines and LHC rings are recalled in this specification to allow for a global overview of the issue.

2. DESCRIPTION OF THE OBSERVABLES

The transverse beam profile is measured in physical space in the plane $\{x,y\}$ perpendicular to the propagation axis *s.* Some measurement methods give access to the one-dimensional transverse distribution, which is the projection on the x or y axis of the beam profile.

There are basically two observation principles:

- passive non-interceptive measurements, using e.g. the synchrotron light photons emitted by the beam in an electromagnetic field,
- interceptive methods where a signal coming from the medium traversed by the beam (secondary emission, nuclear reactions, ionisation, transition radiation) can be investigated.

Interceptive methods can be incompatible with circulating beams, either producing a large beam blow-up or a destruction of the instrument.

They can be made compatible with circulating beams if the beam blow-up produced is small and insignificant with respect to other unavoidable blow-up mechanisms.

We will therefore consider both the instrument principle and their main uses to define a coherent set of requirements.

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3. DESCRIPTION OF THE DIFFERENT USES.

Figure 1 describes the time structure of the nominal LHC beam.

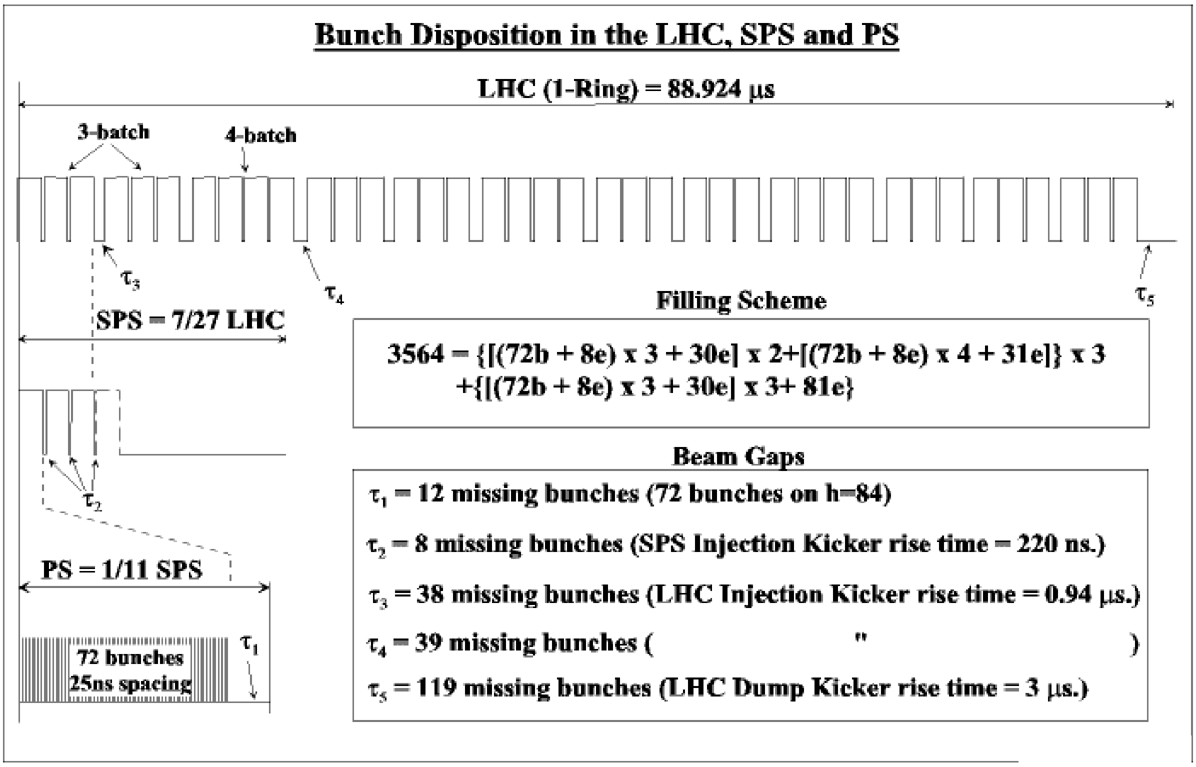

Figure 1: Bunch pattern in the LHC machine.

