6. Diagnostic and Control Systems

The basic requirements to the beam diagnostic and control systems in synchrotron light sources are given by the photon beam stability criteria that are expressed in

- Photon beam position jitter due to electron beam orbit distortion;
- Photon beam size change due to electron beam instabilities;
- Photon energy change due to variation of electron energy or orbit;
- Photon intensity variation due to electron beam or bunch current change;
- Time resolved experiments that imply a fine time structure of electron beam.

Summary of the typical electron stability requirements for moderately demanding light source experiments are given in Table 6.1 [1].

Table 6.1 Summary for the typical electron stability goals.

Photon energy requirements	**Intensity <0.1%. Steering to small sample**	**Photon energy resolution <10^{-4}**	**Timing** $\Delta t < 0.1\sigma_t$
Orbit of electron beam	$\Delta x < 5\%\sigma_x$ $\Delta y < 5\%\sigma_y$ $\Delta x' < 5\%\sigma_{x'}$ $\Delta y' < 5\%\sigma_{y'}$	$\Delta x' <\sim 5\mu rad$ $\Delta y' <\sim 1\mu rad$ (in undulator)	-------------------
Electron beam size	$\Delta\sigma_{x,y} < 0.1\%\sigma_{x,y}$ $\Delta\sigma_{x',y'} < 0.1\%\sigma_{x',y'}$	-------------	$\Delta\sigma_t < 10\%\sigma_t = 2p\sec$
Energy/energy spread of electron beam	$\Delta E/E(coher) < 10^{-4}$ $\Delta E/E(rms) < 10^{-4}$	$\Delta E/E(coher) < 5\cdot 10^{-5}$ $\Delta E/E(rms) < 10^{-4}$ (in undulator)	$\Delta E/E(coher) <\sim 10^{-4}$
Electron beam parameters	Energy – 3 GeV, Emittance $\varepsilon_x = 8nm\cdot rad$, Coupling – 1%.		

The corresponding requirements for the CANDLE beam orbit and beam size stability are given in Table 6.2.

Table 6.2 Orbit and beam size stability requirements for CANDLE.

Dipole			**Insertion**			**Unit**
Source size	**e-orbit stability**	**e-size accuracy**	**Source size**	**e-orbit stability**	**e-size accuracy**	
σ_x=128	Δx<6	$\Delta\sigma_x$<0.1	σ_x=314	Δx<15	$\Delta\sigma_x$<0.1	μm
$\sigma_{x'}$=92	$\Delta x'$<5	$\Delta\sigma_{x'}$<0.1	$\sigma_{x'}$=32.6	$\Delta x'$<1.5	$\Delta\sigma_{x'}$<0.1	μrad
σ_y=41	Δy<2	$\Delta\sigma_y$<0.04	σ_y=20	Δy<1	$\Delta\sigma_y$<0.04	μm
$\sigma_{y'}$=2.1	$\Delta y'$<0.1	$\Delta\sigma_{y'}$<0.002	$\sigma_{y'}$=4.2	$\Delta y'$<0.2	$\Delta\sigma_{y'}$<0.002	μrad

Machine performance, diagnostic tools, feedback and control systems have an adequate importance for satisfaction of these requirements. The beam parameters – orbit, size, intensity and time structure – will be controlled over the entire trajectory of the beam starting from the gun. Intensive study of the beam characteristics during the machine commissioning, that will include the acceleration performance, beam transport, injection extraction and finally the storage of the beam, will be an important stage for the designed goals achievement.

6.1 Diagnostic System

The basic approach to the diagnostic system for the CANDLE light source is based on the well-proven techniques adopted for many modern synchrotron radiation facilities. The system will be upgraded with the progress made in this field. The main function of the Storage Ring's Diagnostic System is to measure the main parameters of the beam in time and space domain, providing the necessary data for the feedback system and machine control. The diagnostic tools of the facility will provide:

- Measurements of the injected and stored beam currents;
- Beam lifetime control;
- Beam position measurement;
- Beam's transverse and longitudinal profiles measurement;
- Aperture and halo measurements;
- Beam loss measurement;
- Longitudinal and transverse instabilities measurements;
- Energy and energy spread measurements;
- Tune monitoring.

