WP13 in a nutshell – Beam Diagnostics & Instrumentation

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<th>WP Leader:</th>
<th>Technologies: Raw Materials, Electrical Equipment, electronics and instrumentation for accelerators</th>
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The extensive array of beam instrumentation with which the LHC is equipped has played a major role in its commissioning, rapid intensity ramp-up, and safe and reliable operation. In addition to all of these existing diagnostics, the HL-LHC brings a number of new challenges in terms of instrumentation that are currently being addressed in this work package.

**HL-LHC High Luminosity LHC Project WP 13 - Beam Diagnostics & Instrumentation Work Package Tasks and their Principal Technologies**

**WP 13 - Beam Diagnostics & Instrumentation - BLM - Beam loss monitors**
- Radiation hard electronics
  - Low noise, high frequency amplifiers
  - Application-specific integrated circuits (ASICs)

**WP 13 - Beam Diagnostics & Instrumentation - BPM - Beam position monitors**
- Semi-Rigid, Radio Frequency, Coaxial Cables
  - Glass-metal or brazed ceramic sealing technology
  - Operation in cryogenic and radiation environments
- Radio frequency UHV feedthroughs
  - Glass-metal or brazed ceramic sealing technology
  - Operation in cryogenic and radiation environments
- 3D printing of complex, metallic components
- Electronics based on field programmable gate arrays (FPGAs)

**WP 13 - Beam Diagnostics & Instrumentation - BRANQ - Luminosity monitors**
- Quartz scintillators
- Photomultiplier assemblies
  - Operation in radiation environments

**WP 13 - Beam Diagnostics & Instrumentation - BPW - Wideband pick-ups**
- Electro-optical crystals
- Fibre-coupled lasers

**WP 13 - Beam Diagnostics & Instrumentation - BSR - Synchrotron light monitors**
- Scientific cameras
  - CMOS
  - Streak
  - High dynamic range

**WP 13 - Beam Diagnostics & Instrumentation - BGV - Beam Gas Vertex Detector**
- Scintillating fibres
- Silicon photo-multipliers

**WP 13 - Beam Diagnostics & Instrumentation - Long range beam-beam compensator**
- Electron gun
- Superconducting solenoid
**Fig. 1** - Beam Loss monitors installed in the LHC

**Fig. 2** - Beam position monitors based on electro-optical crystals for higher bandwidth

**Fig. 3** - Gas jet profile monitoring set-up
Fig. 4 - Beam Gas Vertex Detector demonstrator installed in the LHC

Fig. 5 - Electro optical BPM PoP installed in SPS (left) and mechanical design of BPM for the triplets (right)

Fig.6 - Radiation hard electronics (GBT developed at CERN). Digital signal processing on custom FPGA motherboard (on the right)

GENERAL DESCRIPTION
In order to be able to cope with the new demands of the HL-LHC the beam loss system, designed to protect the LHC from losses that could cause damage or quench a superconducting magnet, will need a significant upgrade. In particular, cryogenic beam loss monitors are under investigation for deployment in the new inner triplet magnets to distinguish between collision debris and primary beam losses. Radiation-tolerant integrated circuits are also under development to allow the front-end electronics to sit much closer to the detector, so minimizing the cable length required, reducing the influence of noise.

The use of crab cavities and possible use of long-range beam–beam compensators and hollow-electron lenses also implies new instrumentation in order to allow for optimization of their performance. Several additional diagnostic systems will therefore be developed. This includes very high bandwidth pick-ups and a streak camera installations to perform intra-bunch transverse position measurements and with new techniques for transverse beam size measurements such as a beam gas vertex detector.

Upgrades to several other existing systems is also envisaged, including the beam position measurement system in the interaction regions and the addition of a halo measurement capability to synchrotron light diagnostics.

**BEAM LOSS MONITORS - BLM**

Monitoring of beam losses is essential for the safe and reliable operation of the LHC. The beam loss monitoring (BLM) system provides knowledge of the location and intensity of such losses, allowing an estimation to be made of the energy dissipated in the equipment along the accelerator. The information is used for machine protection, to qualify the collimation hierarchy, to optimize beam conditions, and to track the radiation dose to which equipment has been exposed. This is currently done using nearly 4000 ionization monitors distributed around the machine and located at all probable loss locations.

