Functional Specification

MEASUREMENT OF THE TRANSVERSE BEAM DISTRIBUTION IN THE LHC RINGS

Abstract
This document discusses the anticipated uses of the 1D transverse beam profiles and 2D beam spot for machine operations and studies. The beam parameters to be derived from these measurements are identified and their required precision estimated. These requirements are converted into functional specifications for the beam diagnostics instruments. The whole range of LHC beams is considered as well as the design constraints.

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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. The monitors to be installed in the transfer and dump lines are covered in separate documents [1] [2]. The monitors foreseen at the junction of the transfer lines and LHC rings are recalled in this specification to allow for a global overview of the issue.

2. OBSERVABLES AND RELATED BEAM PARAMETERS

2.1 OBSERVABLES

The budget for emittance blow-up over a full LHC cycle is only 7%. This amounts to a change of the beam size by 10 $\mu$m in the arcs at 7 TeV. At this accuracy level, the definition of the observables requires precision as well.

Whether this is allowed or not by the technology, we take as the primary observable a single 2D image measured on one bunch on a given turn. This image that we will refer to as the ‘beam spot’ is the projection in the $\{x,y\}$ plane of the beam ellipsoid. It is a function of the emittances, of the local optics functions including coupling, of the momentum spread and of the closed orbit corresponding to the average particle momentum.

Averaging over bunches and machine turns improves the accuracy and provides an effective beam size relevant for aperture issues, collimation, luminosity and hence performance. However this effective beam size may include contributions from a spread in emittance, in closed orbit, ... between bunches or from a drift in time. The ability to measure turn by turn and bunch by bunch is therefore an asset to disentangle the various possible contributions.

If the linear coupling, naturally large in LHC, is locally corrected, the 1D projection of the averaged beam spot on the x axis or on the y axis become the most commonly used quantities. We refer to them as the beam profiles.

The observation of the beam spot shall not cause any significant blow-up for circulating beams. On the other hand, a single pass pilot beam may only be observed with intercepting devices. We will thus specify for each use the tolerance on the beam blow-up.
2.2 RELATED BEAM PARAMETERS

In order to predict the beam spot at any azimuth in the machine, its various components must be disentangled or the possible spreads and drifts shown or assumed to be negligible. The various uses analysed in section 3 show that the basic spot parameters:
- the rms betatron beam size,
- the average beam position,
should be complemented by more sophisticated ones:
- the local tilt in the $(x,y)$ plane,
- other parameters of the core distribution: edges of the distribution, integral (beam intensity),...
- the distribution in the tails (non-Gaussian tails).

An appropriate azimuthal sampling of the beam spot and an accurate knowledge of the (coupled) linear optics parameters at the position of the monitors are necessary to calculate these parameters. This is likely to require a combination of instruments.

3. ANTICIPATED USES OF THE BEAM PROFILES

By convention, we refer to the rms beam size by ‘the beam size’. This should avoid confusion with the specification of the precision of the latter, which may itself be expressed in rms value (default) or in tolerance ($\pm$).

The initial requirements on profile measurements [3] are summarized in [4]. The initial demand for an accuracy of $\pm 1\%$ on the measurement of the rms value exceeded the anticipated performance of all monitors. These requirements are therefore re-assessed in this document with a revised justification. A summary of the updated conclusions was also presented in [5].

3.1 MEASUREMENTS IN SINGLE PASS MODE

3.1.1 INJECTION INTO THE LHC

The aperture available to the beam is reduced in the injection area. The measurement of the beam position and beam size is therefore required at each of the aperture limits. In addition, the profile measurement offers an easy means of checking the kick angles of the injection magnets. Monitors are planned:
- at the entry and exit of the injection septa,
- at the entry and exit of the injection kickers,
- in front of the TDI absorber.

The justification and requirements for these monitors are discussed in [1].
3.1.2 TRAVERSAL OF THE FIRST LHC ARC

At commissioning or re-commissioning, it may be useful to verify that a gross systematic error e.g. in powering has not been made. Hence, for a global check, a profile monitor is useful after the traversal of the first arc. The position between quadrupoles Q7 and Q6, i.e. before the dogleg and the first collimators of the cleaning insertion seems appropriate.

This operation stage is normally carried out with a pilot beam at 450 GeV/c. However, a proper injection of a single bunch cannot guaranty the correct injection of a whole batch. We therefore require measuring as well an SPS batch, e.g. of pilot bunches to nominal bunches. An overall accuracy of ± 30% on the measurement of the beam size (about 1 mm) in single passage seems sufficient to detect gross errors. We assume an injection mode dedicated to establishing beams: the beam is injected and dumped as soon as it reaches the dump insertion. Interception devices are then acceptable.

