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12 Diagnostic system

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12.1 Introduction

The diagnostic system will monitor the accelerator performance and beam conditions in different scenarios:

– the initial commissioning;

– periodic start-ups; and

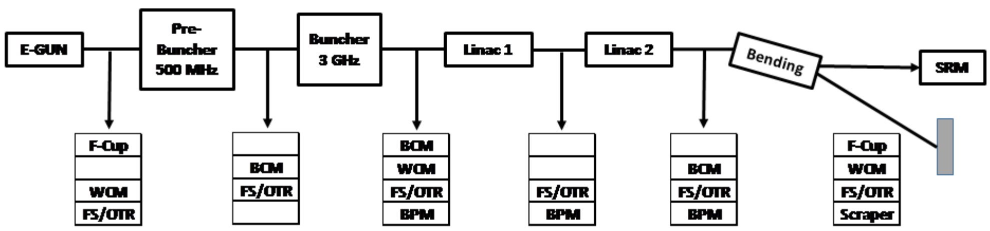
– normal operations for the scientific programme.

For this reason, the diagnostic system [12.1, 12.2] has to be complete and flexible enough to cope with the different situations. In addition, due to the foreseen top-up operation, particular attention should be given to systems that monitor component stability and beam quality in the injector. The goal is to guarantee a steady beam within the nominal specifications. In the main ring, constant beam current and beam stability at the sub-micron level are essential. To this end, a series of electron and photon beam position monitors (BPMs) are distributed around the storage ring.

In summary, the diagnostic system will monitor beam production in the pre-injector (linac), transmission through the beam transport lines, injection efficiency into the booster, injection into the main ring, and, in particular, stored beam quality. This chapter outlines the proposed diagnostic systems for each portion of the accelerator complex.

12.2 Pre-injector diagnostics

In this section diagnostics are specified for a standard linac-based pre-injector system. There will be two main modes of beam production: single- and multi-bunch pulse trains. Also, for top-up, a low-current mode is necessary. In order to maintain high beam quality during extended top-up periods, it is important that the beam energy, bunch charge, and bunch timing remain stable for up to several weeks at a time.



F-CUP: Faraday Cup	Destructive	Charge; Time
BCM: Beam Charge Monitor	Non-Destructive	Charge
WCM: Wall Current Monitor	Non-Destructive	Charge; Time
FS: Fluorescent Screen	Destructive	Position; Size
OTR: Optical Transition Radiation	Semi-Destructive	Position; Size
BPM: Stripline Beam Position Monitor	Non-Destructive	Position
SRM: Synchrotron Radiation Monitor	Non-Destructive	Position; Size; Time

Fig. 12.1: Schematic diagram of pre-injector diagnostic systems (linac)

A schematic diagram indicating the location of the linac diagnostics is shown in Fig. 12.1. Specifically, Faraday cups and wall current monitors measure charge before and after the linac, integrating current transformers (ICTs) measure beam transmission efficiency, and BPMs measure beam position. Fluorescent screens and optical transition radiation monitors (OTRs) are used for beam steering, qualitative beam size measurements, and lattice diagnostics. A synchrotron light monitor viewing radiation from the first LTB dipole magnet measures beam size and time structure of the 100 MeV beam [12.3]. A diagnostic beam line at the end of the pre-injector contains a fluorescent screen, scraper, and Faraday cup to monitor 100 MeV beam properties, including energy spread.

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12.2.1 Faraday cup (F-cup)

A retractable Faraday cup is located at the exit of the e-gun to measure macropulse length and total charge prior to entering the linac. The data are used to optimize the single- and multi-bunch pulse modes from the gun. The measurement bandwidth is suitable for transient measurements (total number of S-band buckets). A second Faraday cup is located in the diagnostic beam line following the linac as part of the energy spread measurement.

12.2.2 Beam charge monitor (BCM)

BCMs are located after the pre-buncher, 3 GHz buncher, and linac. The charge monitors provide non-destructive measurement of transport efficiency and are used to optimize linac operation. A likely candidate is the Bergoz BCM with the integrated hold–reset option.