3.1 RELATED BEAM PARAMETERS

From the various uses analysed, one can infer that the following beam parameters should be extracted from the measurement of the transverse profiles or distributions:

- the average beam position
- the rms beam size
- other parameters of the core distribution: integral (beam intensity), edges of the distribution, higher-order momenta such as the skewness,…
- the distribution of low intensity tails
- the tilt with 2D images (beam transverse cross-section)

Further data processing involving the knowledge of beam optics parameters (Twiss functions, coupling parameters) allow access to:

- the beam emittance
- the beam energy spread

3.2 TRANSFER LINES BETWEEN THE SPS AND THE LHC AND INJECTION INTO THE LHC

Transverse beam size measurement requirements in the transfer lines and at injection are analysed elsewhere [1]: at injection into the LHC, one monitor is needed at the injection septa and another one at the injection kickers to verify the beam position at these locations and check the correct functioning of the devices. Some redundancy in such a critical area is desirable and justifies the duplication, (upstream and downstream each of the two magnet families) of these monitors. A further monitor is requested in front of the TDI absorber.

Another monitor is proposed downstream the insertion to check how the beam behaves after having travelled through the first arc of the ring. It can be positioned between quadrupoles Q7 and Q6, i.e. before the dogleg and the first collimators of the cleaning insertion.

Table 1 summarises the requirements on the positioning of the monitors. The total number of monitors is 11, preferably 13, per injection line. Details of the proposed positions in the line TI2 and TI8 and on measurement tolerances are given in [1].

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Location	No. of monitors	Main use
Before first TED	3	Beam quality at line entrance: common with CNGS line in the case of TI8.
Centre of line	3	Measurements in the regular FODO cells
Before last TED	1	Beam quality at entrance of the LHC ring.
LHC injection septa and kickers	2, preferably 4	Beam position in and functional check of injection devices.
TDI	1	Adjustment of TDI.
Between Q7 and Q6 after first arc cryostat	1	Look at first turn trajectory

Table 1 : Location and number of monitors required for each transfer line.

When a train of bunches is transferred, the measurement can be integrated over the whole batch. Precision determinations of the beam optics will be performed with single bunches. Although not strictly necessary, the possibility to select the profile of a bunch (or of several selected bunches) inside a batch should be evaluated as an extra asset.

3.3 MEASUREMENT ON THE FIRST TURNS

3.3.1 USES AND LOCATION

Before a closed orbit is fully established, transverse profile measurements are useful, to check roughly how an injected beam circulates around the machine. This permits:

- to identify a possible aperture restriction, by looking at the signal evolution from turn to turn
- to detect a source of blow-up (rms value).

These preliminary checks must be made carefully and with a pilot bunch, in order to limit the risk of a quench in one of the super-conducting magnet units. The installation of dedicated first turn study TV screens around the rings is not fully justified. However additional TV stations will be available in LSS4, for matching studies, and in LSS6, to adjust the beam extraction to the dump, see sections 4.3.3 and 4.4. They could be employed for injection studies.

3.3.2 TOLERANCES

An accuracy and a resolution of 10% are expected at this stage on the rms value, which is close to 1 mm at 450 GeV

3.3 CIRCULATING BEAM(S)

3.3.1 USES

When circulating beam conditions are established, the beam current can be increased progressively up to the population of a nominal bunch. The beam transverse distributions are measured using non-interceptive devices and with adequate sampling times.

One important application is the progressive tuning with increasing current of the collimation system and of the various absorbers. For this application, the question of the need of dedicated profile monitors in the cleaning insertions must be clarified.

