CHALLENGES IN BEAM INSTRUMENTATION AND DIAGNOSTICS FOR LARGE RING COLLIDERS – BASED ON THE LHC EXPERIENCE

R. Jones, M. Wendt[#], J. Wenninger, CERN, Geneva, Switzerland

Abstract

An overview on some of the major challenges for beam instrumentation and diagnostics for large ring colliders is given. In the Introduction the general challenges are listed, independent of particle type and accelerator specifics. After a short LHC introduction, examples from the LHC experience are presented, related to observed issues, and to the present upgrade and improvement efforts, made during the long shutdown 1. A list, however not comprehensive, of relevant beam instrumentation R&D activities closes this summary.

INTRODUCTION

The next generation of a ring collider for high energy physics (HEP) will have >50 km circumference, and collide leptons, as a Higgs factory, or hadrons, for beyond standard model physics exploration, at highest energies (up to 100 TeV center-of-mass) and luminosities. At the time of this article we operate the Large Hadron Collider (LHC) at CERN (Geneva, Switzerland) for the HEP community at the energy frontier, colliding proton beams with up to 7+7 TeV [1].

Table 1: Large Ring Colliders for HEP

Collider	Years of operation	Circumference [km]	Beam type	Beam Energy [GeV]	Luminosity [$cm^{-2}s^{-1}$]
Tevatron	1983-2011	6.3	p-$\bar{\text{p}}$	980-980	4e32
LEP	1989-2000	27	e^+-e^-	104.5-104.5	2.1e31
HERA*	1992-2007	6.3	p-e	920-27.5	5.1e31
LHC	**2008-…**	**27**	**p-p/Pb^{82+}**	**4000-4000****	**7.7e33****

* achieved >50 % longitudinal polarization of the e-beam
** achieved performance in 2012

Table 1 summarizes recent large ring colliders, which all have common goals, i.e. highest center-of-mass (CoM) energy, high integrated luminosity (reliable operation), reasonable low investment and operation costs, and in case of leptons high spin polarization. All these ring accelerators made heavy use of superconductive technologies for magnets, RF or both. For any future large ring accelerator project the time span from the initial concept to the first stored beam will be large, 20 years, or more. With the LHC now in operation, the case for a future HEP machine has to be made, this also includes first thoughts on the challenges for the beam instrumentation.

The beam instrumentation and diagnostics systems have to characterize mission critical beam parameters, e.g.:

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#manfred.wendt@cern.ch

Intensity Beam and bunch intensities, beam life time, abort gap, etc.

Orbit and Position Beam position monitors (BPM) with bunch-by-bunch, turn-by-turn and high resolution beam orbit measurement capabilities. All BPMs integrated into the orbit feedback system, some BPMs integrated into technical interlock systems. Special BPMs for specific tasks, e.g. BPMs integrated into collimator jaws.

Beam Losses The beam loss monitors (BLM) are the central element of the machine protection system (MPS).

Tunes and Instabilities Monitoring and feedback of the betatron tunes should be accomplished with no or minimum beam excitation. The measurement on the tunes of individual bunches (single bunch tunes) is desirable. A system for the early detection of instabilities, e.g. head-tail motion is of great benefit.

Beam Profile (Emittance) and Halo A non- or minimum invasive measurement of the transverse beam profile, with single bunch capability is essential to monitor the beam emittance. Techniques with high dynamic range have to be developed to monitor the transverse beam halo, which need to be eliminated.

Chromaticity measurement based on a direct, non-invasive measurement technique, e.g. monitoring of the *Schottky* bands.

Challenges

Regardless of beam type and exact machine layout, all future large ring accelerators will have some major challenges for the beam instrumentation in common:

- The large physical size requires a large number of components and subsystems, thus a tight control on costs and reliability. E.g. the use of copper cables over long distances is not adequate, optical fibers have to replace copper wherever possible.
- Low temperatures for superconductive operation of magnets and/or RF give additional challenges for nearby beam monitors, e.g. cryogenic RF vacuum feedthroughs, RF cables, beam monitors (BPMs, BLMs) inside the cryostat.
- High order mode (HOM) and wakefield effects of beam detectors have to be well understood to minimize their impact on the accelerator's impedance budget, and to prevent damages e.g. due to RF heating.
- Basically all beam detection methods have to be non-invasive as of the damage and residual loss potential of high intensity, high brilliance beams.
- An early observation and damping of beam instabilities, e.g. head-tail, e-cloud, etc. will be crucial.