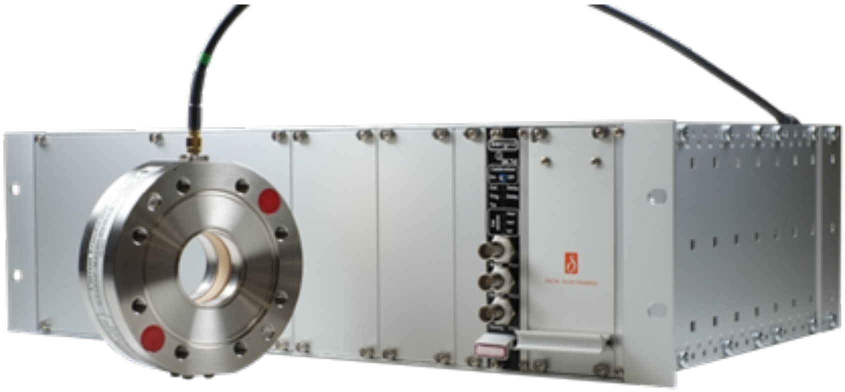

Fig. 12.2: Beam charge monitor from Bergoz [12.16]

12.2.3 Beam position monitor (BPM)

Stripline BPMs measure beam position after the 3 GHz buncher and after each accelerating section. BPMs provide non-destructive measurements for manual beam steering and automatic steering feedback. Where possible, stripline BPM receivers will utilize the same technology as the main ring [12.4].

12.2.4 Fluorescent screen (FS)

Fluorescent screens are relatively simple to construct and provide beam position information at low current. Referring to Fig. 12.1, six such screens are installed in the pre-injector for beam alignment. The YaG:Ce crystals are remotely inserted into the beam path on command, and charge-coupled device (CCD) cameras broadcast the signal back to the control room for visual inspection and digital analysis [12.12].

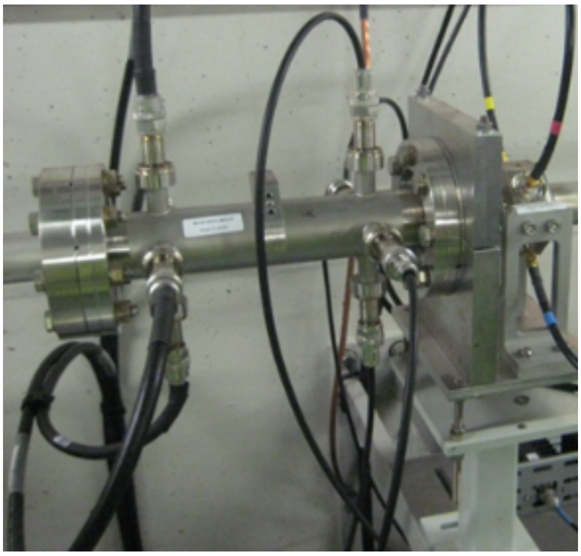

Fig. 12.3: Stripline monitor installed at ALBA [12.5]

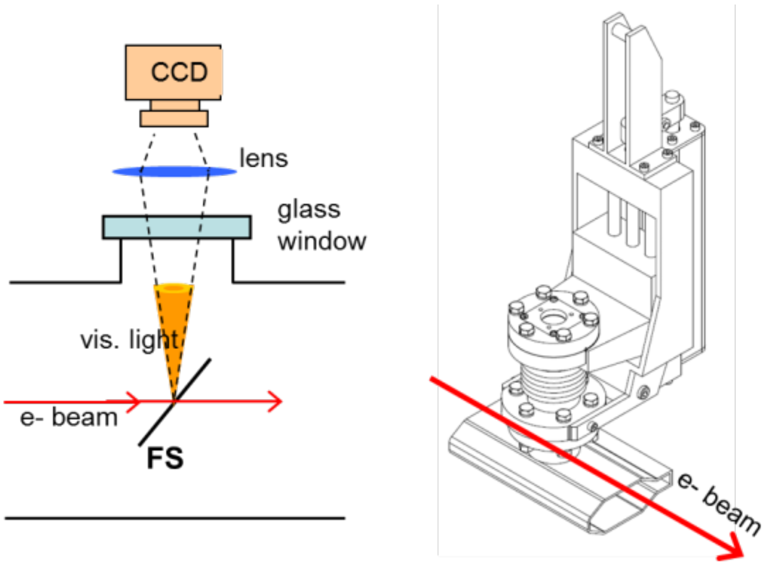

Fig. 12.4: Schematics and drawing of the ALBA fluorescent screen [12.5]