The other studies to perform are:

- when several bunches are injected, the verification of the injection conditions: stability between bunches, reproducibility between batches.
- the injection matching conditions optimisation, by looking at the modulation of the rms values over consecutive turns after injection [2]. This adjustment can be started with a single bunch, using a dedicated TV monitor and then refined with passive monitors on the nominal beam.
- Loss mechanisms and visual checks of optics and coupling, (with 2D images).
- Bunch to bunch or batch to batch differences (average position, rms value).
- Presence of tails, 10^{-3} down to less than 10^{-4} the maximum of the bunch distribution, up to distances of 5 rms values from the average position, first at 450 GeV, then during the ramp and at top energy (shape). This study can be performed by integration on several hundreds of turns.
- Dynamic aperture determination (rms, edges, shape).
- Beam size / emittance control at 450 GeV and during the ramp and squeeze processes (rms value)
- in the case of ions, to detect any intra beam scattering effect affecting the bunch shape.

- Apart from injection optimisation, the same studies are relevant once the beams are colliding at top energy. In addition, when several bunches circulate in each beam, the differences between bunch species, (average position, rms value, shape), is reinforced under the influence of beam-beam effects. Hence, bunch to bunch discrimination is important to be able to distinguish between bunch families.

3.3.2 TOLERANCES

Accuracy and resolution of 4% are needed on the determination of the beam transverse dimensions under nominal conditions. In particular, this is useful to adjust the collimators and to determine the beam emittance. These investigations are interesting on single bunches, or bunch and batch families. The useful dynamic range in current over which good accuracy is required extends from 10^{11} protons, the population of a nominal bunch, to a beam of 4.8 10^{14} protons, made of 2808 bunches at ultimate current; 40 MHz sampling is needed in order to investigate single bunches but not necessarily on consecutive bunches simultaneously.

3.3.3 LOCATION

When possible, the beam instruments are located in LSS4. This is a clean insertion and in addition the separation between the two beams is increased from the nominal value of 194 mm up to 431 mm in the region where the RF system is installed, Figure 2. This is also a good opportunity for a few instruments which otherwise would be difficult to incorporate.

For injection matching studies, it is suggested to place one TV monitor in each ring in the middle of the drift between quadrupoles Q5 and Q6, Figure 2. At this location the horizontal and vertical amplitude functions are both in the order of 200 m, hence rms values of 1.25 mm at 450 GeV will be measured. This screen can also be used for first turn studies, (section 4.2.1).

Based on the experience in LEP and in the SPS, two kinds of monitors are proposed to work on a circulating beam. They will guarantee some redundancy, which is highly useful, and the possibility of cross-calibration.

In each ring a synchrotron radiation monitor is investigated [3]. Dedicated super-conducting undulators can be installed for this purpose upstream the D3 separator magnet, Figure 2. Their light signal can be extracted 10 m downstream D3, profiting from the beam deflection generated by the separator, and providing a 2D transverse image of the beam.

In addition, gas monitors are recommended exploiting either the rest gas ionisation signal or looking at the luminescence light resulting from de-excitation of the gas atoms [4,5]. For each beam one monitor with good resolution in each transverse plane is required. A location close to D3, Figure 2, where the separation between the beams is the largest and where the amplitude functions are bigger than 250 m is again favourable.

Wire scanners can withstand only a fraction of the nominal beam current [6]. However they are needed to calibrate at limited current these monitors and they will also be used for tail distribution studies. Hence they have also to be incorporated in this region. Due to their calibration function, they should provide data with a more demanding accuracy, better than 2%.

