

## SUMMARY FROM WORKING GROUP 9: INSTRUMENTATION AND CONTROL\*

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### Abstract

Since the discovery of the Higgs particle at the Large Hadron Collider at CERN in 2012, feasibility studies for a very large future circular collider are ongoing for two designs in particular: the FCC in Europe and the CEPC-SppC in China. Both designs aim for initial operation as a Higgs factory. This workshop on High Luminosity Circular e+e- Colliders (HF2014), held in Beijing, China and hosted by the Institute of High Energy Physics (IHEP) and the Chinese Academy of Sciences (CAS), included a Working Group on Instrumentation and Control to consider important issues associated with these systems. While instrumentation and control designs are just starting, HF2014 provided the opportunity to discuss these systems and their challenges.

Y. Funakoshi (KEK) presented “Lessons learned from the B-Factories and implications for a high-luminosity circular e+e- Higgs factory” [1]. M. Wendt (CERN) presented “Challenges in beam instrumentation and diagnostics for large ring colliders – based on the LHC experience” [2]. The B-Factories have in common with the accelerator designs under consideration similar particle species while the LHC shares similarities in the context of the overall scale (many 10’s of kilometre circumference). Concerning instrumentation and control (as well as many other aspects) both accelerators share certain similar challenges with technological developments of great importance for future large ring colliders ongoing.

### INTRODUCTION

Instrumentation and Control are vital subsystems for a future e+e- collider operating for high luminosity Higgs boson production and beyond. The applied technologies must guarantee the challenging design parameters and collider luminosity. As the accelerator parameters are stabilizing, the diagnostic designs have recently started. These developments are expected to direct control system design, the technology for which is rapidly evolving and expected to continue so.

As instrumentation designs were anticipated by the working group conveners (M. Minty and H. Schmickler), prior to the workshop, as being quite similar to those demonstrated at existing accelerators with new challenges pertaining to the large-scale aspects of a future Higgs factory, presentations were solicited with the aim of understanding essential features, challenges and solutions based on experiences at existing accelerators most similar to those of a future e+e- collider.

### PRESENTATIONS

The working group activities consisted of invited talks and a discussion session starting with an additional talk on instrumentation in the CEPC design (instrumentation design for the FCC project has yet to start).

M. Wendt’s presentation contained an overview of instrumentation design challenges common to all future large ring colliders including:

- (1) Large physical size of accelerator and correspondingly large number of instrumentation devices, impact on reliability and costs
- (2) Issues associated with low temperatures in superconducting environments
- (3) Higher-order modes and wakefields generated by the instrumentation
- (4) For high power beams, the need for non-invasive beam detection methods
- (5) Need for early observation and damping of beam instabilities
- (6) Large dynamic range of instrumentation and compatibility with different particle species, need to anticipate changes as learned from operational experiences
- (7) Damage potential from beams with high stored energy and impact on machine protection system (MPS) including all related components

Other challenges and motivations for requirements addressed by the presentations are given below.

Beam position monitors (BPMs) – The stringent tolerances on beam orbit stability, with rule-of-thumb scaling as  $\sim 1/10^{\text{th}}$  the beam size  $\sigma$ , imply the need for commensurately high accuracy beam position data. Real life experiences were presented showing susceptibility to ambient temperature variations which introduced significant systematic errors in the beam position

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measurements. Once identified these sensitivities were remedied.

- At KEKB, where BPM measurements are used for orbit feedback in the interactions regions (as well as for correction of the global orbit) up to 20% day-night variations in luminosity were essentially removed after application of thermal insulating sheets over the cables as diagnosed using an ingenious scheme involving signal processing using different combinations of signals from the BPM electrodes.
- At the LHC, the beam positions at an interaction point (IP) was reported to vary by up to 7  $\mu\text{m}$ , a fraction of the beam size at the IP. Prototype tests with temperature controlled racks housing the BPM electronics virtually eliminated such variations in the reported beam positions.

For very large colliders other practical considerations for the BPMs and BPM electronics include the cumulative impedance of the large number of pickup electrodes, proximity of electronics for minimum cost and highest reliability and signal transport over long cables for which optical fibers were suggested to preserve signal quality. Signal-to-noise and dynamic range considerations will require special attention particularly in the single-ring collider scheme.