3.2 BETATRON AND DISPERSION MATCHING MEASUREMENT ON THE FIRST TURNS

It was shown in the PS and SPS that the matching quality can be accurately measured by recording the turn-by-turn modulation of the beam size [6] [7]. In the LHC, one may have to face the additional complication that the optics may not be stable over the multi-injection process i.e. the matching might change from one injection to the next. Hence, we require being able to measure a possible mismatch at each injection of a SPS batch. If this would turn out to be too difficult, the minimum requirement is to measure in a dedicated session the first turns with an intercepting device, assuming that the beam is dumped after a programmable number of turns.

In order to disentangle the betatron and dispersion mismatches, the detector shall be installed in an area of significant dispersion. The beam size oscillation at the betatron frequency is specific to the dispersion. The oscillation at twice the betatron frequency becomes a measure of the betatron mismatch once the dispersion mismatch is corrected [29]. As an option/upgrade, a combination of monitors at high and vanishing dispersion allows directly to disentangle the two matching sources. The wanted resolution of 1% on the emittance requires to resolve a relative beam size oscillation of 10%. Assuming a sequence of 14 measurements allowed by the present-day technology and the identification of 8 parameters (three partially independent sine waves), the accuracy to which the beam size shall be measured is about ± 20%. A better accuracy or a larger number of turns would be a benefit for the process accuracy.

As noted in [6], a betatron tune of .25 may blind the monitor. If the tune becomes close to 0.25, either the observation period shall be extended beyond 14 turns, or one can use 14 acquisitions obtained by sampling every few turns.

This kind of measurements is not expected to be carried out with pilot bunches. One should rather foresee using a single nominal bunch, a PS batch (72 bunches) of the intermediate intensity beam or a nominal injected SPS batch (train of 3 to 4 PS batches) if it is injected in normal operation (when circulating beam is established). There is no identified requirement to measure each bunch separately.
3.3 MEASUREMENTS ON CIRCULATING BEAM(S)

In this mode, the instrumentation is assumed to reach its highest statistical accuracy and work in non-intercepting mode. The beam blow-up arising from quasi-continuous profile measurements should be less than 1% (rms) during an LHC cycle (injection, ramp and collision). Hence, fully passive devices for the beam must be available.

3.3.1 EVOLUTION OF THE RMS BEAM SIZE

The beam may blow up due to small drifts of optics parameters, to the beam-beam kicks, or to the intra-beam scattering for the ions. Conversely, a beam size reduction of the order of 20% in 10 hours resulting from synchrotron radiation damping may be observed[8].

The continuous measurement of the beam size evolution averaged over all bunches is one of the key tool for the understanding and improvement of the machine performance, collimation system, etc.... The target resolution should be of the order of ±1% to be consistent with the blow-up budget. The integration time can reach 100 ms and the measurement frequency 10 Hz. However in a few cases, fast phenomena may have time constants of the order of 10 ms [9] (for example the electron cloud [10]); then, integration times of a few milliseconds will be necessary. In this case, a resolution of ±5% would not lead to a serious degradation of the machine performance but the study of the blow-up sources will be less easy.

3.3.2 SPREAD OF THE BEAM SIZE AMONGST BATCHES AND BUNCHES

Imperfections or beam dynamics phenomena may cause the LHC batches/bunches to differ in transverse size and other parameters. The production and acceleration of the intense LHC beams in the injectors, the beam-beam or electron cloud effects in LHC are examples of mechanisms which may lead to a spread amongst bunches within a batch, or amongst batches, or even generate instabilities.

Within a PS batch, the last bunches are expected to be more affected in case of electron cloud than the ones located in front of the batch [10]

The beam-beam effect is probably the most demanding one on performance and it is estimated that the resolution on the beam size of single bunches shall be equal or better than ±5% when measuring several bunches using the same monitor [11]. Such studies are only relevant for intensities well above the intermediate intensity when the machine approaches nominal performance.

The measurement of the individual bunch sizes is a useful parameter to understand and optimise the machine performance. This information is also needed by the experiments to compute the bunch by bunch luminosity and to reconstruct events [12].

The measurement of the spread in average relative position may be a useful redundancy with the BPM measurement, in case the latter is perturbed by e.g. transient effects in the electronics due to the holes in the beam pattern. The target resolution on the relative position should be ±σ/10 or better. The beam-beam effect causes a spread of orbits between bunches which is expected to be about σ/10 [13]. In comparing their sizes and average positions, issues of offsets or non-linearities should not be significant.