12.2.5 Scraper

The LTB diagnostic beam line contains a horizontal scraper to measure energy spread (the first LTB dipole acts as a spectrometer). The resulting variation in intensity with scraper position is monitored at the second Faraday cup. Since the electron beam must be diverted into the diagnostic beam line, the scraper/Faraday cup system is used only during commissioning, in machine development periods, or as a diagnostic in the event of pre-injector mis-tuning.

12.2.6 RF signal distribution system

Although not a direct beam measurement, RF signal diagnostics are essential to the tuning of the electron gun, bunching systems, and linac. The RF signal distribution system will monitor, among other signals, forward and reflected power waveforms at the gun and each linac section.

12.3 Transfer line diagnostics

Transfer lines direct the electron beam from the linac to the booster (LTB) and from the booster to the storage ring (BTS). The LTB steers the beam at 100 MeV while the BTS steers the beam at full energy (2.5 GeV). For both transfer lines, it is important that beam quality and transport efficiency are maintained for long periods of time, particularly in the top-up mode. Transfer line diagnostic systems will be similar to those of the linac systems where possible.

12.3.1 Fast current transformer (FCT)

Each transfer line will be equipped with two fast current transformers (one at the beginning and one at the end) to measure charge transfer efficiency. By normalizing capture rates in the booster and the main ring to current in the respective upstream transfer lines, injection efficiency can be monitored. Fast current transformers can be used to monitor single-pulse injection efficiency into the main ring.

Fig. 12.5: Fast current transformers (Bergoz) [12.16]

12.3.2 Fluorescent screen (FS)

The LTB and BTS will be equipped with YaG:Ce fluorescent screens at the beginning, middle, and end of the transfer lines, depending on the length of the line. In each case, the third (downstream) screen will be located after the injection septum. CCD cameras will monitor the beam image, with display in the control room and analysis carried out on the digital image [12.14].

12.3.3 Beam position monitor (BPM)

Single-pass BPMs will be installed along the transfer lines to monitor electron beam position. The BPM receivers will be purchased from a commercial vendor or through collaboration. Where possible, the BPM receivers should be the same as the booster/storage ring units to unify systems within the accelerator complex. Readouts will be viewed on the GUI by the operators and stored in the database for diagnostic and analysis purposes.

12.4 Booster diagnostics

The main parameters of the booster synchrotron are not yet fixed, but its function will be to increase the energy of the beam from the 100 MeV of the linac to the 2.5 GeV of the storage ring. The diagnostics listed here are essentially the same for any kind of booster, with the exception of the number of BPMs, which will depend on the circumference, number of cells, and tune of the booster.

12.4.1 Fast current transformer (FCT)

A fast current transformer measures beam current in the booster under a variety of operating conditions. It is important to know the total current and bucket distribution prior to injection into the main storage ring. For top-up mode, total bunch charge and single-bunch purity must be carefully monitored and controlled.

12.4.2 DC current monitor (DCCT)

The DCCT provides an absolute measure of the average beam current and is used to determine injection rates, loss rates, and beam lifetime. DCCTs are commercially available both as 'off-the-shelf' models and as units custom-designed to meet special requirements (www.bergoz.com).

Typical performance features include: 1) DC-to-100 kHz bandwidth, 2) dynamic range of up to 10^7, and 3) absolute error less than 5×10^{-4}. High-quality, shielded cables will connect the sensor to the front-end electronics and link the front-end electronics to the output chassis.