6.1.1 Beam Current Monitors.

To measure the injected and stored beam currents, the commercially available Parametric Current Transformers (PCT) produced by *Bergoz Precision Beam Instruments (France)* will be used. They will provide the non-destructive measurement of particle beam currents. The typical scheme of the PCT is shown in Fig. 6.1.1. In PCT, a high permeability torroidal magnetic core surrounds the beam, coupling to its magnetic field. In the absence of a beam, a magnetic modulator periodically drives the core into positive and negative saturation, and the sense winding produces a perfectly symmetrical positive and negative output voltage without even harmonics. Magnetic field from the beam causes the B-H loop to become slightly offset, resulting in generation of a 2^{nd} harmonic in the sense winding. This signal is filtered, rectified, amplified and fed back to the third winding, which just cancels the disturbing flux from the beam. A precision resistor, in series with this bucking winding, then produces a voltage proportional to beam current. Being a null measurement, the linearity and accuracy of the method are high. Typical performance parameters are:

- Dynamic range up to 10^7;
- Absolute accuracy < $5\cdot10^{-4}$, linearity error < $1\cdot10^{-4}$;
- Resolution down to 0.5 μA (1 sec integration);
- Full scale ranges from $\pm$1 mA to $\pm$10 A, true bipolar;
- DC - up to100 kHz bandwidth.

Since PCT has a large dynamic range, relatively high bandwidth and high resolution it will be handy as an instrument to measure:

- Injection efficiency into the storage ring;
- Beam lifetime;
- Top-up injection dynamics.

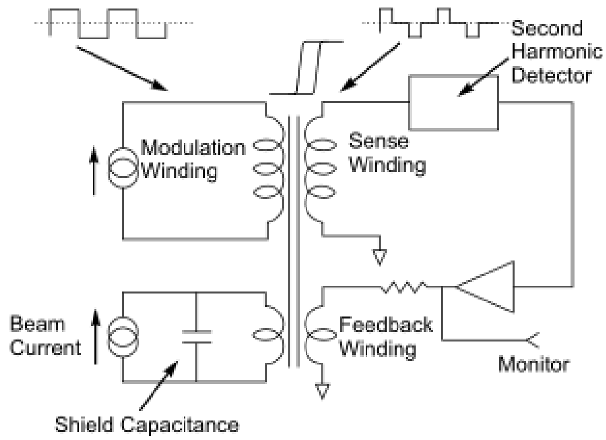

Fig. 6.1.1.Typical Scheme of Parametric Current Transformer.

The PCT consists of 3 units: a sensor head, a front-end electronics box and an output chassis. The cables between the sensor and the front-end box can be up to 75 meters. The cable between the front-end and the output chassis can be up to 300 meters.

6.1.2. Beam Position Monitors.

Electron beam position in the Storage Ring will be measured by 80 of 4-buttons Beam Position Monitors (BPM) located in the CANDLE storage ring. The following operation modes will be available for the CANDLE beam position measurement:

- First Turn Mode;
- Turn-by-Turn Mode;
- Averaged Orbit Mode;
- Feedback Mode;
- Tune Mode.

Each BPM includes four button electrodes, which will be mounted on the diagonals of the vacuum chamber – two mounted on top and two mounted on the bottom of the chamber (Fig. 6.1.2).

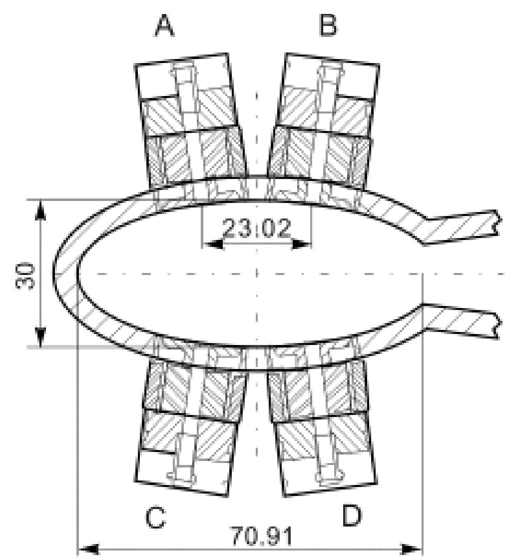

Fig. 6.1.2 Beam Position Monitors for the CANDLE Storage Ring.

Buttons are mounted fast with the stainless steel vacuum chamber. The button diameters of 1.5 cm provide an efficient coupling with the 999.308 MHz processing frequency. Center-to-center button spacing (23 mm in horizontal and 30 mm in vertical) equalizes the horizontal and vertical beam position sensitivities.