3.3.3 DETERMINISTIC SETTING-UP OF THE COLLIMATORS

Beam size monitors will not be used in operation for deterministic settings of the collimator [14]. They nevertheless will be used to commission and understand their behaviour. The requirements of sections 3.3.1 and 3.3.4 are relevant for this use.
3.3.4 EMISSANCE MEASUREMENT

The measurement of the absolute emittance $\varepsilon = \sigma^2 / \beta$ would allow an unambiguous assessment of the emittance preservation in the transfer lines and in the LHC. To be consistent with the LHC emittance blow-up budget of 7%, it should be carried out with an absolute accuracy of 1 to 2%. This requirement is technically out of reach and probably far-fetched as compared to other LHC tolerances (e.g. expected $\beta$-beating). Yet, we wish to keep this very ambitious goal on the long term. An intermediate goal of $\pm 10\%$, already quite ambitious, seems to be sufficient at first to judge on a correct preservation of the emittance between machines. Special running conditions are acceptable (e.g. low current, single bunch, etc...) to reach this accuracy.

The second and most important goal in measuring the emittance (and not simply the local effective beam size) is to be able to reconstruct the beam size at any azimuth in the machine (collimators, aperture limits, collision points, etc...). Given the requirements of a resolution of $\pm 2\%$ set by the monitoring of the blow-up in LHC, the resolution on the measurement of transverse profile and optical functions must be $\pm 1\%$ or better. The dispersion and beam momentum spread must as well be measured.

The most suitable position for a monitor is at a place where the nominal dispersion vanishes or is smaller than the expected parasitic dispersion taken to be equal to 0.5 m. Proper instrumentation should be foreseen at the azimuth of the transverse profile monitors to measure the $\beta$ and dispersion functions. In view of past LEP experience, it should be possible to cross-check the measurements, e.g. by providing both BPM-based [15, 16] and K-modulation based [17] measurements of the optics.

3.3.5 ENERGY SPREAD MEASUREMENT

Assuming a parasitic dispersion of 0.5 m and an amplitude function of 200 m at the transverse profile monitor, the knowledge of the term $D_x \Delta p / p$ to 25% is sufficient to ensure a measurement of the emittance to 1% at 450 GeV ($\sigma_x=1.2\text{mm}$) and at 7 TeV ($\sigma_x=0.3\text{mm}$)... The measurement of the beam size is rather insensitive and therefore does not appear suitable as an energy spread measurement. The latter is better measured using the bunch length and the knowledge of the RF voltage. As noted in [18], beam loading might produce a bias for large beam intensities. The relevance of the energy spread to LHC performance does not seem to justify dedicated high precision beam size monitors at large values of the dispersion function.

3.3.6 TILT DUE TO COUPLING

The local tilt of the eigen-modes, appearing as a tilt of the transverse beam ellipse, can provide a clue at the coupling strength. This is certainly useful but has limits, since the local tilt of the eigen-modes is not an unambiguous measure of coupling. Since the nominal transverse emittances are equal in LHC, the preferred position for a 2D transverse profile monitors should have unequal $\beta$-functions, e.g. by a factor of 2, to be able to appreciate the tilt of the 2D transverse space ellipsoid projection; a location with the largest possible amplitude functions ($\beta_H, \beta_V$) must be found to keep a good resolution even in the plane where the beam dimension is the smallest.

A further refinement would be to have available another profile monitor at an azimuth where the phase relevant to coupling ($\mu_x - \mu_y$) is different by $\pi/2$ as compared to the first monitor. This would prevent any mis-interpretation of the observed tilt. It should be noted however that coupling measurements are also foreseen with the BPM’s.
3.3.7 GEOMETRIC/DYNAMIC APERTURES

One of the methods that may be used to study the machine aperture is to gradually blow-up the beam by resonant excitation until its edges reach the limit. Probing the aperture with orbit bumps may disentangle the dynamic and geometric apertures. The BLM system would be used to stop either the resonant excitation or the orbit bumping. A dynamic range of 1 to 100 between the maximum density and the low-density ‘edge’ of the beam seems appropriate for this application. It will most probably be performed with a pilot bunch.

3.3.8 TRANSVERSE TAILS

It can be expected that the magnet non-linearity, the beam-beam effects, etc...cause non-Gaussian tails extending up to the collimator position, i.e. between 6 and 7 \( \sigma \).

The density and the diffusion rate in these tails are not known. It seems appropriate to be able to detect densities \( 10^5 \), for single bunches, to \( 10^6 \), for PS batches or for the beam, lower than the maximum of the distribution. Hence the tails in this specification are defined to extend from 1/10\( \text{th} \) of the peak density to 1/1000\( \text{th} \) or 1/10000\( \text{th} \). When the tails are to be measured, there is no requirement to measure beyond the above-mentioned range, i.e. there is no demand to extend the dynamic range up to the peak density of the bunch/beam. The processes occurring in the tails are not expected to vary rapidly and the integration time of the measurement can be made long (seconds or minutes): a measurement at 50 tail amplitudes, each acquisition requiring 1 s, would be suitable.

