LHC Beam Size Measurement Review

Findings, comments and recommendations

G. Arduini, A. Dabrowski, M. Lamont, J. Wenninger, K. Wittenburg

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Charge to the Reviewers

- Are the limitations of the existing devices being addressed correctly?
- Is the case for a new, non-invasive beam size measurement device solid in the context of the long-term future of the LHC?
- Are the specifications clear?
- Is the current HL-LHC baseline of a BGV device the most adapted to reach these specifications?

Detailed budget & planning issues will not be directly reviewed. The aim will be to make recommendations for one or more future instruments for which a full design review will be held at the end of 2020.

Programme

- **Performance of existing devices & plans for Run 3**
  - Summary of uses of beam profile measurements in LHC - S. Papadopoulou
  - LHC wire scanner system Run 1&2 & plans for Run 3 – F. Roncarolo
  - LHC synchrotron light imaging system Run 1&2 & plans for Run 3 – G. Trad
  - LHC BGV demonstrator Run 2 - B Würkner
  - Quadrupolar BPM beam size measurements – D. Louro Alves

- **Future Possibilities**
  - Beam size measurement requirements for HL-LHC – R. Tomas
  - Current BI & WP13 Baseline for relevant HL LHC instrumentation – R. Jones
  - Possible wirescanner upgrades for HL-LHC – R. Veness
  - Possible synchrotron light upgrades for HL-LHC (interferometry / slit scanner / ….) E. Bravin
  - Proposal for an upgraded beam gas ionisation system – J. Storey
  - Gas jet diagnostics for HL-LHC – S. Mazzoni
  - Proposal for a BGV system for HL-LHC – R. Kieffer

General comments

- The reviewers were impressed by:
  - the excellent and very informative presentations
  - The level of understanding of the limitations of the present instruments
  - The quality of the solutions proposed and of the design of new instruments and the performance of the prototypes being developed

General comments

- The success of the LHC commissioning and performance ramp up is due to a large extent to the quality of its beam instrumentation
- The LHC beam profile measurements rely on two main devices:
  - **Wire scanners** providing beam profile measurements and beam size measurements with excellent accuracy but on a limited number of bunches (limited by wire heating at injection and beam losses on downstream SC magnets at flat top). Used for calibrating any other beam profile/size measurement device in the LHC

General comments

- **Beam Synchrotron Radiation Telescope (BSRT)** providing beam size measurements for any number of bunches, bunch-by-bunch, *continuously all through the cycle* but the measurement is not meaningful during the ramp due to the intrinsic uncertainties in the source of the synchrotron radiation

Instrument	Beam Type	Average			Bunch by Bunch (All)		
		Systematic Error	Precision / Reproducibility	Time	Systematic Error	Resolution	Time
Wire Scanner	Calibration	3%	2-10%	-	3%	10-20%	-
Synchrotron Light	Physics beam	10%	<1%*	30s	10%	2%	30s

*Reproducibility has been an issue. The quoted value was obtained on a short term basis after calibration.

Are the limitations of the existing devices being addressed correctly? Wire Scanners

- Findings
  - Impressive number of scans performed each year (operation, special modes like van der Meer scans, calibration).
  - Initial issues with bellow failures and HOM have been addressed successfully making the wire scanners a very reliable system
  - Photo multiplier non-linearities and observed loss of tension of the wire have been a source of non-reproducibility of the measurements
    - The first one is being addressed
    - The second has not been understood yet but it has been observed only on one wire scanner and “hot spare” could be used instead
  - The discrepancy (~10%-15%) between emittances extracted from WS and emittance scans is not yet understood
  - The discrepancy with the emittance derived from luminosity measurements cannot be explained simply by errors on the optics parameters (non-gaussianity of the transverse and/or longitudinal distributions could explain part of the discrepancy)
  - A test bench to calibrate the wire position as a function of the potentiometer reading is not available
  - The system is obsolete (LEP design)

Are the limitations of the existing devices being addressed correctly? Wire Scanners

- Comments
  - The present linear scanning speed is a trade-off between limiting wire damage and high density of measurement points.
  - Operation at higher speed with rotational wire scanners being studied would imply multi-scans for bunch-by-bunch profiles to obtain a significant sampling of the beam profile
  - The major limitation of the present system for HL-LHC is the maximum number of bunches at injection (120 to be compared with 288 bunches per injection). This can be lifted either by increasing the scanning speed or by addressing the causes of wire damage/breakage.