Ground motion effects – Sensitivity to slow orbit deviations depends on many factors including accelerator layout (single or double-ring collider), circumference scale (CEPC:  $\sim 50$  km, FCC: 80-100 km, LHC: 27 km) and time scales of the variation. The effects of relatively slowly varying accelerator geometries were reported by both speakers.

- At KEKB slow vertical ground deformations of up to 25 mm were reported over the lifespan (construction to shutdown for SuperKEKB installations). Fortunately, almost no degradation of performance was observed provided the optics were corrected, which at KEKB were performed approximately every two weeks [1].
- At the LHC, orbit distortions due to gravitational forces (tidal forces) of  $\sim 200$   $\mu\text{m}$  peak-to-peak varying bi-diurnally were corrected by continuous operation of orbit feedback for which robust operation was of course essential.

Orbit stabilization in the presence of high power synchrotron radiation from high energy lepton beams – Orbit deviations caused by unexpected thermal heating (and cooling after a beam abort) of the vacuum chambers due to synchrotron radiation have been observed at KEKB (and PEP-II) despite elaborate vacuum chamber cooling designs. To address this, at KEKB, capacitive position sensors were installed to detect the relative position change between the BPMs and the adjacent sextupoles. The acquired data were then used to correct the BPM data. After implementation together with other cooling power reinforcements for the vacuum chambers

in the interaction region and introduction of enormously beneficial continuous beam injection, orbit corrections performed as expected without any degradation to collider luminosity. Displacement sensors are planned for installation in SuperKEKB [3].

Electron clouds – Photoemission and secondary electron emission (electron cloud) formation was a limiting factor at both KEKB and the LHC.

- At KEKB, emittance dilution and degradation of the specific luminosity were observed due to electron clouds (in the positron ring). Several diagnostic tools have been developed to aid in their study including a sideband measurement sensitive to head-tail motion within a bunch, retarding field analysers and bunch-by-bunch position measurements. Counter-measures included solenoid windings around the drift spaces and a portion of the quadrupole magnets.
- At the LHC, electron clouds have included other adverse consequences such as particle loss and increased heat loads in the cryogenic systems. Instrumentation developments at the LHC have included a fast beam current transformer for measurement of the relative bunch intensities and gated cameras to allow measurement of the relative bunch sizes. In development also are a head-tail monitor and a multiband instability monitor to enable intra-bunch measurements.

Beam instabilities – Evaluation of electron cloud, fast-ion as well as impedance driven instabilities will need careful evaluation to ensure sufficiently high beam intensity thresholds. If instability thresholds appear marginal, fast feedback systems, both intrabunch and bunch-by-bunch may be applied to damp such instabilities. Careful engineering designs coupled with beam physics simulations should be performed. At SuperKEKB, for example, remediation efforts are planned with simulation results [3] showing a threshold electron density approximately 4-6 times higher than required.

Collision feedback – Y. Funakoshi presented a detailed overview of three algorithms used for maintaining collisions of  $e^+e^-$  beams in a double-ring collider: the beam-beam deflection method (as applied at the SLC and, in the vertical plane, at KEKB and planned for use at SuperKEKB), the luminosity dithering method (from PEP-II and planned for use at SuperKEKB) and beam size feedback (as applied in the horizontal plane of KEKB). At KEKB, special BPMs (OctoPos BPMs) were included close to the IP each with 8 electrodes used to measure the orbits of the two beams simultaneously. For routine beam operations however the orbit feedback systems used the set of four regular BPMs (each traversed by a single particle species). The orbit feedback was vital for maintaining luminosity and operated at a 0.25 Hz rate with a  $\sim 2$   $\mu\text{m}$  resolution. For single-ring colliders or anywhere where beams share a common vacuum

chamber, care must be taken to minimize coupling of BPM signals from different beams.

Luminosity tuning – Table 1 (from Ref. [1]) shows, the many tuning variables (knobs) used at KEKB and the measurements used to optimize these variables (observables). The frequency of corrections is also given. In addition to measurements of the beam position, the tuning algorithms require also measurements of the beam sizes from the synchrotron radiation interferometer (SRM) and of the luminosity. In addition to these corrections, it was found that linear optics corrections, performed approximately every two weeks, were essential for suppressing beam-beam blowup effects.

Beam orbit fluctuations due to triplet magnet vibrations will challenge measurement and correction schemes for future colliders with extremely small beam sizes at the interaction points.