3.3.9 DETECTION OF HIGHER-ORDER BEAM OSCILLATIONS

The transverse profile monitor must be able to detect oscillations of the transverse beam profiles. In this mode, the whole beam distribution is also interesting in addition to the rms beam size. The demand on the resolution is more modest with errors in the 10% to 20% range. The integration time shall however be fast enough, of the order of 10 to 100 turns with a corresponding measurement frequency. A n-turn-by-n-turn observation of the beam, during about 1000 samples, can also be useful.

3.3.10 POST-MORTEM ANALYSIS

Proper recording should allow answering the following questions:

• Was there any blow-up of the beam on the time scale of seconds? Slower phenomena are assumed to be covered by the logging system. For faster ones, it seems more efficient to record the other beam parameters.

• Were there any higher-order beam oscillations on a time scale of about 100 turns? This is not required initially but may become useful when the beam intensity approaches the nominal one.

3.3.11 OPERATION WITH IONS

The LHC operation with Pb ions is the most stringent case as far as beam intensity is concerned: 592 bunches per beam will circulate, each with a charge roughly equivalent to a pilot proton bunch [19] but decaying during the run. Their spacing will be 100 ns and they will have a normalised transverse emittance of 1.5 \( \mu \)m, yielding the same beam size as that of a nominal proton beam.

The performance of the LHC with ions is closely related to [19]:

• the initial luminosity

• the beam lifetime, of the order of 10 hours and governed by intra-beam scattering when the beam are not colliding and of about 4 hours when the beams are put head on.
It is important to measure the beam transverse dimensions at the beginning of a run and then to continuously monitor them. Accuracy on the initial rms value and then resolution of a few per cents are required, averaged over the whole beam.

The luminosity in the insertion and hence the bunch current are limited on purpose in order to stay below the quench threshold in the adjacent dispersion suppressors. Hence, no fast instability is to be expected and integration times of the order of 100 ms can be considered.

4. FUNCTIONAL REQUIREMENTS

4.1 FUNCTIONAL TYPES OF MONITORS

The analysis of the anticipated uses (section 3) allows the definition of four functional modes to be mapped on the different types of hardware monitors:

1. Simple and robust single-pass monitor of high sensitivity (pilot beam) with a modest demand on accuracy and few restriction on the beam blow-up due to the traversal.
2. Few-pass monitor (typically 20 turns) dedicated to the intermediate to the nominal injected beam intensity for calibration or matching studies. The blow-up per turn should be small as compared to the effect to be measured.
3. Circulating beam monitor working over the whole intensity range. No blow-up is expected from such monitors.
4. Circulating beam tail monitor optimized to scan low beam densities. In this mode one may not be able to measure the core of the beam. The measurement should not disturb the tail density significantly.

4.2 LAYOUT

We take into account that IR4 is the default LHC insertion for instrumentation when there are no constraints requiring another location.

4.2.1 SINGLE PASS MONITORS

In addition to the monitors foreseen for the injection into LHC, discussed in [1], a monitor is needed between quadrupoles Q6 and Q7 at the exit of the first arc after the injection point. Its location is chosen in the middle of the drift where both the H and V amplitude functions have same value (about 100m), hence providing equal beam size in either plane. For completeness the position of the single-pass-monitors in the LHC rings are summarized in Table 1

<table>
<thead>
<tr>
<th>Entry septum MSI</th>
<th>Exit septum MSI</th>
<th>Entry kicker MKI</th>
<th>Exit Kicker MKI</th>
<th>Entrance TDI absorber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Q6 and Q7 in LSS3 left for ring1</td>
<td>in LSS7 right for ring2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Q5 and Q6 in LSS4 for ring1 &amp; ring2 (used also for matching studies)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Layout of single-pass monitors
4.2.2 FEW-PASS MATCHING MONITORS

For matching studies at injection (section 3.2.2) a matching monitor is needed in each ring at a position where the dispersion is significant (> 1 m) and the horizontal and vertical beam sizes are both large enough to offer the best sensitivity. The best compromise is usually encountered in the middle of a drift where both amplitude functions are equal. The optional matching monitor (dispersion free) can be installed in IR4 in the middle of the drift between quadrupoles Q5 and Q6 (Figure 1). At this location the amplitude functions are both in the order of 350 m, hence rms values of 1.25 mm at 450 GeV will be measured. Another possible application of a monitor at this location would be first turn observation during injection studies (section 3.1.2 and Table 1). The nominal matching monitor (with large dispersion) has to be installed possibly in IR3.