- As with all past HEP machines, the beam instrumentation systems for a future ring accelerator have to be prepared for small and major changes in the lifespan, e.g. different beam formatting and timing, changes in beam / bunch intensities, different particle species, changes in the machine optics and lattice, etc.
- The high stored energy of the high brightness beam goes along with a severe damage potential. This results in a substantial challenge for the MPS and all the related components and subsystems, particular the BLM system.

THE LARGE HADRON COLLIDER
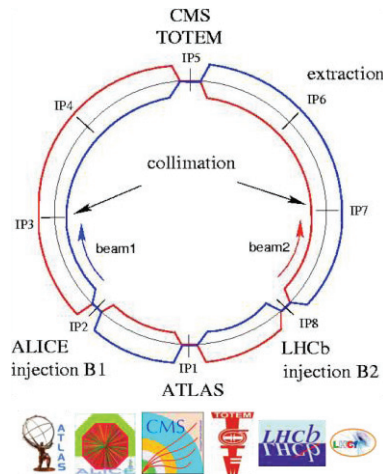
Figure 1: LHC layout.

Figure 1 shows the layout of the LHC, with two separate rings, each 26.7 km circumference, which provide proton and lead ion collisions at 4 interaction points (IP). The machine is divided symmetrically in eight arc sectors, each ~3 km long, and eight long straight sections, each ~700 m long. The guide fields for the beams are provided by ~8000 superconducting magnets, fed by 1600 power supply circuits. The 2-in-1 design dipole magnets are ramped to a field of 8.3 T.

Also for some of the beam diagnostics the quantities are impressive, about 1000 BPM systems to monitor and correct the beam orbit, and 4000 BLM systems based on ionization chambers for beam loss detection and machine protection.
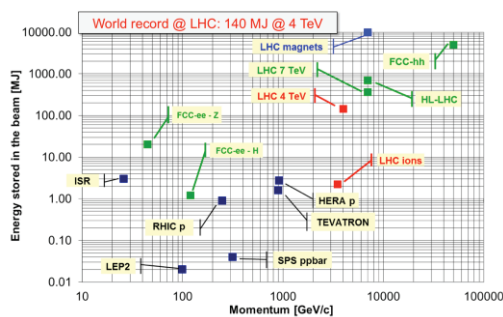

Figure 2: Stored energy in ring accelerators.

At nominal operation, i.e. 7 TeV beam energy and 0.58 A beam current, the stored energy of each proton beam is 360 MJ, equivalent to a 200 m long train travelling at 155 km/h, or 90 kg of TNT. The related high damage potential requires particular attention on the BLMs, some of the BPMs, and all other systems that are in direct contact to the MPS [2]. Figure 2 compares beam energy and the stored energy of different ring accelerators, showing some relaxation for colliding leptons in future rings (FCC).

A severe power incident at the LHC, in September 2008 during no beam operation, required a safety limit to 4 TeV beam energy. Starting 2015, after 1-1/2 years of consolidation the full beam energy operation will be restored.

EXAMPLES OF LHC BEAM INSTRUMENTATION CHALLENGES

Regardless if the next large ring accelerator is a "*Higgs factory*" lepton collider or an energy frontier proton machine, the lessons learned and challenges from the present LHC will be of great benefit, of course not only for the subject of beam instrumentation [3,4]. The following list of examples is neither complete nor comprehensive.

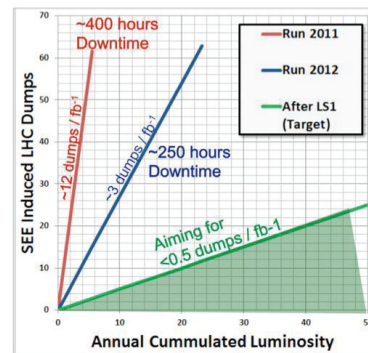### *Minimizing Radiation to Electronics*

Figure 3: Beam dumps and downtime due to single event effects in LHC front-end electronics.