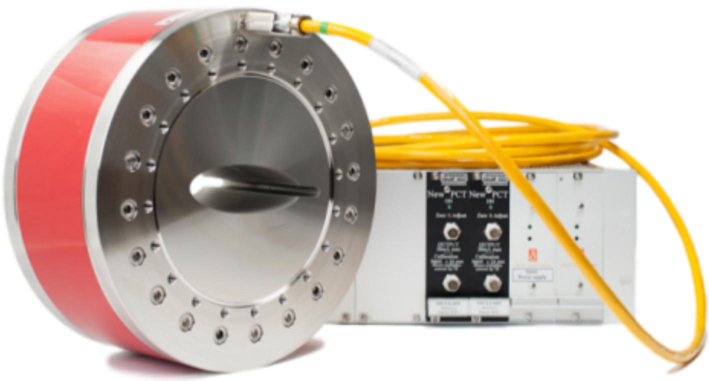

Fig. 12.6: DC current transformers (Bergoz) [12.16]

12.4.3 Fluorescent screen (FS)

A retractable fluorescent screen is located just after the injection septum to monitor location and intensity of the incoming 100 MeV beam. A second screen at the downstream end of the extraction septum serves two functions: 1) half insertion mode—view extracted full-energy beam; and 2) full insertion mode—view first half-turn of the 100 MeV beam. In addition, fluorescent screens can be distributed along the booster, each quarter or half of the ring, in order to check injection parameters, mainly during commissioning and start-ups.

12.4.4 Beam position monitor (BPM)

A certain number of BPMs with single-turn measurement capability will measure beam position in the booster. The exact number will depend on the number of cells and the tune of the machine. It is recommended to have a minimum of four BPMs for each betatron oscillation.

The booster BPM receivers can be interchangeable with the main ring so that after booster commissioning is complete, some receivers can be moved to the main storage ring or used as spares. The BPM receivers will be purchased from a commercial vendor or through some kind of collaboration.

12.4.5 Synchrotron radiation monitor (SRM)

Synchrotron radiation from the booster can be transferred inside the tunnel by simply opening a port in one or two of the bending magnets and installing an optical system to send the beam image to a camera located in a vertical position, outside the plane of radiation [12.6]. Since the emittance of the booster beam is non-critical to within 10% approximately, the transverse beam profile only requires qualitative inspection.

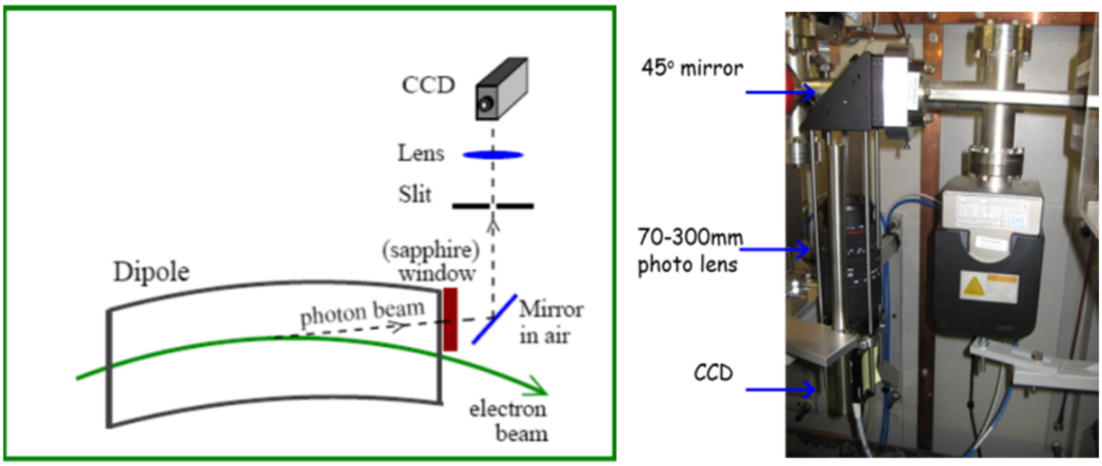

Fig. 12.7: Synchrotron radiation monitor for the booster of ALBA: schematic drawing (left) and photo of the ALBA installation (right) [12.6].

12.4.6 Striplines

One stripline will excite the betatron frequency and a second will serve as a receiver of the excitation, allowing the determination of the horizontal and vertical tunes. A signal generator (either a tracking generator, a swept-frequency generator, or a pink-noise source) will drive the orthogonal striplines in parallel, and a real-time spectrum analyser capable of processing the input through a bank of parallel digital filters creates a histogram of the response.