4.2.3 CIRCULATING BEAM AND TAIL MONITORS

Given the ambitious precision goal, this type of monitor shall be placed at large $\beta$-values, i.e. one monitor per plane. In addition, with a $\beta$-ratio between planes of 2 or more, the tilt due to the coupling of a round beam becomes easily observable.

Otherwise, no requirement was identified which favours preferred machine azimuths from the beam dynamics or machine operation point of view. In particular, we did not identify the case for a monitor at large dispersion (section 3.3.5). In former studies, the following positions/solutions have been selected and fulfill the requirements both for the baseline programme and for extensions allowing more precise or dedicated monitors if the need arises:

- **IR4 synchrotron light monitor:** In each ring a synchrotron radiation monitor is under development [20], using a signal provided by super-conducting undulators installed upstream the D3 separator magnet, Figure 1. The light is extracted 10 m downstream D3, profiting from the beam deflection generated by the separator, and providing a 2D transverse image of the beam.

![Figure 1: Configuration of transverse profile monitors in IR4.](image-url)
- **IR5 synchrotron light monitor**: This position provides the best resolution for the flat top energy operation on the collision optics, with local amplitude functions of 590 m and 1600 m respectively in the horizontal and in the vertical planes. The monitor uses the light emitted by the beam within the separator magnet D2, extracted 20 m later, upstream quadrupole Q5 (Figure 2).

![Figure 2: Telescope configuration in IR5.](image)

- **IR4 Gas monitors**: gas monitors exploiting either the rest gas ionisation signal or looking at the luminescence light resulting from de-excitation of the gas atoms [21,22] are investigated. For each beam one monitor with good resolution in each transverse plane is required. A location close to D3, Figure 1, where the separation between the beams is the largest and where the amplitude functions are close to 250 m is again favourable.

- **IR4/IR5 Wire scanners**: they are proposed in IR4 (Figure 1) for absolute calibration of the other monitors and as tail monitors. The use for calibration imposes the most demanding accuracy, typically 1% on the beam size. To overcome uncertainties related to $\beta$-beating, they would ideally be at the same location as the SC undulators or the other emittance monitors. However in order to minimize the risk of quench in the D3 separator magnet when they are used at top energy [23], it is proposed to install them immediately downstream this magnet as represented in Figure 1.

The installation of a Synchrotron Light telescope in IR5, shall also be complemented by the installation of wire scanners (Figure 2) for absolute calibration.
### 4.3 RESOLUTION IN TIME AND OF THE BEAM PATTERN

<table>
<thead>
<tr>
<th>Monitor type/mode</th>
<th>Observation range (gating)</th>
<th>Beam scenario</th>
<th>Integration time per acquisition</th>
<th>Number of acquisitions per measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-pass to Few-pass</td>
<td>Beam spot</td>
<td>1 pilot to 1 nominal SPS batch</td>
<td>1 turn</td>
<td>1 to 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intermediate bunch to intermediate PS batch</td>
<td>1 turn every 1 to 3 turns</td>
<td>20</td>
</tr>
<tr>
<td>Matching</td>
<td>SPS batch</td>
<td>Intermediate to ultimate SPS batch</td>
<td>1 turn</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>from bunch-by-bunch to beam</td>
<td>Pilot to ultimate beam</td>
<td>20 to $10^3$ turn (2 to 100 ms)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intermediate to ultimate beam</td>
<td>$10^4$ turn (1 s)</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 pilot to one intermediate bunch</td>
<td>$10^3$ to $10^4$ turn (.1 to 1 s)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pilot bunch to one nominal PS batch</td>
<td>$\leq 100$ ms</td>
<td>1</td>
</tr>
</tbody>
</table>

*: Calibration can normally be performed using a single bunch. However there might be some interest in performing also the study when several bunches are circulating, in the limit of the maximum current tolerated by the wire scanners, in order to identify possible intensity dependent causes of discrepancy between instruments. At higher currents these comparative studies will have to be performed without the wire scanners, between instruments able to withstand the beam intensities.

**Table 2: Resolution requirements on the beam structure and on the time**

The gating options are defined as follows:

- beam: the gate integrates all the bunches present in a time window corresponding to the design LHC beam, whatever the actual number of bunches.

- SPS batch: the monitor integrates all the bunches present in a time window corresponding to the longest SPS batch, whatever the actual number of bunches.
• Bunch-by-bunch: all bunches can be acquired individually. The measurement of all bunches need not necessarily be done simultaneously. This could be carried out in subsets as long as the precision and measurement frequency targets are met. The bunch data may or may not be averaged over part or all bunches depending on the use (see section 3).