To cope with reasonable cable installation lengths and signal levels, most of the front-end electronics is installed in the LHC tunnel, or in the alcoves running parallel to the straight sections. Therefore the electronics hardware is exposed to residual radiation from the accelerator, namely highly energetic ionized particles (>20 MeV) causing single event effects (SEE) in the active silicon areas of the electronics chips. SEEs are further divided into categories, i.e. single event upset (SEU), single event latchup (SEL), single event burnout (SEU), all have a malfunction of the transistor in common. Figure 3 shows the number of LHC beam aborts, along with the caused downtime per fb integrated luminosity for the years 2011 and 2012 due to electronics SEEs (not only those of beam diagnostics electronics). Major shielding and electronics relocation efforts in the long shutdown 1 (LS1) aiming for a

substantial reduction of these SEEs, the goal is <0.5 dumps/fb^{-1}.

Beam Loss Monitors (BLM)

The BLM system is the "primary line of defence", feeding the machine protection system (MPS), and has to cope with several substantial challenges [5].
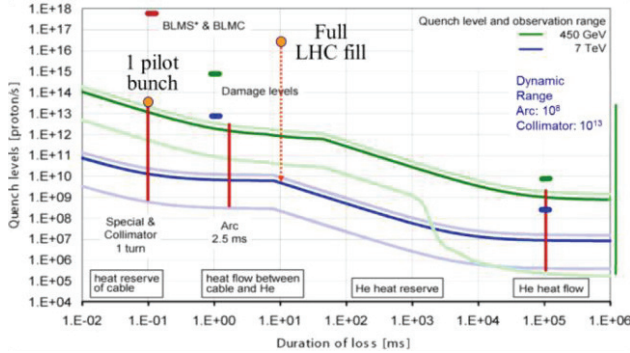

Figure 4: LHC quench and damage thresholds.

As Figure 4 indicates, with beam energies of >6.5 TeV at Run II, the quench and damage thresholds are significantly reduced. A single 5e9 protons pilot bunch is at 7 TeV already close to the damage level, and losses of >3e-7 of the nominal beam current over a time period of 10 ms will cause a quench at this energy.

The BLMs have to cover a large, ~8 orders of magnitude dynamic range to detect small losses at the quench level, as well as scraping losses at the collimators. The LHC collimation system [6] consists out of 100 movable devices, arranged in a multi-stage layout with a cleaning efficiency of 99.98 %. The gap of the primary collimators is set to 2.2 mm.
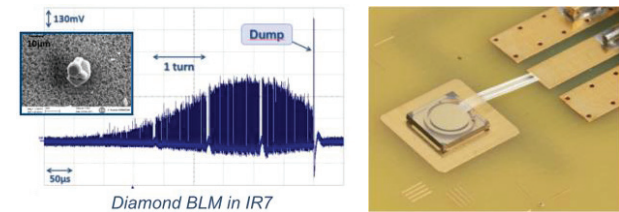

Figure 5: Beam loss induced dump due to UFOs (left), Diamond-BLM detector (right, courtesy E. Griesmayer).

During LHC Run I a series of beam aborts, e.g. 14 dumps at 4 GeV under stable luminosity run conditions have been triggered by the BLM system. Figure 5 shows in post-mortem the beam loss just before abort (last turn) of a prototype diamond-based BLM [7]. The fast response time of the BLM, typically ~1 ns, shows the loss pattern of the individual batches and bunches, the reason for the sudden beam loss is not yet fully understood [8]. The best explanation so far: "unknown flying objects" (UFO), i.e. small dust particles, perhaps from the injection elements. Even though only 21 events caused a BLM triggered beam abort, ~17000 below dump threshold UFO candidates have been found when analysing the BLM data for the same loss pattern. To increase the system

sensitivity (up to a factor 30) BLM detectors have been redistributed more uniformly, they are not anymore located only at high beta areas, i.e. quadrupole magnets.

Other efforts are made on BLM detector R&D, e.g. to locate the BLM inside the cryostat, keeping the distance to the beam pipe short. Diamond, silicon and liquid-He ionization chambers are candidates for cryogenic BLMs.

Beam Position Monitors (BPM)

The LHC BPM read-out electronics design goes back to the time of analog signal processing, and is based on the wideband amplitude-to-phase normalizer, capable to acquire the beam position of each passing bunch – at 25 ns bunch spacing – at each of the ~1000 BPM pickups [9]. The single bunch-processing schema minimizes the requirements for the dynamic range, and as of the fast, low latency electronics also allows BPMs at critical locations to be included into the MPS.
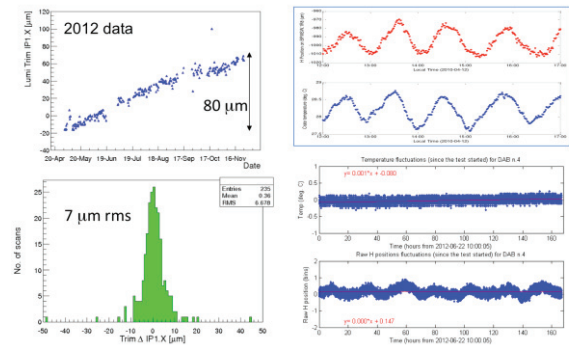

Figure 6: LHC orbit stability at the IP (left), correlation of BPM data and ambient temperature before and after BPM rack modifications (right).