Are the limitations of the existing devices being addressed correctly? Wire Scanners

- Recommendations
  - Hot spare should be maintained fully operational
  - Given their main function (calibration) any upgrade should not compromise on accuracy and reliability
  - We recommend to:
    - to pursue the design of a new linear system to address obsolescence issues
    - to understand and mitigate the causes of wire damage/breakage by investigating materials/configurations
  - The development of the rotational design as a back-up is supported. However, the potential advantages of this solution as presented are not enough to warrant it becoming baseline.

Are the limitations of the existing devices being addressed correctly?
BSRT

- Findings
  - Complex radiation source (Dipole, edges, undulator, …) not easy to simulate and to calibrate in situ with an “artificial” source:
    - ➔ No meaningful beam size measurement during the ramp
    - ➔ Non-Gaussian beam profiles cannot be resolved due to limited Point Spread Function/Line Spread Function smearing out the details of the profile structure. This appear to be an intrinsic limitation for which there is no evident solution
  - Quite some effort required to keep good performance. However, it is the only instrument measuring beam size (bunch by bunch) over the entire cycle with nominal beams
  - Relies on the availability of another device (WS) for absolute calibration at injection and at flat-top
  - Problems with mirror, image intensifier, vacuum window have been encountered and have affected availability (in run 1) and reproducibility in Run 2:
    - The solutions proposed should address the reproducibility issues
  - A new synchrotron light extraction per beam will be designed and installed to allow additional features (halo monitoring, streak camera, etc.) but with no expected gain in performance for beam profile and size measurement

Are the limitations of the existing devices being addressed correctly? BSRT

- Comments
  - Pin-hole camera and the implementation of Pockels cells have been proposed as possible upgrades
    - Pin-hole camera is a complex system that might be difficult to implement in vacuum (e.g. impedance) in addition it is not clear that it will provide a significant improvement in the quality of the light source
    - The present optical quality of Pockels cells is not sufficient for the purpose of bunch-by bunch measurements

Are the limitations of the existing devices being addressed correctly?
BSRT

- Recommendations
  - We believe that the continuous measurement based on the camera is to be maintained as a work-horse
  - Among the presented upgrades it is recommended to pursue:
    - Ramp down undulators at high energy
    - Installation of Fluorine/Chlorine free components (cfr. experience in SR sources)
    - Move components out of focus
    - New SR extraction tank
  - Further study
    - Implementation a dynamic position for the mirror to evaluate the benefits wrt to the additional complexity (e.g. machine protection)

Is the case for a new, non-invasive beam size measurement device solid in the context of the long-term future of the LHC?

- Findings
  - None of the present instruments provides a bunch-by-bunch profile measurement for the physics beam along the whole cycle. An additional non-invasive measurement device complementary to the WS and BSRT devices is therefore required
  - Yes the case is solid
- Recommendations
  - Concentrate on the development of at least one beam profile measurement device type allowing precise bunch-by-bunch measurement during the cycle

Are the specifications clear?

- Findings
  - The initial specifications have been based on the need to measure emittance blow-up during the cycle with a budget of only 7%

Instrument	Beam Type	Average			Bunch by Bunch (All)		
		Systematic Error	Precision / Reproducibility	Time	Systematic Error	Resolution	Time
LHC Specif. LHC-B-ES-0006	Calibration	1%	-	Any	-	-	-
	Physics beam	5%	1%	100ms	-	5%	100ms
	Special cases	-	5%	10ms	-	-	-

  - The HL-LHC specifications are based on the same need to identify potential sources of blow-up during the ramp but with an emittance blow-up budget of 10 - 15 % on top of that due to IBS for a total emittance growth budget of 20 - 25%
  - Currently there is a 10-15% level agreement between all methods in SB.

Are the specifications clear?