4.3.1 BEAM SIZE

The range of beam sizes is a combination of the range in emittance from the injectors and of the adiabatic shrinking due to the acceleration. We assume that the smallest beam results from the expected early-days normalized emittance of $1 \times 10^{-6}$ rad and that the maximum beam size is 50% higher than nominal ($\beta$-beat, blow-up). The maximum beam size will be observed during the studies described in section 3.3.7. The rms beam size is given at $\beta$=180 m (maximum in the arcs) and must be scaled to the monitor positions.

<table>
<thead>
<tr>
<th>Rms beam size</th>
<th>Minimum</th>
<th>Maximum (operation)</th>
<th>Maximum (studies)</th>
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</thead>
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<tr>
<td>0.15 mm</td>
<td>1.8 mm</td>
<td>12 mm</td>
<td></td>
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</table>

*Table 3: Range of rms beam sizes*

4.3.2 TRANSVERSE DENSITY

The range in transverse peak density $N_p/2\pi\sigma_x\sigma_y$ is very large. For this reason we distinguish the two types of monitors and the function they are used for.

Depending on the frequency at which the monitors are operated, the relevant density may be either the bunch or the beam density. We summarize in Table 4 a set of sub-ranges consistent with the anticipated uses. We quote density figures at a location where the amplitude function value is 100 m in one transverse plane and 200 m in the other one. They must be scaled to the exact monitor position. The following figures are considered at 450 GeV in Table 3:

- $0.8 \times 10^9$ p/mm$^2$: peak density of a pilot bunch with nominal emittance.
- $3.9 \times 10^9$ p/mm$^2$: peak density of an intermediate bunch of $27.5 \times 10^9$ p with nominal emittance.
- $15.8 \times 10^9$ p/mm$^2$: peak density of a nominal bunch of $1.1 \times 10^{11}$ p with nominal emittance
- $24.4 \times 10^9$ p/mm$^2$: peak density of an ultimate bunch with nominal emittance
<table>
<thead>
<tr>
<th>Monitor type / mode</th>
<th>Energy (GeV)</th>
<th>Peak bunch density at injection (10^9/mm^2)</th>
<th>Peak bunch density at collision (10^9/mm^2)</th>
<th>Integrated density observation range at injection (10^9/mm^2)</th>
<th>Integrated density observation range at collision (10^9/mm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-pass to Few-pass</td>
<td>450</td>
<td>0.8</td>
<td>12.4</td>
<td>0.008</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.8</td>
<td>380</td>
<td>25 *</td>
<td>380 *</td>
</tr>
<tr>
<td></td>
<td>matching</td>
<td>3.9</td>
<td>.4</td>
<td>.4</td>
<td>.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.4</td>
<td>7000</td>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td>Circulating</td>
<td>450</td>
<td>3.9</td>
<td>61</td>
<td>0.004</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.4</td>
<td>380</td>
<td>7000</td>
<td>10^5</td>
</tr>
<tr>
<td></td>
<td>tail</td>
<td>3.9</td>
<td>61</td>
<td>0.0008</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.4</td>
<td>380</td>
<td>7000</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>dynamic aperture</td>
<td>0.8</td>
<td>12.4</td>
<td>0.008</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.9</td>
<td>61</td>
<td>0.4</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>calibration</td>
<td>0.8</td>
<td>12.4</td>
<td>0.008</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
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<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
<td>-&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.4</td>
<td>380</td>
<td>25 **</td>
<td>380 **</td>
</tr>
</tbody>
</table>

*: Gating on one (ultimate) bunch; to be multiplied by the number of bunches depending on the gating which is chosen.

**: When calibration is performed using a single (ultimate) bunch. However there might be some interest in performing also the study when several bunches are circulating, in the limit of the maximum current tolerated by the wire scanners, in order to identify possible sources of discrepancy between instruments.

**Table 4: Range of transverse densities**

Two densities are used in the table:

- peak bunch density: the proton density at the maximum of the bunch distribution,
- integrated density: the peak density integrated over the relevant beam observation range (gate) as specified in Table 2.
4.3.3 PRECISION

Accuracy and resolution to be achieved in the various modes of operation are summarized in Table 5.