While the LHC BPM system operates flawless and in general very reliable, the orbit stability was not completely satisfactory. Figure 6 (left) shows, the orbit at the IP varies over the course of year 2012 by ~80 μm, however stays within 7 μm from run to run, which is smaller than the beam size at the IP. The main reason is found to be the temperature dependence of the BPM analog electronics [3], which now is improved by the implementation of temperature controlled racks (<0.1 degree), see Figure 6 (right).
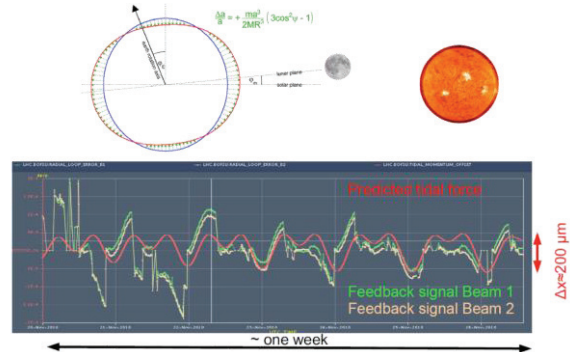

Figure 7: Correlation between tidal forces (red) and the orbit feedback signals (green – beam 1, yellow – beam 2).

The beam orbit of the LHC, as of any future large ring accelerator, relies heavily on a seamless operating orbit feedback system. Figure 7 illustrates the correlation between the tidal forces and the orbit feedback error signals, which accounts for ~200 μm orbit deviation.

To speed up the setting of ~100 collimators at the beginning of a physics run, button BPMs are now embedded in the 18 tertiary LHC collimators [10], see Figure 8. Instead of operating one-by-one on the rather slow BLM response, the local beam position is used for positioning of the collimator jaws, measured with a resolution of ~100 nm, based on the direct diode detection principle [11]. This system will speed up the setting procedure by two orders of magnitude, all collimator jaws can be aligned simultaneously within 20 s [12].
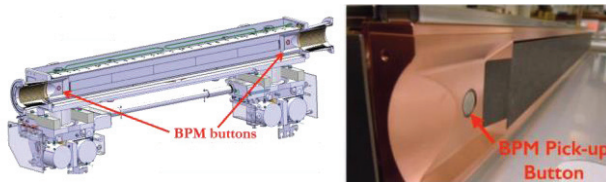

Figure 8: Button BPM electrodes embedded inside a collimator jaw.

Another upcoming BPM challenge is related to the position monitoring of both beams near the IP in the shared vacuum chamber, foreseen for the high luminosity upgrade HL-LHC. Stripline BPMs have directivity properties, but there is some remaining cross-coupling between upstream and downstream signals. A different arrival time of the bunches of each beam can be used in the signal processing to further entangle the individual position signals. For the BPM system of a future ring collider the decision one vs. two rings is of great relevance, as two beams in a single chamber with many bunches will give this additional challenge to the BPM system.
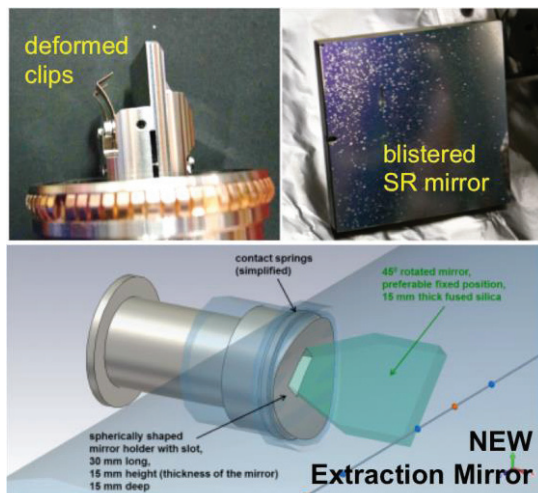
Wakepotential, HOM Effects and RF Heating

Figure 9: RF heating issues on the LHC BSRT synchrotron light extraction mirror.