Beam position is determined by the “difference over sum” method. The signals from the button array are processed as

$$X = \frac{(A+D)-(B+C)}{A+B+C+D} S_x, \tag{6.1.1}$$

$$Y = \frac{(A+B)-(C+D)}{A+B+C+D} S_y, \tag{6.1.2}$$

where A, B, C, D are the button signal amplitudes, that have been compensated for BPM electrical offset and differential channel gain information, $S_{x,y}$ are the scaling factors, determined by the BPM geometry. The resolution and accuracy of the BPM measurements are dominated by the mechanical and electrical offsets of each BPM assembling. In addition, the BPM misalignment with respect to nearby quadrupole center is a drift due to temperature variations and girder motion. The quadrupole modulation system will be used to stabilize the relative BPM offset at the level of the 100 μm. Driving a particular quadrupole trim winding by a bipolar power supply, a low frequency (~10Hz) modulation of the magnetic field is excited, that causes beam orbit change. The beam is then steered by magnet until the BPM registers the minimum motion, thus locating the quadrupole’s magnetic center.

The CANDLE BPM processing system is composed of a network of 4:1 switched-button RF-IF Converter modules and 80-channels digital intermediate frequency (IF) processing system. To reduce the differential processing offsets, a common RF-IF converter processes the 4 buttons of each BPM sequentially (Fig. 6.1.3).

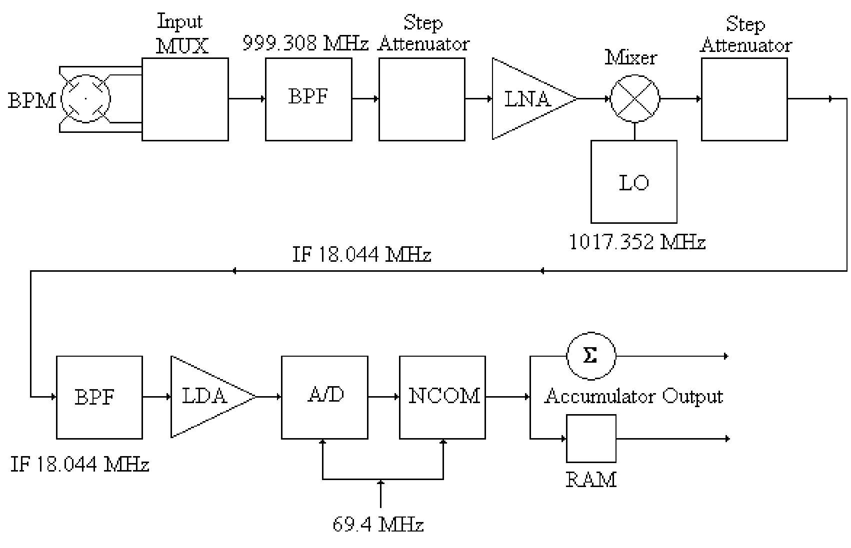

Fig. 6.1.3 RF-IF Converter Followed by Digital IF Processing Components.

The 999.308 MHz signal at the output of the 4:1 switch is filtered by a 1% band pass filter (BPF), attenuated, amplified and mixed with a 1015.964 MHz Local Oscillator (LO) signal to produce an IF of 16.656 MHz (12 times 1.388 MHz ring revolution frequency). The IF is filtered with a 2.2 MHz Bessel bandpass filter and amplified for detection by the IF processor. The BPM processing system specifications are given in Table 6.1.1.

Table 6.1.1 CANDLE BPM Processing System specifications.

Number of BPMs	80
RF button multiplexing	4:1
IF processor multiplexing	1 processor per BPM
Button switch period (μs)	2.161 (3 ring turns)
Orbit update rate (kHz)	28
Ring RF frequency (MHz)	499.654
Ring revolution frequency f_{RF} (MHz)	1.388
Ring harmonic number	360
RF processing frequency (MHz)	999.308 (2 f_{RF})
RF-IF processor bandwidth (3 dB) (MHz)	2.2
Local Oscillator frequency (MHz)	1015.964 ($2f_{RF} + 12f_{rev}$)
IF frequency (MHz)	16.656 ($13f_{rev}$)
IF processor digitizing frequency (MHz)	69.4 ($50f_{rev}$)
Nominal beam current range (mA)	1-350
First turn resolution –0.03 nC/bunch (mm)	1.5
Turn-turn resolution (> 5 mA) (μm)	12.0
Orbit feedback resolution at 2 kHz (μm)	1.0
Orbit feedback resolution in 1 sec (μm)	0.045
Absolute BPM alignment (μm)	< 100

The BPM Processing system can operate in the following modes:

- First Turn Mode

In a single (first) turn mode the BPMs measure the single short position of the injected beam by synchronizing the BPM processing signal with the injection kicker system. The four buttons of each single BPM are processed in parallel by 4 RF-IF converters. For the 0.03 nC injected bunch from the 2 Hz booster the bunch position will be detected with a single short position resolution of 1.5 mm.