12.5 Storage ring diagnostics

The primary function of the beam diagnostics is to monitor the electron beam current, orbit position, orbit stability at the source points, and beam cross-section (emittance). Measurement of the betatron tunes is also required in order to maintain proper operation of the storage ring. More sophisticated measurements—such as beam-based alignment, response-matrix analysis to control beta functions and coupling, turn-by-turn pinger experiments, and measurement of the electron beam energy—are performed periodically.

This section describes the electron beam diagnostics and a system of diagnostic synchrotron light monitors. Although important for operation of the storage ring, measurements of the photon beam properties (beam position, beam stability, flux, etc.) are not covered. Also, beam loss monitors will be left as a possible upgrade [12.9].

12.5.1 Fluorescent screen (FS)

One fluorescent screen is located just after the injection septum to check the presence and position of the injected beam. The construction, operation, and display system are similar to those of the FS systems in the booster and transport lines. In addition, screens can be distributed along the ring, each quarter or half of the ring, to check injection parameters, mainly during commissioning and start-ups.

12.5.2 Fast current transformer (FCT)

The FCT measures the injected beam current on a pulse-to-pulse basis. Comparison with a similar monitor at the end of the transfer line allows direct determination of the injection efficiency. The FCTs and signal processing electronics will have the same design as in the booster synchrotron.

12.5.3 DC current monitor (DCCT)

The DCCT provides an absolute measure of the average beam current and is used to determine injection rates, loss rates, and beam lifetime. DCCTs are commercially available both as 'off-the-shelf' models and as units custom-designed to meet special requirements (www.bergoz.com). Typical performance features include: 1) DC-to-100 kHz bandwidth, 2) dynamic range of up to 10^7, and 3) absolute error less than 5×10^{-4}. High-quality shielded cables will connect the sensor to the front-end electronics and link the front-end electronics to the output chassis.

12.5.4 Beam position monitor (BPM)

A certain number of BPMs with high-precision measurement capability will measure the beam position in the storage ring [12.10]. The exact number will depend on the number of cells and the tune of the machine. It is recommended to have a minimum of four BPMs for each betatron oscillation. They will be of the button style and be installed in the main vacuum chambers. Extra BPMs will be installed in the diagnostic straight sections for tune measurement, turn-by-turn diagnostics, and potentially fast-feedback pick-ups. Insertion devices may include additional BPMs integrated into the ID vacuum chambers.

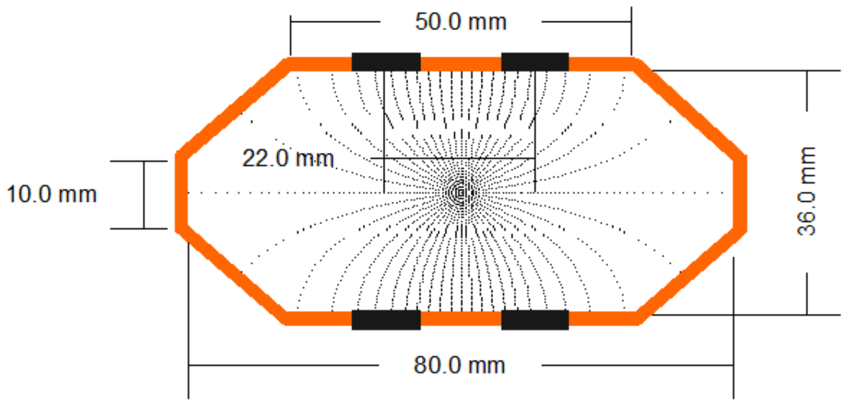

Fig. 12.8: Typical BPM geometry [12.10]

Leading candidates for the BPM receiver systems include ITech [12.17] and the newly developed system of NSLS-II. It is worth noting that when BPMs are used in the fast-orbit feedback system, both the corrector magnet currents and the BPM signals become important diagnostics for monitoring electron beam and power supply stability [12.11].

12.5.5 Beam-based alignment

The purpose of beam-based alignment is to calibrate the centre of each BPM to the magnetic centre of adjacent quadrupoles [12.13]. Individual quadrupole supplies are modulated by ±1–2% as the electron beam orbit is swept through the centre of the magnet. The BPM offset is determined by plotting the induced orbit shift as a function of beam position.