A bad surprise during LHC run I was related to beam excited RF resonance effects of various components, including beam pickups [13]. Particular the light extraction mirror of the beam synchrotron radiation telescope (BSRT) suffered from RF heating [14], which damaged the mirror and its holder substantially, see Figure 9. Modifications and redesign, including extensive studies on wakepotential and RF impedances had to be undertaken, still the operation with 25 ns bunch spacing could give further surprises.

Early Detection of Beam Instabilities

A broadband stripline monitor connector to a wideband oscilloscope is currently used to detect transverse beam instabilities. These head-tail motions are also observed by the fast beam current monitor, as single bunch intensity modulation, and by the BSRT synchrotron light monitor, as emittance blow-up of individual bunches. The limited dynamic range of the oscilloscope however limits the resolution to ~100 μm. At those oscillation amplitudes the instability has already grown significantly, too late to generate an early trigger for other beam monitors.
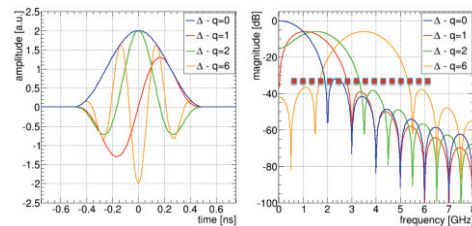

Figure 10: Transverse head-tail modes in time and frequency domain.

A new multiband instability monitor is under development [15], dividing the observed frequency range 0.4-6.4 GHz in 16 individually monitored bands, spaced by 400 MHz. Figure 10 illustrates how head-tail modes map in the frequency domain, indicating the foreseen observation bands. A measurement of magnitude and phase of each band may also allow reproducing the time domain signal. The present stripline pickup and Δ-hybrid installation could be replaced by an electro-optical front-end system, which could cover the entire frequency range.

The early detection of beam instabilities will receive more attention with the 25 ns bunch spacing in the upcoming run II, which has the potential to generate higher electron-cloud densities, and therefore will lower the head-tail instability threshold [16].
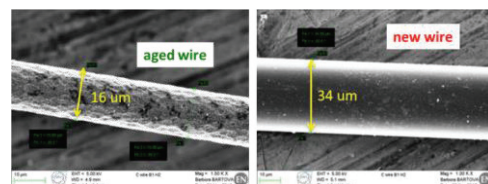
Non-invasive Beam Profile Monitors

Figure 11: Aging effect of the LHC carbon wire.

The monitoring of the beam profile of the LHC is one of the biggest challenges, as it is for any high intensity, high brightness accelerator. Physical wires producing secondary emission for monitoring the beam profile during the wire-scan have several drawbacks, e.g. wire heating and sublimation, residual losses, and at higher beam intensities, wire destruction. Figure 11 shows the aging effect of the LHC carbon wire [17]. This limits the use of the LHC wire-scanner to low beam intensities, a total of 2.7e13 protons at 450 GeV injection energy, and only 2.7e12 protons at 7 TeV (equivalent ~20 bunches). However, the wire scanner remains relevant for calibration and beam commissioning purposes.
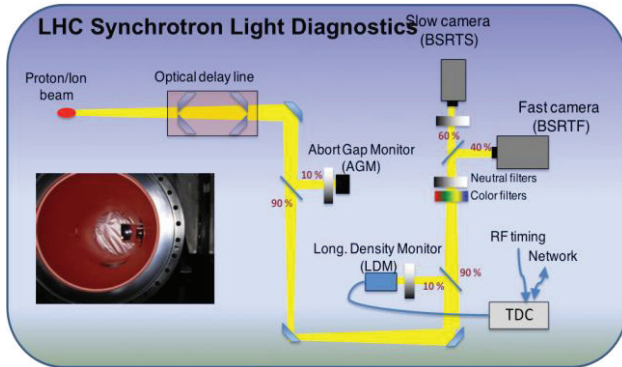

Figure 12: The LHC beam synchrotron radiation telescope (BSRT).

