1 HL-LHC IP AND RING BPMS: READ-OUT TECHNOLOGY AND EXPECTED PERFORMANCE (MANFRED WENDT)

This is a report on the activities for the LHC and HL-LHC IR BPMs. Several installation and R&D activities are underway, e.g. (but not limited to) the test installation of new read-out electronics for the interlock BPMs in point 6 (to avoid problems in operation with doublet-bunches), the integrated collimator BPMs with buttons embedded in collimator jaws (planned to be installed on all HL-LHC collimators), and the HEL stripline BPM which will monitor both the hollow-electron and the LHC proton beams. For the HL-LHC with a completely different beam-line layout in points 1 and 5, 32 new "cold" BPM pickups have been designed, of which 24 will utilize a common chamber for the two beams, and need a different, new read-out system. The final prototyping of the read-out electronics is planned before LS3 and the full deployment at the end of it. As a long-term project the ring BPM consolidation is ongoing, with final prototyping done by the end of Run 3 and following installation in LS3/LS4.

Today, most BPMs use the WBTN (Wide-Band Time-Normalizer) acquisition system, except for the collimator and some IR BPMs, which use the high-precision DOROS read-out system (in case of the LHC IR BPMs both systems operate in parallel on the same BPM pickups). While the WBTN BPM read-out system fulfills most of the LHC BPM requirements, it has a few limitations, such as temperature sensitivity, aging effects (*e.g.* offset drifts), and it suffers from signal reflections between the pickups and the read-out electronics. The single bunch dynamic range is limited to ~46 dB, and the long-term maintainability of this complex analog electronics causes "headaches". The ring BPM consolidation project should meet all the requirements defined by the current system, and should have improvements in long-term stability and reproducibility, higher resolution, as well as add some flexibility. The main challenges are radiation-tolerant components for the hardware in the tunnel and the maximum raw data throughput limited by the existing fiber installation. The expected single bunch resolution is 10-15 μm, depending on the implemented signal processing scheme.

For the high-luminosity LHC upgrade, six new stripline BPMs in the common regions and two new button BPMs after D2 on each side of the IP are foreseen. The tungsten-shielded type-B IR BPMs are rotated by 45° to protect the striplines from collision debris. All IR "cold" BPMs will be carbon-coated to suppress the e-cloud. The rotated BPMs with large aperture (octagonal 112.7 mm / 119.7 mm) have a rather weak coupling (7.5 % for a centered beam), a low sensitivity (0.4 dB/mm at the BPM center) and suffer from high nonlinearities. Since these stripline BPMs are not perfect directional couplers, they also adds parasitic signal contents from the counter-rotating beam bunch to the bunch signal to be measured. The directivity is defined as the ratio of the upstream (wanted) signal to the downstream (unwanted) signal. For HL-LHC stripline BPM pickups the directivity is ~26 dB. A BPM read-out system with includes a compensation scheme based on a digital signal processing is currently being studied (infrastructure, hardware and algorithm). So far, the bunch signal power compensation algorithm was found to be the most promising. The simulation of the signals expected on the stripline ports are based on a pair of counter-rotating B1/B2 beam bunches, characterized by their positions in the BPM plane, bunch crossing timing, intensities and (Gaussian) bunch lengths. The effects of the long coaxial cables, filter stage and variable attenuator / gain (given step size) are also included. The resulting analog signals are used as the basis for an ensemble of waveforms, as generated by a digitizer with an asynchronous clock with given sampling frequency, amplitude quantization and a random noise amplitude factor. In simulations with bunches of same intensity the relative accuracy errors are below 10^{-4} in all planes. Comparing the absolute errors without compensation and by applying a 5th order polynomial correction for the pickup position non-linearities (presently used in the LHC) it is possible to get the accuracy error from 100 µm to well below 10 µm. For the case of unequal bunch intensities (one order of magnitude difference), and assuming no bunch lengthening the relative errors increase. The absolute position errors in this case are difficult to reduce the error below 10 µm in some BPM locations, even when applying correction polynomials of higher orders.

In short, various activities on the LHC BPMs are ongoing and the current R&D efforts were presented. All these new developments are based on digital signal processing, which will improve the reproducibility, flexibility and performance. All future BPM signal processing schemes assume 25 ns minimum bunch spacing (except the interlock BPMs, which can handle doublet bunches). The expected performance for these kinds of systems for single bunch resolution is 10-15 µm and the orbit resolution is expected to be below 1 µm. For the HL-LHC IR BPMs the accuracy is ~7 µm when compensating the errors of same intensity counter-rotating bunches, and ~70 µm for the compensation of ten times lower intensity counter-rotating bunch (assuming a 5th order polynomial correction of the non-linearities). During Run 3 some parasitic and dedicated beam studies with prototype hardware will be performed, and a dedicated MD on stripline BPMS.4L5 is planned to verify the compensation scheme.

- **Rogelio** asked if doublets are driving any design choice, since they are not foreseen for any practical use. **Manfred** replied that they are considered only for the interlock BPMs that are a part of machine protection system. For other BPMs doublets are not taken into design considerations.
- **Gianluigi** asked if there are any estimates for the orbit stability, especially for the IR BPMs. **Manfred** replied that for the IR BPMs they will rely on the calibration and adjustments for the drifts. There is no number that can be given. The present WBTN system is based on analog components, which are aging, thus there are drifts. The new system will be based on digital signal processing, minimizing the number of analog components, which will reduce aging effects, but some drift effects will still be present. **Rogelio** pointed out that the stability on the 24h scale is more interesting. **Manfred** replied that this will be tested in Run 3 to get the number.
- **Rogelio** asked if the improvements, performance and tolerances would be addressed during the Run 3 tests. **Manfred** replied that the test will be done first offline and then with the beam. The R&D has to be finalized before LS3.
- **Riccardo** asked why the compensation is considered only up to 5th order and if there is a limit. **Manfred** replied that there is no limit (the 5th order polynomial has "historical" reasons), 7th or 9th order can be tested.
- **Riccardo** asked if the bunch lengthening and changes is charge can be compensated for. **Manfred** said that there is work ongoing to study the compensation for the bunch lengthening, but the effects of individual bunch intensities cannot be corrected.
- Rogelio asked if the 10-15 µm precision is estimated for the high bunch charge (10^{11} ppb). **Manfred** replied that the effect of smaller bunch charges ($2x10^{10}$ ppb) will be small, because the gain will be adapted.