12.5.6 Scrapers

A horizontal and a vertical scraper will be installed to measure the dynamic acceptance and to function as a limiting aperture to protect the low-gap insertion devices.

With finite dispersion throughout the accelerator, the horizontal scraper can be used as an aperture-defining instrument for energy-acceptance measurements. The vertical scraper has the important function of measuring electron beam lifetime as a function of vertical chamber acceptance. The acceptance data is used in planning for future small-gap devices.

It is advisable to implement extra radiation protection around the scrapers, since they are the source of high radiation losses.

12.5.7 *Synchrotron radiation monitor (SRM)*

SRMs make a versatile diagnostic tool for longitudinal and transverse bunch measurements [12.8]. The system ideally consists of two beam lines with viewports accepting light from low-dispersion and high-dispersion emission points on a dipole magnet. For the diagnostics of the electron beam at the storage ring, we expect to use a minimum of two synchrotron light beam lines: 1) an X-ray pinhole beam line and 2) a visible light beam line.

12.5.7.1 X-ray pinhole front end

The X-ray pinhole beam line is intended for measuring the beam size and emittance of the electron beam. Due to the small vertical dimension of the electron beam, the use of X-rays is necessary in order to have a diffraction limit below the beam size.

The use of X-rays outside the shielding wall requires a shielded hutch, which will make the implementation of this beam line quite expensive, though it will of course provide greater flexibility.

Without completely relinquishing the flexibility and relying on motor-controlled positioning, one can foresee a beam line that is completely inside the shielding wall, so we can call it the X-ray pinhole front end. For it to be effective a long front end is needed (longer than 15 m).

12.5.7.2 Visible light beam line

The visible light beam line is intended for several types of measurements—bunch length, bunch purity, and instabilities—and for providing visually straightforward information about the beam spot (TV camera in the control room). To accommodate the kind of instrumentation to be placed in this beam line, the optical hutch has to be installed outside the shielding wall. No shielded hutch is required [12.7]. To have a large amplification factor, a short front end is desirable for this beam line.

To extract the visible light, two approaches can be taken: at 90° or at 0.5 m below the electron path. In both cases no beam shutter is required since no X-ray has to be stopped. A good candidate front end would be one that is short, not used by the experiments, and placed after the wall to locate the optical hutch.

A proposal is to use the first bending after the injection point in order to meet the above conditions, so that:

- at front end no. 1, coming from the first bending after the injection point, the visible light beam line can be placed;
- the light is extracted at 90° and at 0.5 m below the electron orbit, in order for the hutch to be placed in the area of the experimental hall that will not be used by the experiments (because it corresponds to the front end no. 33, occupied by the X-ray pinhole front end);
- the X-ray is not stopped, so an X-ray beam line can still be located in port 1.