- Turn-by-Turn Mode

In turn-by turn operation mode the signals from BPM buttons are stored in the IF processor memory for further data analysis and feedback by the CANDLE Control system. In this mode the processor resolution at the level of 10.0 μm can be reached for the beam current larger than 5 mA. During the turn-by-turn BPM processing an effective measurement of the betatron oscillation phase and amplitude can be performed to determine lattice properties.

- Averaged Orbit Mode

This mode will be predominant providing highly resolved orbit information based on the averaging of the BPM readings over many turns. Averaging will take place on two time scales: a fast time scale for orbit feedback processing and a longer time scale for higher resolution monitoring. Averaging over 2000 orbits with orbit updates once every second will lead to 0.025 μm processing resolution.

6.1.3 Diagnostic Beamline.

The synchrotron radiation of the electron beam in the CANDLE storage ring is the unique non-destructive source for the direct observation of the beam profiles. Therefore, one specialized bending beamline from the storage ring is dedicated to electron beam diagnostics. A diagnostic beamline of CANDLE will allow performing electron beam transverse profile and consequently the emittance measurements.

Transverse Profile. The most direct way to obtain information about the transverse profile is to produce a direct image [2]. The direct image of the electron source is produced in X-ray region by the compound refractive lens (CRL). The CRL has a parabolic shape and is made of aluminum. The refractive and absorption properties of such a lens are best suited for the photon energy between 8 and 30 keV. The experimental setup of the beamline is shown in Fig. 6.1.4. The synchrotron radiation from the bending magnet passes the Double Crystal Monochromator that produces a highly monochromatic beam at photon energy of 10 keV. The beam is focused on both directions by the CRL into the image plane. The source-to-lens and lens-to-image distances L_1 and L_2 are equal to $2f$ (with f the focal length of the lens), and therefore the image has the same size as the source. A small pinhole is located at the image plane and is scanned over the image plane. The scintillation counter behind the pinhole is detecting the transmitted radiation.

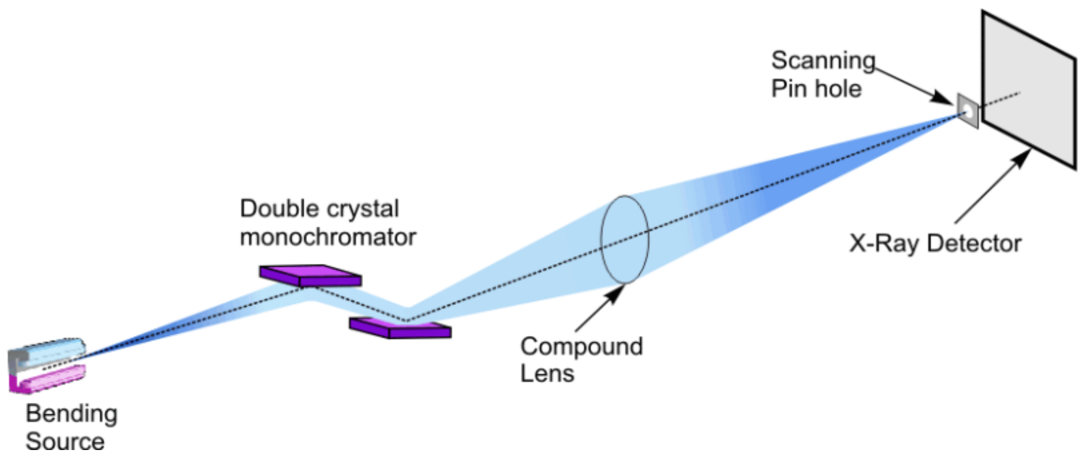

Fig. 6.1.4 Diagnostic beamline. Beam profile observation in X-ray region using CRL.

The focal length for a compound lens with N elements is given by $F = R/2N\delta$, with R radius of curvature and δ refractive index decrement. For the aluminum lens ($\delta = 5.46\cdot 10^{-6}$) with 500 μm curvature, five series of multiple lenses will provide the focal length of 7.7 m. This corresponds to source-to-lens and lens-to-image distance of 15.4 m ($2f$), when the focusing of the primary source produces a direct image of the photon source.