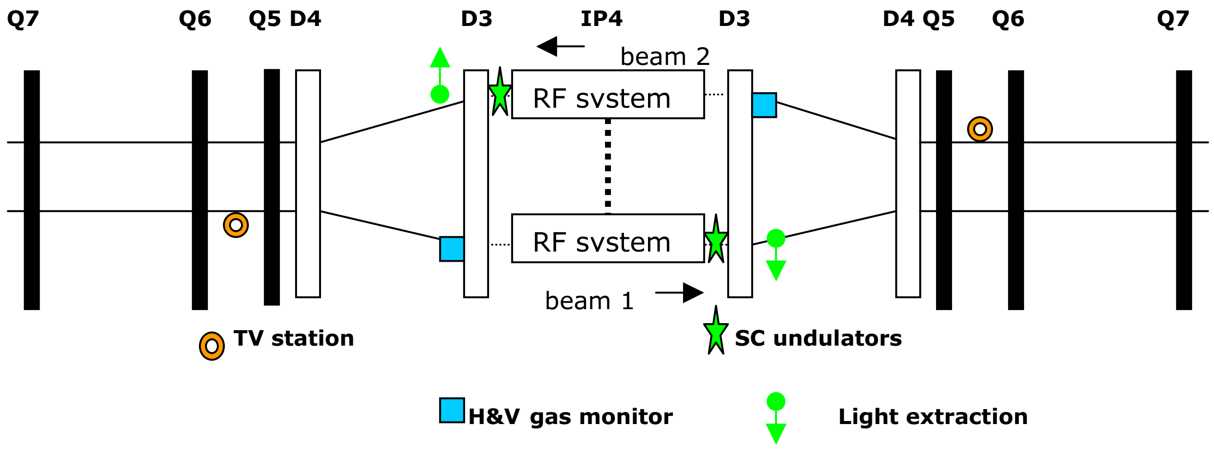

Figure 2: Configuration of transverse profile monitors in LSS4.

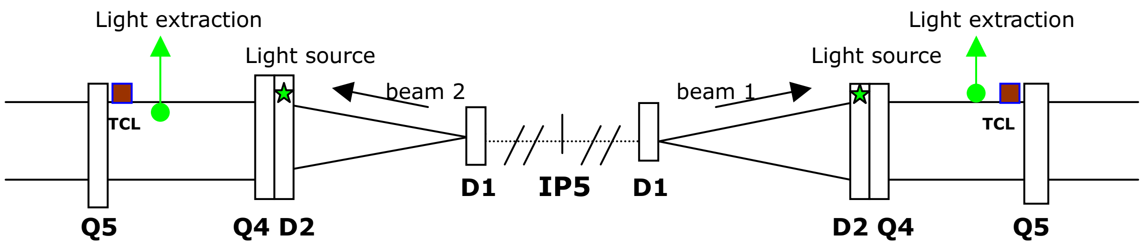

Figure 3: Telescope configuration in IR5.

Another monitor based on synchrotron radiation is recommended in LSS5 for beam size measurements at 7 TeV. It will use the light emitted by the beam within the separator magnet D2, extracted 20 m later, upstream quadrupole Q5, Figure 3. This monitor will provide the best resolution for the high energy operation on the collision optics, with amplitude functions of 590 m and 1600 m respectively in the horizontal and in the vertical planes.

3.4 IN THE DUMP LINES

The trajectory (average position) and dimensions (width and shape) of the extracted beam must be measured along the dump transfer lines from the entrance of the extraction septum up to the dump block input face. In particular, the function of the diluter magnets must be closely monitored to avoid damages from high current beams.

As a minimum, four dedicated monitors are required located upstream the extraction septum, upstream and downstream the diluter magnets and upstream the dump block.

The first one is still located in the ring. Hence, it will also serve for first turn studies, (section 4.2.1).

The dynamic range to be covered extends from the pilot bunch intensity, $5.\ 10^{9}$ protons, up to the ultimate current of a circulating beam, $4.8\ 10^{14}$ protons. The diagnostics should in principle be permanently available after any dump trigger whether requested, interlocked or erratic.

Single bunch sampling is in this case not essential and an accuracy of 100 μm is suitable.

4. FUNCTIONAL REQUIREMENTS

4.1 PERFORMANCE PARAMETERS

Table 2 summarises the required performances according to the various modes of operation.