<table>
<thead>
<tr>
<th>Monitor type/mode</th>
<th>Beam scenario</th>
<th>Observation mode</th>
<th>Precision mode/value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-pass to</td>
<td>Beam spot</td>
<td>Turn-by-turn</td>
<td>Accuracy:</td>
</tr>
<tr>
<td>Few-pass matching</td>
<td>1 pilot to 1 nominal SPS batch</td>
<td></td>
<td>• 20% rms on $\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• average position:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\approx 300$ $\mu$m rms</td>
</tr>
<tr>
<td>Circulating</td>
<td>matching</td>
<td>Turn-by-turn</td>
<td>Resolution:</td>
</tr>
<tr>
<td></td>
<td>1 intermediate bunch to SPS batch</td>
<td></td>
<td>over 20 turns</td>
</tr>
<tr>
<td></td>
<td>Intermediate to ultimate SPS batch</td>
<td></td>
<td>± 20% on $\sigma$</td>
</tr>
<tr>
<td></td>
<td>Pilot to intermediate beam</td>
<td>10^3 turns</td>
<td>Resolution:</td>
</tr>
<tr>
<td></td>
<td>intermediate to ultimate beam</td>
<td></td>
<td>• 1% rms on beam $\sigma$</td>
</tr>
<tr>
<td></td>
<td>beam size and profile</td>
<td></td>
<td>• 5% rms on bunch $\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• 10% rms on transv. distribution points</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• $(\pm \sigma/10$ in beam position)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10^2 turns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Resolution:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5% rms on transv. distribution points</td>
</tr>
<tr>
<td></td>
<td>Beam emittance</td>
<td>10^3 turns</td>
<td>Accuracy:</td>
</tr>
<tr>
<td></td>
<td>intermediate to ultimate beam</td>
<td></td>
<td>± 5% on beam $\sigma$</td>
</tr>
<tr>
<td></td>
<td>tail</td>
<td>10^4 turns</td>
<td>Resolution:</td>
</tr>
<tr>
<td></td>
<td>1 intermediate to ultimate beam</td>
<td></td>
<td>10% rms on transv. distribution points</td>
</tr>
<tr>
<td></td>
<td>dynamic aperture</td>
<td>10^3 to 10^4 turns</td>
<td>Resolution:</td>
</tr>
<tr>
<td></td>
<td>1 pilot to one intermediate bunch</td>
<td></td>
<td>± 10% on transv. distribution points</td>
</tr>
<tr>
<td></td>
<td>calibration</td>
<td>10^3 to 10^4 turns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pilot bunch to nominal PS batch</td>
<td>No constrain</td>
<td>Accuracy:</td>
</tr>
</tbody>
</table>

*Table 5: Necessary accuracy and resolution*
4.4 CALIBRATION AND CROSS-CALIBRATION

Experience shows that it has been difficult to reach consistency between emittance from profile monitors and from luminosity data at LEP [24] and elsewhere. With the outstanding precision goal assigned to the LHC profile monitors, in relation with the tight emittance budget, proper calibration and redundancy should be foreseen:

- Calibration: It must be possible to measure the $\beta$-function with high accuracy (about 1%) at the profile monitors. This requires a BPM in the immediate vicinity of the monitors and preferably two BPM’s nearby without quadrupoles in between. This is included in the BPM layout specification [25].

In addition, the two quadrupoles on either side of the profile monitors should be equipped with K-modulation for an independent way of measuring the $\beta$-function.

- Cross-calibration: At least two independent profile monitors should be foreseen. They must be installed in the same straight-section to profit from the facilities to measure the $\beta$-function and as close as possible from each other.

For the time being, the tail monitors are foreseen to be wire scanners (the synchrotron light monitors may fulfil also this function). Although wire scanners can withstand only a fraction of the nominal beam current [23], they are also ideal for an absolute calibration. To minimize the risk of quench in the D3 separator magnet [23], they ought to be installed immediately downstream of this magnet as represented in Figure 1.

- It is strongly recommended to keep the space available in IP5 and to continue the study of a further profile monitor which can withstand the whole beam and would have improved performance for the overall flat top energy operation.

4.5 TOLERABLE EMITTANCE BLOW-UP

- Single-pass monitors: in order to extend the use of these monitors to few passes, it is advisable to keep the blow-up below 1% per turn.

- Circulating beam monitors: A continuous monitoring of the beam size over the period from injection to the beginning of the collisions should cause a blow-up not larger than 1%.

- Circulating beam tail monitors: The measurement should not disturb the tail density by more than 10%.

4.6 SYNCHRONISATION

For single-pass or few-pass measurements, the monitors will be triggered by timing events. Typical examples are an injection pre-pulse for first turn or injection matching studies or a start of ramp signal. For measurements on circulating beams, the monitors will be either triggered by machine events, clock events or operator requests.
4.7 DATA FLOWS AND RESPONSE TIME

At the specification level, we define the logical data flows and response times acceptable for an efficient operation of the machine.

To avoid as much as possible digitized spot transmission over the network, it is felt necessary that the front end instrument already extract the main observables of the spots or profiles (beam size, position and tilt at the monitor location).

For normal machine and experiment operation, it is foreseen that the following information should be made available for logging, fixed displays and feedback loops over the entire run:

− The rms beam sizes and tilt at the monitor location integrated over the entire beam at 10 Hz.
− The rms individual bunch sizes and tilt at the monitor location every minute.