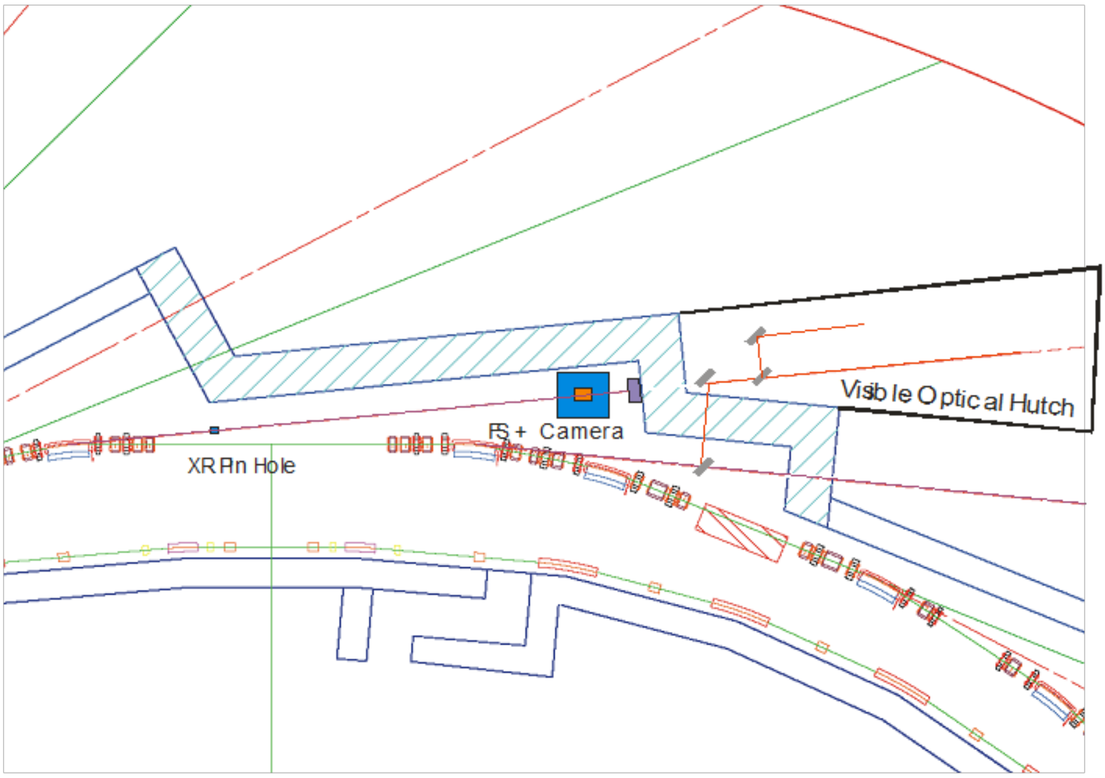

Fig. 12.9: Sketch of proposed combination of X-ray pinhole and visible light synchrotron radiation monitors

12.5.8 Stripline kicker and tune measurement

For the tune measurement, a four-electrode stripline can be used to excite the beam in the horizontal and vertical planes. Alternatively, transverse fast-feedback kickers can be used, but tune excitation increases the overall complexity of the feedback architecture and requires the system to be operational on day one of the machine commissioning phase.

The tune measurement can be processed on the signal generated at a single BPM button, thereby reducing the vacuum chamber complexity and impedance introduced by multiple striplines. Additional striplines may be required 90° from the fast-feedback kickers if the signal from individual BPM buttons is not sufficient for feedback applications.

12.5.9 Fast-feedback kickers

Two transverse feedback kickers, one horizontal and one vertical, will be installed for bunch-by-bunch feedback. As small-gap insertion devices are introduced into the vacuum chamber and the current is increased, resistive wall instabilities will manifest. Ideally, the kicker magnets will be approximately 90° from the pick-up electrodes (BPM or stripline). Examples of both transverse and longitudinal feedback systems are abundant, often developed by the high-energy physics community; see, for example, the transverse feedback systems installed at PEP-II, ALS, Daphne, etc. (reported in PAC and EPAC proceedings).

12.5.10 Pinger magnets for turn-by-turn beam dynamics

Turn-by-turn diagnostics for beam dynamics have become a popular means of analysing single-particle behaviour in simulations and measurements [12.15]. The single-turn pinger magnets kick charge that is stored in a single bunch in either the horizontal or the vertical direction. Turn-by-turn BPM measurements sample the ensuing bunch motion, and sophisticated analysis programs (NAFF, frequency-map analysis) decipher tune shift with amplitude. Based on the insight into beam dynamics, pinger magnets should be included to complement the storage ring diagnostic systems.

12.6 Summary of diagnostic system

The number of diagnostic elements used for the different parts of the accelerator complex are summarized in Table 12.1; $Q_{x,y}$ denotes the working point or tune in the horizontal and vertical directions.

Table 12.1: Diagnostic components used in the different parts of the accelerator

Component	Linac	LTB	Booster	BTS	SR	Total
Faraday cup	2					2
BCM	3					3
FCT		2	1	2	1	6
DCCT			1		1	2
Fluorescent screen	6	2	2	2	4	16
SRM	1		1		1	3
Pinhole X-ray					1	1
Stripline			2		1	3
Scraper		1		1	1+1	4
BPM	3	2	$4 \times Q_{x,y}$	4	$4 \times Q_{x,y}$	N
Exciter/kicker					2	2

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