	Pilot pulse 5.10^{9} p	Nominal/ultimate bunch $1.1/1.7.\ 10^{11}$ p	One batch or several batches > 72 bunches
Transfer line: Accuracy on average position on rms value for TDI setting	100 μm 100 μm	N R 20 to 40 μm = 0.04 σ σ_{TDI} /5=100 μm	N R 20 to 40 μm = 0.04 σ < σ_{TDI} /5=100 μm
First turns (450 GeV) Accuracy on average position, on rms value	100 μm 100 μm	N R 100 μm	***individual bunch sampling*** N R 100 μm
Circulating beam Accuracy on rms value tails 2D picture: coupling	100 μm	15 to 50 μm = 0.04 σ Amplitude $<10^{-3}$ A_{MAX}	***individual bunch sampling*** 15 to 50 μm = 0.04 σ 10^{-4} A_{MAX},< Amplitude$<10^{-3}$ A_{MAX}
Dump lines Accuracy on average position and rms value	100 μm	100 μm	100 μm SHALL WITHSTAND HIGH CURRENT

NR: not relevant – should be dealt with by BPM system

Table 3: Required accuracies, sensitivity and sampling mode

4.2 SYNCHRONISATION

Measurements will be initiated by timing events like an injection pre-pulse or a start of ramp signal. It should also be possible to trigger them at any time via the control system.

4.3 DATA FLOW

4.4 AVAILABLE DATA

4.5 POST MORTEM

For post mortem analysis, data will be stored in two different buffers to be frozen by external events (triggers):

- one buffer containing the last data recorded on one turn
- another buffer with data recorded with lower time resolution.

5. DESIGN CONSTRAINTS

5.1 INSTALLATION

5.1.1 ALIGNMENT

5.1.2 IMPEDANCE

5.2 RADIATION HARDNESS

As far as radiation is concerned, the location in LSS5 is the most stringent, IP5 being a high luminosity insertion point. The expected activity in the detector region has been evaluated [7] and [8]. A dose between 10 Gy/year and 100 Gy/year is expected.

5.3 INB CONSTRAINTS

The LHC has been classified as an "Installation Nucleaire de Base" by the French Authorities. CERN is therefore obliged to conform to their relevant regulations, guidelines and procedures. Within this context CERN has to establish traceability & waste management procedures and maintain a radiological and zoning system. In order to meet these requirements, information such as: material content, location history, sub-assemblies, etc…, shall be supplied by the Contractor and will be maintained in a CERN database. CERN has created a set of procedures and conventions as part of the Quality Assurance System for LHC, which will also be used to facilitate these INB requirements. The relevant quality documents are listed below and shall be applied by the Contractor during the production, testing and assembly of components: "The Equipment Naming Convention", "The LHC Part Identification", "The Manufacturing and Test Folder".

6. RELIABILITY, AVAILABILITY AND MAINTAINABILITY

The information provided by the monitor will contribute to clean machine operation. It is not intended for the time being to use it as an active element of interlock chains.

The profile monitors must be designed to offer reliable and continuous operation during the LHC running periods.

7. SAFETY AND REGULATORY REQUIREMENTS

The longitudinal profile monitor must meet the safety guidelines put forward by the CERN Technical Inspection and Safety Commission (TIS). TIS have issued safety documents in compliance with LHC-PM-QA-100 rev1.1, and the guidelines in these documents will be incorporated into the monitor design.

8. REFERENCES

[1] J. Wenninger, Intrumentation for the TI2 and TIi8 Transfer Lines, Functional Specification to be published.

[2] C. Bovet, R. Jung, LHC Project Report 3, March 1996, and EPAC96, Sitges,Spain.

[3] L. Cadet Ponce, LHC Emittance Workshop, CERN, July 2000.

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[5] R. Jung, The Luminescence Profile Monitor in the CERN SPS, EPAC2000, Vienna.

[6] J. Bosser, C. Bovet, Wire scanners for LHC, LHC Project Note 108-Rev, October 1997

[7] N. Mokhov, FNAL, unpublished.

[8] P. Cruikshank et Al., LHC engineering Specification- LHC-PM-ES-0002.rev1.1, p11.