Resolution of the method is defined by the rms opening angle of the photon source [3] that for the bending source in the region of the critical photon energy X-ray can be presented as

$$\sigma_\psi \approx \frac{2}{\gamma}\left(0.324 - 0.172\frac{\Delta\varepsilon}{\varepsilon_c}\right) \tag{6.1.3}$$

for $\Delta\varepsilon/\varepsilon_c << 1$ and $\varepsilon_c = 7.9keV$ critical photon energy for dipole source. Diffraction limited source size corresponding to the angle σ_ψ is approximately given by

$$\sigma_r = \frac{\lambda}{4\pi\sigma_\psi} \tag{6.1.4}$$

with λ photon wavelength. Thus, the diffraction limited source size and divergence at 10 keV of the emitted photon in bending magnet are $\sigma_r = 0.1\mu m$ and $\sigma_\psi = 0.1 mrad$ respectively. Fig. 6.1.5 shows an image of the 10 keV diffraction limited source at the image plane after the focusing of the photon beam by the compound refraction lens located at the distance of 15.2 m from the point source and the screen.

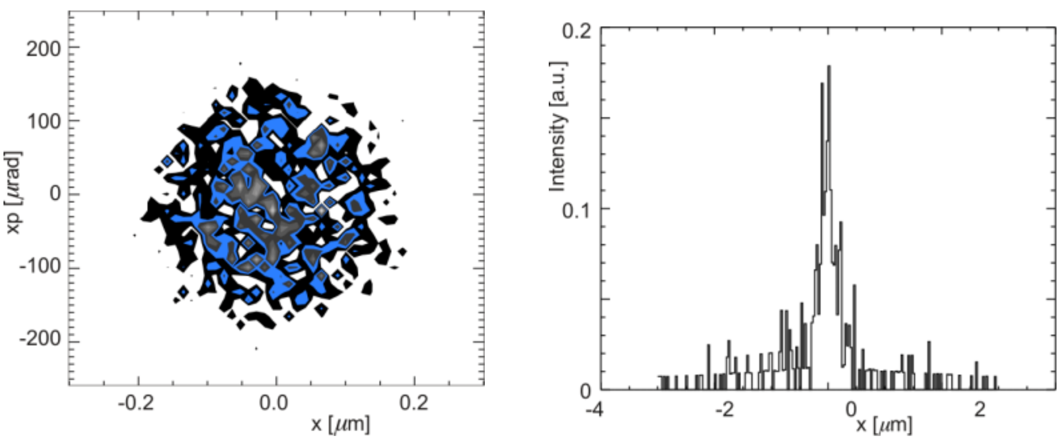

Fig. 6.1.5 Photon beam phase pattern (left) and intensity profile (right) of the point electron source after focusing by CRL ($\varepsilon = 10 keV$).

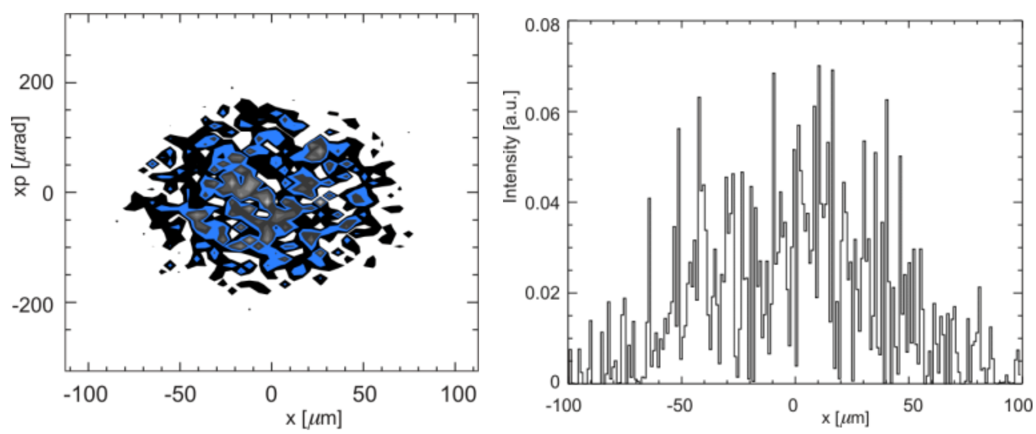

Fig. 6.1.6 Photon beam phase pattern (left) and intensity profile (right) produced by electron beam after focusing by CRL ($\varepsilon = 10 keV$).

The image profile of the photon beam has the Gaussian shape with the rms spread less than 1 μm that defines the minimum expected resolution of the detector. The corresponding image on the detector produced by electron beam in bending source is given in Fig. 6.1.6 The parameters of the beamline components and the photon beam are given in Table 6.1.2.