The BSRT synchrotron light monitor [18] is the primary non-invasive beam profile monitor (Figure 12). With its gated camera it allows to display the transverse beam profile at injection energy, utilizing the synchrotron light generated by a superconducting undulator, and at higher beam energies (>1 TeV) using the light from a SC dipole. Beside single bunch beam profile measurements, it also monitors the longitudinal beam profile and unwanted residual particles in the beam abort gap. However, at the nominal 7 TeV beam energy the system operates at the diffraction limit, therefore an interferometer setup is under investigation [19].
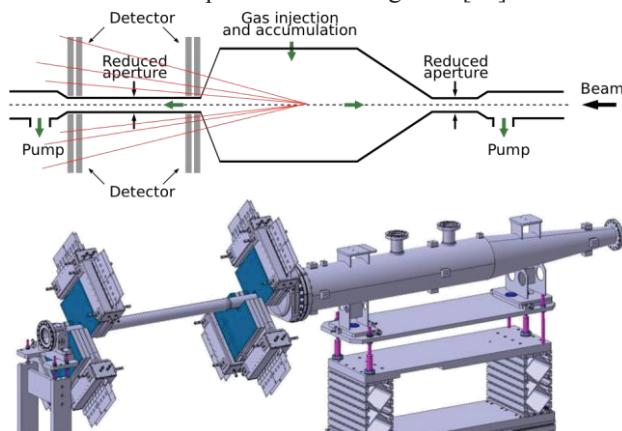

Figure 13: The LHC beam gas vertex detector (BGV).

A variety of other non-invasive beam profile monitors are studied, e.g. the ionization profile monitor (IPM) [20,21], and the beam gas vertex detector (BGV) [22]. The BGV system is based on the LHCb vertex detector principle [23,24], see Figure 13. It requires some statistics, i.e. integration time to reproduce the transverse beam profile from the particle tracks after their collision with residual gas molecules, detected by the two multichannel detector planes.
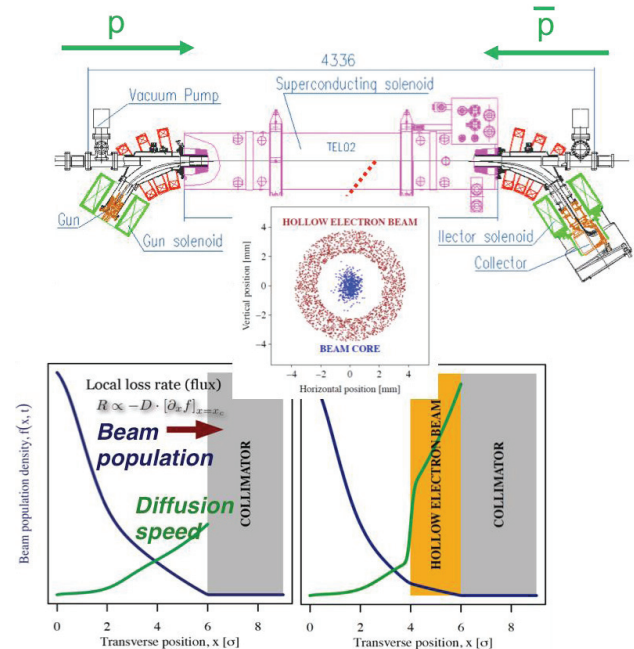
Beam Halo Mitigation

Figure 14: Hollow electron lens.

The unwanted transverse beam halo can be mitigated, e.g. by a hollow electron lens [25] (see Figure 14). Particles experience a non-linear field, which increase the diffusion speed towards the collimator jaws, and results in a clean up of the beam tails.

BEAM INSTRUMENTATION R&D

There is much more R&D on beam instrumentation, as well as trends in electronics, digital signal processing and electro-optical systems. Some of these developments are very valuable for future large ring accelerators, e.g.:

- R&D on radiation tolerant chips, including FPGAs
- Radiation tolerant optical fibers and related transceivers for the transmission of high volume digital data and broadband analog signals.
- Laser-based wire scanners and emittance monitors are further developed towards a turnkey operational system.
- In-depth studies, analyses and minimization of impedance effects of BPM button electrodes.
- Development of a high resolution gas-jet beam profile monitor.

- Non-invasive hadron beam profile monitor R&D based on coulomb interaction with a perpendicular electron beam (e-beam scanner).
- Schottky monitor R&D for bunched hadron and ion beams.
- R&D on beam halo detectors.
- Broadband, bunch-by-bunch and intra bunch feedback systems.

State-of-the art developments and technologies on beam instrumentation are presented at the yearly IBIC and IPAC conferences, past events of interest are also the BIW and DIPAC workshops.

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