In the HL-LHC high luminosity insertions the magnets will be subjected to a greatly enhanced continuous radiation level due to the increase in collision debris resulting from the higher luminosity. With the presently installed configuration of ionization chambers in this region the additional signal from any dangerous accidental losses would be completely masked by that coming from collision debris. This is a critical issue for LHC machine protection and therefore R&D has started to investigate possible options for placing radiation detectors inside the cryostat of the triplet magnets as close as possible to the superconducting coils. The dose measured by such detectors would then correspond much more precisely to the dose deposited in the coils, allowing the system to be used once again to prevent a quench or damage.

Three detectors are currently under investigation as candidates for operation at cryogenic temperatures inside the cryostat of the triplet magnets:

- single crystal chemical vapour deposition (CVD) diamond with a thickness of 500 μm, an active area of 22 mm2, and gold as the electrode material;
- p+-n–n+ silicon wafers with a thickness of 280 μm, an active area of 23 mm2 and aluminium as the electrode material;
- Liquid helium ionization chambers.

**A RADIATION-TOLERANT APPLICATION-SPECIFIC INTEGRATED CIRCUIT FOR THE HL-LHC BEAM LOSS MONITORING SYSTEM (ASIC)**

The current front-end electronics for the LHC BLM system, while providing a 40 μs integration time, is limited in the dynamic range it can handle and is only radiation tolerant up to ~500 Gy. The latter implies the use of long cables in the higher radiation LSS regions, which further limits the dynamic range and in some cases brings the noise floor close to the quench level signal at 7 TeV. Instead of the discrete component currently used, an
optimized ASIC is therefore under development. This is based on the current-to-frequency conversion used in the existing system, but is packaged in a compact, radiation-tolerant form with an increased dynamic range. The technique employed allows the digitization of bipolar charge over a 120 dB dynamic range (corresponding to an electric charge range of 40 fC-42 nC) with a 40 μs integration time and a conversion reference provided by an adjustable, temperature-compensated current reference.

The main parameters of the ASIC are listed below:

<table>
<thead>
<tr>
<th>ASIC Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Integration time</td>
<td>40 μs</td>
</tr>
<tr>
<td>Input current range</td>
<td>−1.05−1.05 mA</td>
</tr>
<tr>
<td>Input charge range</td>
<td>−42−42 nC</td>
</tr>
<tr>
<td>Offset</td>
<td>&lt;40 aC at 40 μs integration, &lt;1 pA</td>
</tr>
<tr>
<td>Default least significant bit step</td>
<td>50 fC ±20%, adjustable</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>120 dB</td>
</tr>
<tr>
<td>Linearity error</td>
<td>&lt;±5%</td>
</tr>
<tr>
<td>Peak signal/noise ratio</td>
<td>53 dB</td>
</tr>
<tr>
<td>SFDR at 999 Hz, 1 mA</td>
<td>50 dB</td>
</tr>
<tr>
<td>Total ionizing dose</td>
<td>10 Mrad (Si)</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>2.5 V</td>
</tr>
<tr>
<td>Clock</td>
<td>12.8 MHz</td>
</tr>
<tr>
<td>Power</td>
<td>40 mW</td>
</tr>
<tr>
<td>Reference charge</td>
<td></td>
</tr>
<tr>
<td>Drift with TID</td>
<td>3% at 10 Mrad (Si)</td>
</tr>
<tr>
<td>Drift with temperature</td>
<td>&lt;600 × 10^6/°C</td>
</tr>
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Total ionizing dose (TID) effects on a prototype ASIC have been investigated using an X-ray beam with 20 keV peak energy. The characteristics of the device were measured up to 100 kGy (Si), followed by a one-week annealing cycle at 100°C. From the beginning to the end of the irradiation cycles, the functionality was always preserved, with the conversion offset remaining below 1 least significant bit (LSB) and the value of the full-scale charge drifting by less than 3%. Development will now continue to address the issues found using the prototype and to implement more advanced logic blocks.

It is foreseen that a total of some 300 detectors will be equipped with such a radiation hard front-end ASIC.

**BEAM POSITION MONITORING - BPM**

With its 1070 monitors, the LHC beam position monitor (BPM) system is the largest BPM system in the world, comprised of 3820 electronics cards in the accelerator tunnel and 1070 digital post-processing cards in surface buildings. Several upgrades to this system will be required for HL-LHC.

**BEAM POSITION MONITORING - STRIPLINE BEAM POSITION MONITORS**

In the HL-LHC high luminosity insertion regions a total of 28 new strip-line BPMs will be installed in the common beam-pipe sections of the highluminosity regions.