Table 6.1.2 The beamline components and photon beam.

CRL Material	Aluminum
Photon energy (keV)	10
CRL refractive index decrement	5.46×10^{-6}
CRL radius of curvature (μm)	500
CRL number of elements	6
CRL focal length f (m)	7.62
Diffraction limited source size μm	0.1
Source size angular spread $mrad$	0.098
RMS size of the image (μm)	<1

6.1.4 Scrapers and Beam Loss Monitors.

Scraper. To perform the precise beam transverse shape measurement, one scraper with four blades is located in the storage ring of CANDLE. One blade pair is spaced vertically and the second pair horizontally and each pair is movable towards and into the beam independently. Observing the decrease in the beam intensity due to particles scattering on the blade, one obtains the beam size for a given fraction of the total intensity [4]. The divergence of the intensity dependence on the blade position gives then the amplitude distribution of original beam. The measurement is performed for horizontal and vertical directions separately.

If the blade is located at the distance of x_b from the beam center, then the particles colliding with blade will be scattered, after successive turns the betatron amplitude will grow beyond the machine acceptance and a particle will be lost somewhere in the ring. This is true also for the particles with amplitude larger than x_b, because the corresponding particle betatron oscillations tune is far from the nearest resonances. The residual circulating current I_r is then given by

$$I_r = 2\pi \int_0^{a_b} aP(a)da \,, \tag{6.1.5}$$

with $a_b = x_b / \sqrt{\beta_b}$ and $P(a)$ - particle transverse distribution in terms of the phase ellipse invariant

$$\gamma x^2 + 2\alpha x x' + x'^2 = a^2 \,. \tag{6.1.6}$$

In particular, for Gaussian distribution

$$P(a) = \frac{1}{\sqrt{2\pi\varepsilon}} \exp\left(-\frac{a^2}{2\varepsilon}\right) = \frac{1}{\sqrt{2\pi\varepsilon}} \exp\left(-\frac{1}{2\varepsilon}\left(\gamma x^2 + 2\alpha x x' + x'^2\right)\right), \tag{6.1.7}$$

where α, β, γ are Twiss parameters, ε is the beam emittance. The particle distribution is then expressed via the measured residual current as

$$P(a_b) = \frac{1}{2\pi a_b} \frac{dI_r}{da_b} \,. \tag{6.1.8}$$

The mechanical support of the scraper has to be very stable in order to guarantee a sub-micrometer resolution of the blade position. The motor-actuated scraper beam blades are operated from the control panel in the CANDLE control room. A separate DC motor and a power supply unit are situated in the same equipment rack. The control panel displays the scraper position, as detected by linear potentiometers on the instruments. Devices incorporate micro-switch interlocks, preventing excessive travel.

Beam Loss Monitor.

Beam Loss Monitors (BLM) measure and localize the beam losses in the storage ring.
The BLM manufactured by Bergoz has very small sizes and low unit cost, which makes it possible to monitor all locations, where beam loss is predicted. Vacuum distribution can be measured based on BLM count rate. Two PIN-photodiodes, mounted face-to-face, detect charged particles. Coincidence counting makes it insensitive to synchrotron radiation. Spurious count is very low: less than 1 count in 10 seconds. Up to 10 MHz counting rate: the dynamic range > $1\cdot10^8$. It recovers in 100 ns after a hit. Choice of a detector solid angle is possible. Output is a TTL compatible pulse for easy counting. It is tested successfully up to $1\cdot10^8$ Rads for radiation damage. The charged particle crosses both PIN-diodes, which causes a coincidence. Synchrotron radiation photons, if stopped by the first PIN-diode, do not cause coincidence.

6.1.5 Closed Orbit and Tune Stabilizations.

The stability requirements for the CANDLE light source are the consequence of the small electron beam size and the tolerable photon beam parameters, which are designed for an ideal machine performance. In a real machine, the components of the storage ring have static and dynamic imperfections that cause the disturbance of the electron and consequently photon beams parameters.

Closed Orbit Correction.

The most critical issue that defines the stability of the electron beam in the storage ring is the quadrupole misalignment, which leads to the distortion of the central orbit. The most straightforward way to correct the orbit is the global correction of the disturbed closed orbit based on the BPM y_i readings of the beam positions around the ring. The close orbit correction is performed by means of powering correctors to steer the beam trajectory in BPM.