- For HL-LHC:
  - Emittance measurement accuracy below 10% is required for performance
  - A precision of about ~1% for relative changes over time and bunch-by-bunch measurements is needed to identify potential sources of emittance growth and to control sources of bunch-by-bunch luminosity variations (HL-LHC performance will be limited by detectors more than in LHC)
  - The maximum integration time for the bunch-by-bunch measurements scale is dictated by the need of qualifying the beam at injection and to localize in the cycle the potential occurrences of emittance growth. ~1 minute appear to be a reasonable requirement taken into account the typical time scales of the processes (optics changes, ramp progression, longitudinal emittance blow-up, separation collapse, etc.)
  - Non Gaussian Profiles may explain discrepancies between measurements. Requirement of profile measurement at HL-LHC is important. In particular for off-line analysis and more detailed studies
  - Trustful absolute calibration (within 10%) is a requirement for HL-LHC

Are the specifications clear?

- Comments
  - Precise/accurate emittance measurements rely on equally precise/accurate optics measurements and prediction (beta functions, dispersion, coupling) at the location of the instruments (and at the IPs if comparison with emittance scans and luminosity is needed)
  - While K-modulation in IR4 provided β function measurements with ≤ 2% precision in steady state measurements during the ramp are more challenging (5 %). Possible developments have been outlined

- Recommendations
  - Continue the effort of improving the accuracy/precision of the optics measurement during the ramp (AC dipole?)

Is the current HL-LHC baseline of a BGV device the most adapted to reach these specifications?

- Findings
  - Beam Gas Vertex (BGV)
    - We are impressed by the performance of the BGV demonstrator and by the quality of the analysis performed
    - The demonstrator could be operated in “correlation” mode due to the limited number of tracks per interaction Only beam size (no beam profile) measurements can be obtained.
    - The HL-LHC BGV design promises to address the requirements for beam size and beam profile measurements over the LHC cycle based on the demonstrator experience
    - The HL BGV requires a gas jet to achieve the required performance. Although an additional complexity this technology is well known
  - Beam Gas Ionization (BGI)
    - The results obtained for the BGI in the PS and the presented performance expectations of a similar device for HL-LHC are outstanding and fully match the requirements for a continuous bunch-by-bunch beam profile measurement
    - The BGI does not require a gas jet and can be operated with the nominal vacuum

Is the current HL-LHC baseline of a BGV device the most adapted to reach these specifications?

- Comments
  - At present, BE/BI has limited in-house expertise for the operation of the BGV, in particular w.r.t. event reconstruction techniques.
  - The technologies underpinning the BGI appears to rely on core expertise already available in BI
  - BGV is providing a 2D profile measurement similarly to the BSRT while BGI is providing 1D projections requiring two devices per beam
  - There is not yet a complete design of the BGI system and in particular of the dipole magnet.

Is the current HL-LHC baseline of a BGV device the most adapted to reach these specifications?

- Recommendations
  - Although there is a clear interest to profit of the BGV demonstrator in LHC Run 3 to study the emittance evolution during the cycle in the LHC the operation of such a system should not distract resources from the development of the HL-LHC device
  - The study of the performance of the BGI detector in the PS should be pursued while continuing the development of the LHC technical design. Particular attention should be given to:
    - magnet design
    - impedance issues
    - radiation hardness of the system
  - It appears that both the BGV and BGI are adapted to reach the specifications and it is recommended to provide a technical design for both systems in time for a decision on the solution to be taken for HL-LHC. We recommend that BI be prepared to put one of the two options aside in due time noting that BI should gain in-house expertise on readout and track reconstruction if the BGV option is retained.

Others

- We have been presented with very interesting concepts for other continuous beam size measurement devices:
  - The quadrupolar pick-up:
    - Proof-of-principle based on existing hardware
    - A prototype would require new hardware (movable BPM)
    - Can only provide beam size measurements – no beam profiles
    - Reconstruction of beam size from the electrode signals is not straightforward (systematics to be further understood)
    - Does not look like a robust method one can rely on as workhorse.
  - The gas curtain detector:
    - based on detection of luminescence radiation
    - Conceived for monitoring the overlap between proton and electron beams in the hollow e-lens
    - Not evident its use as a beam profile monitor


HiLumi
HL-LHC PROJECT


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