In the current HL-LHC layout for the HL-LHC high luminosity insertion regions, two types of cold strip-line BPMs, measuring simultaneously the position of both beams in both planes, are foreseen. The BPMs located in the interconnect between Q2A and Q2B as well as, possibly, in front of Q2A and Q3 magnets will be cold strip-line BPMs, rotated by 45° to allow the insertion of tungsten shielding in the median planes of both horizontal and vertical axes. All the other common beam-pipe insertion region BPMs will be cold strip-line BPMs with orthogonally positioned electrodes without the tungsten shielding.

The signal from all of these BPMs will be extracted using eight semi-rigid, radiation-resistant coaxial cables per...
BPM. Two feedthroughs with four coaxial cable connections will be integrated into the Q1, Q2A, Q2B, and Q3 cryostats and into the cryostat of the triplet corrector magnet package, with four such feedthroughs integrated into the D1 cryostat. The outputs of these feedthroughs will be connected to standard \( \frac{1}{2} " \) coaxial cables taking the signal to the electronics in the UA/UJ.

New button electrode beam position monitors are foreseen for the modified regions where the beams travel in separate vacuum chambers, specifically 2 warm BPMs (one per beam) in front of D2, new cold BPMs in Q4 and Q5, as well as one trigger BPM for the experiments between Q4 and Q5 on the incoming beam each side of the interaction point. These will be based on original LHC designs. A total of 28 new button BPMs will therefore need to be produced for HL-LHC.

The tendering for the mechanical Components and RF UHV feedthroughs will take place in the second half of 2018 while the semirigid cables and electronics will be purchased much later (after 2020).

**BEAM POSITION MONITORING - COLLIMATOR BEAM POSITION MONITORS**

All next-generation collimators for HL-LHC will have button electrodes embedded in their jaws for on-line measurement of the jaw-to-beam position. This is expected to provide a fast and direct way of positioning the collimator jaws and subsequently allow constant verification of the beam position at the collimator location, improving the reliability of the collimation system as a whole.

The collimator BPM hardware, i.e. the button electrode located in the jaw, the cable connecting the electrode to the electrical feedthrough mounted on the vacuum enclosure, and the feedthrough itself will need to withstand the radiation dose of 20 MGy expected during the lifetime of the collimator. Radiation hard electronics are also being developed for this system.

The components of the collimator's BPMs (Semirigid cables, flanges, pick-up bottoms, blind plug-ins, etc.) have been already purchased for LS2 and LS3 collimators.

**LUMINOSITY MONITORS - BRANQ**

The measurement of the collision rate at the luminous interaction points is very important for the optimization of the machine. The LHC experiments can certainly provide accurate information about the instantaneous luminosity, but this information is often not available until stable collisions have been established, and is often missing altogether during machine development periods. For this reason simple and reliable collision rate monitors, similar to those now used in the LHC, are also needed for the HL-LHC. This measurement is currently obtained by measuring the flux of forward neutral particles generated in the collisions using fast ionization chambers installed at the point where the two beams are separated into individual vacuum chambers. The detectors (BRAN) are installed inside the neutral shower absorber (TAN) whose role is to avoid neutral collision debris and the secondary showers these induce, which reach and damage downstream machine components. The luminosity monitors therefore already operate in a very high radiation area, which for the HL-LHC is anticipated be a further ten times the nominal LHC value. For this reason the technology chosen for the HL-LHC needs to be radiation-hard, with a geometry adapted to the new TAXN design. Quartz Cherenkov radiators are currently under study to fulfill this task.

**SYNCHROTRON LIGHT MONITORS - STREAK CAMERAS - BSRS**

The use of synchrotron light combined with a streak camera may be an easier alternative to electromagnetic or electro-optical pick-ups for high resolution temporal imaging. Using an optical system to re-image the synchrotron light at the entrance of a streak camera allows the transverse profile of the beam to be captured in one direction (X or Y) with a very fast time resolution. Streak cameras can be used to observe a number of parameters simultaneously: bunch length, transverse profiles along the bunch, longitudinal coherent motion, head–tail motion, etc. The main limitation of the streak camera is the repetition rate of the acquisition, typically <50 Hz, and the limited length of the recorded sample, given by the CCD size.
The longitudinal resolution of around 50 ps required for the HL-LHC is rather easy to achieve using streak cameras, where measurements down to the sub-picosecond range are now possible. In terms of transverse resolution two distinctions have to be made.