The orbit correction system for the CANDLE storage ring will be based on 80 BPMs, 64 corrector magnets and 64 corrector coils incorporated into sextupole magnets to stabilize the beam closed orbit. From 64 corrector magnets, 32 are of the combined functions type, 16 are vertical correctors and 16 are horizontal ones. Thus, from total 96 corrector magnets 48 will deal in horizontal plane and 48 in vertical plane. The location of the correctors and BPMs in a regular lattice is shown in Fig. 6.1.7.

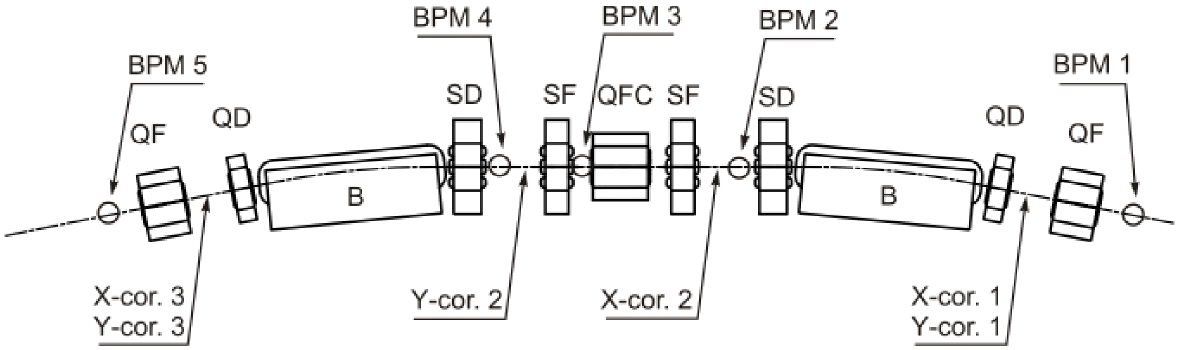

Fig. 6.1.7 BPMs and correctors distribution per magnetic lattice.

To correct the closed orbit, a global orbit feedback system will be adopted for the CANDLE storage ring, which will minimize the orbit variations at all experiments at the same time. Fast orbit correction will require the ability to acquire the orbit of the main ring from 80 beam position monitors around the ring in both horizontal and vertical planes. The new orbit needs to be calculated, and the values are to be distributed to the magnet power supply controllers.

To achieve this, an acquisition system consisting of digital signal processors (DSP) will be installed at each of the 16 sectors, which will acquire the reading from 5 beam position monitors. The obtained values may be selectively averaged over a number of turns of the machine. The values will be packed into a message and will be sent to a central crate equipped with a fast DSP, which performs the scaling of the input signals, calculates the position and current, as well as the fast Fourier transform, etc. The liability of the system to apply different correction algorithms adopted for a single, turn-by-turn and pulse operation modes is very important.

Direct correction. Denoting by θ_k the deflection experienced by a beam in the k-th dipole corrector, the orbit change at the i-th BPM is given by:

$$\Delta y_i = \frac{\sqrt{\beta_i}}{2\sin \pi Q} \sum_{k=1}^{N} \theta_k \sqrt{\beta_k} \cos\left(\left|\phi_i - \phi_k\right| + \pi Q\right), \tag{6.1.9}$$

which in the matrix form is written as $\overline{\Delta y} = M\overline{\theta}$. To correct an orbit, the deflections (strengths) of the correctors are adjusted to $\overline{\theta} = -M^{-1}\overline{y}$. However, the response matrix M is often singular or close to singular, even when the number of BPMs is greater than the number of correctors. There is no unique inverse because there are combinations of corrector magnet strengths that produce zero or very small orbit shift in the BPMs.

SVD correction [5,6]. The singular value decomposition method (SVD) applied for the response matrix M solves the problem. SVD is based on the theorem according to which any matrix can be decomposed as the product of three matrixes $M = USV$ with $U = [\vec{u}_1, \vec{u}_2, ...]$ and $V = [\vec{v}_1, \vec{v}_2, ...]$ orthogonal matrixes, S diagonal matrix. The diagonal matrix S contains all the singular values σ_i of response matrix M. The inverse of response matrix is then given by:

$$M^{-1} = VS^{-1}U^T = \sum_i \vec{v}_i \frac{1}{\sigma_i} \vec{u}_i^{\,T} \qquad (6.1.10)$$

If any of the σ_i is zero or very small, then M^{-1} is infinite or very large (singular). Even a small measured orbit associated with BPM noise would then generate undesirable large changes in corrector magnets. The problem is avoided by deleting all the terms in response matrix with small σ_i thus correcting real orbit trajectory with reasonable magnet strengths and filtering out the BPM noise effectively. Application of this method provides the steering of the closed orbit at the level below 100 μm rms.