Other developments in beam instrumentation – M. Wendt's talk included examples of instrumentation challenges from the LHC based on operating experiences. These include

- Beam loss monitoring (BLM) for the Machine Protection System (MPS) including high dynamic range, interplay with collimation system and measurements to detect unidentified falling objects (UFO)
- BLM R&D for close proximity of detector to beam including detectors (diamond, silicon, liquid-He ionization chambers) located within the cold cryostats
- Collimators with embedded BPMs to enable significantly faster collimator positioning
- High brightness, small beam size measurements including difficulties encountered using synchrotron light monitors (rf heating of mirror), possible use of interferometric methods and a new beam gas vertex detector (BGV) design
- R&D for mitigation of beam halo using a hollow electron lens
- More R&D on radiation tolerant chips and FPGAs

Several other instrumentation-related R&D efforts under consideration at the LHC were also presented including developments in non-invasive beam profile measurements such as gas jets, electron beam scanners and Schottky-based emittance measurements.

## DISCUSSION SESSION

J. Yue (IHEP) presented on “Beam instrumentation of CEPC” which included an overview of design principles and details on the types of diagnostics envisioned for the CEPC. The subsystems described largely followed conventional methods. In the short time remaining, an “Instrumentation Checklist” by H. Schmickler highlighting essential instrumentation subsystems and desirable features was presented and

discussed. Flexibility in instrumentation design was considered absolutely necessary (design for all machine phases including commissioning, experiments and stable operation) with consensus that early written functional specifications should be made.

Questions were addressed on the effect of synchrotron radiation with high critical energy on the instrumentation and electronics. In addition, based on presentations during the plenary session and other working group sessions, it became clear that the physics programs for a future Higgs factory require precision measurements of the beam energy as needed also for determination of the beam's spin polarization and, to allow quantifying of various measurement errors, the beam energy spectrum. Such measurements are not only challenging but may even be needed on a single-bunch basis to determine differences in these properties between colliding and non-colliding bunches.

## SUMMARY

The accelerator designs for a future very large circular collider, with initial goal of operation as a Higgs factory, are now sufficiently advanced to allow development of the supporting instrumentation and control systems. At this conference, technological developments from accelerators sharing common features such as the high luminosity B-factories and the Large Hadron Collider were presented as relevant for the CEPC and FCC design. The instrumentation checklist presented during the discussion session could be extended and used as a basis for further definition of the specifications for instrumentation and control.

## REFERENCES

- [1] Y. Funakoshi, “Lessons learned from the B-Factories and implications for a high-luminosity circular e+e-Higgs factory,” these proceedings SUT1B1, HF2014, Beijing, China (2014).
- [2] M. Wendt, R. Jones and J. Wenninger, “Challenges in beam instrumentation and diagnostics for large ring colliders – based on the LHC experience”, these proceedings SUT1B2, HF2014, Beijing, China (2014).
- [3] K. Ohmi and D. Zhou, “Study of Electron Cloud Effects in SuperKEKB,” TUPRI020, IPAC2014, Dresden, Germany (2014).

Table 1: Tuning variables (knobs), input measurements (observables) and optimization frequency for luminosity optimization at KEKB.

Knob	Observable	frequency: every
Relative beam offset IP	Beam-beam kick measured by BPMs around the IP	1 sec
Relative beam angle IP	BPMs around the IP	1 sec
Global closed orbit	All $\sim 450$ BPMs	15 sec
Beam offset at crab cavities[11]	BPMs around the crab cavity	1 sec
Betatron tunes	tunes of non-colliding pilot bunches	$\sim 20$ sec
Relative rf phase	center of gravity of the vertex	10 min.
Global couplig, dispersion, beta-beat	orbit response to kicks & rf frequency	$\sim 14$ days
LER to HER crab voltage ratio	response in the hor. beam-beam kick. vs. crab rf phase	$\sim 7$ days
Rf phase of crab cavity	hor. kick vs. crab voltage response	$\sim 7$ days
Vertical waist position	$\mathcal{L}$ and $\sigma_y$ at the SRM	$\sim 1$ day
Local x-y couplings and dispersions at IP	$\mathcal{L}$ and $\sigma_y$ at the SRM	$\sim 1$ day each
Sextupole settings	$\mathcal{L}$ and lifetime	$\sim 3$ days
X-y coupling parameter at the crab cavities	$\mathcal{L}$ and $\sigma_y$ at the SRM	$\sim 3$ days
Crab kick voltage	$\mathcal{L}$ and $\sigma_y$ at the SRM	$\sim 7$ days