- Measurement of the beam width is affected by diffraction due to the large relativistic gamma of the beam, with the diffraction disk of the same order as the beam size. This will significantly reduce the resolution of such measurements.
- The centroid motion (i.e. the centre of gravity) is not directly affected by diffraction, which produces a symmetrical blur, and therefore the resolution for this type of measurement will be much better.

Streak cameras are expensive and delicate devices not designed for the harsh environment inside an accelerator. Radiation dose studies are therefore required in order to verify if a streak camera can be installed directly in the tunnel or if, which seems more likely, it has to be housed in a dedicated, shielded, hutch. The latter would imply an optical line to transport the synchrotron light from the machine to the camera, something for which an integration study will be initiated.

The procurement of these streak cameras will not start before 2023.

**SYNCHROTRON LIGHT MONITORS - HALO DIAGNOSTICS - BSRH**

Population of the beam ‘halo’, i.e. particles in between the beam core and the limits set by the primary collimators, can lead to important loss spikes through orbit jitter at the collimator locations. Measurement of the beam halo distribution is therefore important for understanding and controlling this mechanism. Such measurements are also important to determine the effectiveness of equipment that influences the beam halo, such as hollow electron lenses or long-range beam–beam compensators. Moreover, in the HL-LHC, any failure of a crab cavity module could result in the loss of the halo in a single turn. If the halo population is too high this could cause serious damage to the collimation system or to other components of the machine. In order to fulfil all of these diagnostic requirements for halo observation in the HL-LHC, the final system should be capable of measuring halo populations at the level of $10^{-5}$ relative to that of the core.

Two main techniques are currently being considered for halo monitoring in the HL-LHC:

- the use of high dynamic range cameras combined with anodization;
- core masking followed by acquisition using standard cameras;
- use of the beam gas vertex detector.

Apodization consists of shaping the light distribution at the entrance of the optical system using special masks, such that the interference pattern on the image plane reduces the effects of diffraction at the expense of resolution. A system based on an HDR camera with apodizing optics would allow the capture of the full beam image with the core and the halo visible at the same time.

The core masking technique is based on the Lyot coronagraph, which was invented in order to allow the observation of the sun’s corona without the need for a total solar eclipse. The optics contains several stages of re-imaging and masks (stops) such that at the final image plane the bright core is masked and the diffraction rings shifted outside of the image, leaving enough room for observation of the corona. Similar setups have already been used for the observation of beam halo in particle accelerators. In this case there is no need for an HDR camera as the core of the beam is masked. This does, however, imply that it is not possible to observe the core and the halo at the same time. Nevertheless it would still be possible to take consecutive images with and without the mask (adjusting the attenuation filters accordingly), to compose a synthetic image that includes both the core and the halo.

**BEAM GAS VERTEX PROFILE MONITOR (BGV)**
The VELO (vertex locator) detector of the LHCb experiment has shown how beam–gas interactions can be used to reconstruct the transverse beam profile of the circulating beams in the LHC. The new concept under study is to see whether a simplified version of such a particle physics tracking detector can be used to monitor the beams throughout the LHC acceleration cycle. Such a beam shape measurement technique is based on the reconstruction of beam–gas interaction vertices, where the charged particles produced in inelastic beam–gas interactions are detected with high-precision tracking detectors. Using the tracks left in the detectors, the vertex of the particle–gas interaction can be reconstructed so, with enough statistics, building up a complete 2D transverse beam profile. The longitudinal profile could also be reconstructed in this way if relative arrival time information is additionally acquired by the system.

This concept has, until now, never been applied to the field of beam instrumentation, mainly because of the high level of data treatment required. However, the advantages compared to the standard beam profile measurement are impressive: high resolution profile reconstruction, single bunch measurements in three dimensions, quasi non-destructive, no detector equipment required in the beam vacuum, and high radiation tolerance of the particle detectors and accompanying acquisition electronics.

One proof-of-principle demonstrator has been installed based on scintilating fibre technology and silicon photodiode detectors. A second prototype is foreseen for 2020, with a possible upgrade of both systems for the HL-LHC. This upgrade is currently not part of the HL-LHC baseline.

The tendering of the vacuum system required for the BGV is foreseen to be started by the 2Q of 2021.