For specific studies, like first turn or matching, data will be transmitted when the measurement will be requested. In these cases, the spots and/or profiles will also be transmitted to allow more precise treatment and studies at the application level.

4.8 POST MORTEM

During normal running, the beam circulating monitoring devices shall be able to recognize total beam losses and take appropriate action.

Provisionally, it is foreseen that:

• a first circular buffer should store the rms beam sizes, beam position and tilt whenever possible measured every 20 ms over the last 20 s of beam.
• a second circular buffer should store the last measured individual bunch sizes, positions and tilt recorded over the last ten minutes (i.e. 10 set of values per bunches).

5. DESIGN CONSTRAINTS

5.1 PREFERRED LOCATION FOR THE BEAM MONITORS

When possible, the beam instruments are located in LSS4. This is a rather 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 1. One can profit from this opportunity to install instruments which otherwise would be difficult to incorporate. However a serious worry is that when the RF cavities are under conditioning or even during normal operation, the radiation level might reach a prohibitive level in this area [26].

5.2 INTERLOCKS VS BEAM CURRENT AND NUMBER OF TURNS

The range of beam parameters being large in LHC, the intercepting profile monitors shall be protected against a possible misuse. In the interlock strategy,

• the beam current,
• the beam energy,
• and the number of revolutions
  must be considered.
5.2.1 BTV MONITOR

If a BTV screen of OTR type (Optical Transition Radiation, commonly observed in the SPS with a 15 μm thick Ti sheet) is used at injection energy, its overheating limit must be avoided; therefore if the rms beam size at the monitor is 1 mm in both transverse planes:

- 1.1.10^{11} protons (one nominal bunch) can circulate during 300 consecutive turns
- a current of 3.10^{13} protons (288 nominal bunches = one SPS batch) is allowed only on 2 turn(s).

The control of BTV monitors must be inhibited if any beam is circulating.

5.2.2 WIRE SCANNERS

The calibration device, foreseen to be a wire scanner, must be inhibited above current levels which are beam energy dependent [23], decreasing from 8 PS batches, each of 72 nominal bunches, at 450 GeV, down to 2 nominal PS batches at 7 TeV. This later current level at 7 TeV might however have to be divided by 2 to prevent any risk of quench, depending on the exact wire-scanner location.

5.3 ALIGNMENT

Residual misalignment errors of 0.15 mm (rms) are acceptable. Profile monitors are in general not intended to provide precise absolute positioning.

5.4 IMPEDANCE

The transverse profile monitors will be incorporated along the machine vacuum chamber. Hence they may have a contribution to the global impedance value seen by the circulating beam. Therefore their design must be submitted to the Impedance WG at the most important steps of their development study in order to ensure compatibility with the LHC machine impedance budget.

5.5 RADIATION HARDNESS

As far as radiation is concerned, both locations in LSS4 and LSS5 need careful investigations.

In the IP4 region, without suitable protection, the radiation level will be very high during conditioning of the RF cavities. Radiation can also compromise a good functioning of the profile monitors even during normal operation [26]. For the time being, precise data are not available. An evaluation is required and once the results are known proper actions will be necessary to protect the critical monitor components: installation of appropriate shielding is a solution.

IP5 will be a high luminosity insertion point and the expected activity in the detector region has been evaluated [27] and [28]. A dose between 10 Gy/year and 100 Gy/year is expected.
5.6 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 is of importance for several critical phases of machine operation (injection, ramping, squeezing, collimator setting).

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

7. SAFETY AND REGULATORY REQUIREMENTS

The transverse profile monitors 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

[18] LHC Commissioning Committee, 20/11/2002, where this functional specification was presented.
9. ANNEX

Figure 3 describes the time structure of the nominal LHC beam.

**Bunch Disposition in the LHC, SPS and PS**

- LHC (1-Ring) = 88.924 μs

**Filling Scheme**

3564 = {((72b + 8c) x 3 + 30e} x 2 + ((72b + 8c) x 4 + 31e) x 3
+ {((72b + 8c) x 3 + 30e} x 3 + 81e

**Beam Gaps**

- $\tau_1$ = 12 missing bunches (72 bunches on $b=84$)
- $\tau_2$ = 8 missing bunches (SPS Injection Kicker rise time = 220 ns.)
- $\tau_3$ = 38 missing bunches (LHC Injection Kicker rise time = 0.94 μs.)
- $\tau_4$ = 39 missing bunches ("")
- $\tau_5$ = 119 missing bunches (LHC Dump Kicker rise time = 3 μs.)

**Figure 3**: Bunch pattern in the LHC machine.