Beam Based alignment [7]. In the beam based alignment technique, the beam is steered to the magnetic center of the quadrupoles. This provides better steering of the closed trajectory because usually the alignment error of the quadrupoles from design orbit is smaller than the combined errors caused by BPM positioning and electrical noises.
In beam based alignment technique, the quadrupoles strength is changed which affects the closed orbit. Minimization of orbit difference by the corrector magnets then leads to the orbit that is adjusted to the quadrupole magnetic center, as the trajectory through the quadrupole center is not affected by the change of quadrupole strength.

Photon Beam stabilization. After the closed orbit steering, the dynamical change and control of the closed orbit will be based on the photon beam position stabilization. To control the vertical stability of the electron beam at the source point (changes in position Δy and angle $\Delta y'$), two photon position monitors spaced by the distance Δd will incorporate in each beamline. From the simple geometrical considerations, the vertical position Δy and angle $\Delta y'$ changes of the electron beam trajectory at the source point result from the vertical displacements of the photon beam y_{p1} and y_{p2}, measured at the positions of d_1 and d_2 along the beamline. If the precision associated with the photon measurement is δ_p for both photon BPMs and there is no error associated with the positions d_1 and d_2, then the precisions of the position δ_y and angle $\delta_{y'}$ detections of the electron orbit drift are given by:

$$\begin{aligned} \delta_{y'} &= \sqrt{2}\delta_p / \Delta d \\ \delta_y &= \delta_p \sqrt{\left(d_1^2 + d_2^2\right)} / \Delta d \end{aligned} \qquad (6.1.11)$$

The photon BPMs usually have the resolution of the order of few microns. Two photon BPMs with $1\mu m$ resolution spaced at the distance of 15 and 25 m from the electron source, will then detect the position and angular change of the electron beam with the accuracy of $3\mu m$ in position and $0.16\mu rad$ in divergence.

Betatron Tunes Measurement [8]. The particles of the beam perform the betatron oscillations around the closed orbit and the knowledge of the betatron oscillation frequencies is an important part of the machine stable operation. The betatron function change in the ring is caused basically by the quadrupole errors. Consequently, betatron frequency is shifted, which can lead to instability development. The measurement of the betatron tunes for the CANDLE booster and storage ring will be performed generating the coherent beam oscillations by the single transverse kicker and turn-by-turn measurements of the beam position in a single BPM, the signal processing of which is separated from the general BPM sets, that are associated with the closed orbit feedback system. The transverse kicker is a stripline kicker, with four electrodes spaced diagonally for simultaneous excitation of the horizontal and vertical coherent oscillations. The single BPM in each turn will then measure the shift of the beam transverse position according to generated coherent oscillations

$$\Delta y = \Delta G \sqrt{\beta_{kick} \beta_{BPM}} \cos[\Delta\phi + 2\pi Q n], \tag{6.1.12}$$

where $\Delta G = \Delta B / B\rho$ is the strength of the kicker with ΔB magnetic field and $B\rho$ particle rigidity, β_{kick} and β_{BPM} are the betatron functions in the kicker and BPM positions consequently, $\Delta\phi$ is the phase advance between the kicker and BPM, Q is the betatron tune in horizontal (vertical) plane, n is the number of turns. The BPM will detect the oscillations that contain the sideband frequencies at

$$f_m = (m \pm Q) f_{rev} \tag{6.1.13}$$

with f_{rev} particle revolution frequency. The processing of the BPM is based on standard electronics that include the digital downconverter with bandwidth containing the sidebands generated by the tune. The fractional tune is obtained by Fast Fourier Transformation of the resulting signal, performed by the Digital Signal Processing module. The application of the tune measurement based on the single excitation of the beam coherent oscillations provides the tune measurement with the accuracy of 10^{-4}.

References

1. R. O. Hettel, " Beam Stability Issues at Light sources", 25th ICFA Advanced Beam Dynamics Workshop SSILS, Shanghai, SSRC 02-1, March 2002.
2. A. Hofmann, " Diagnostics with Synchrotron Radiation", CAS, Grenoble, CERN 98-04, August, 1998.
3. A. Hofmann, Characteristics of Synchrotron Radiation, CAS, Grenoble, CERN 98-04, August, 1998.
4. K. Potter, "Beam Profiles", CAS, Paris, CERN 85-19, November, 1985.
5. James A. Safranek, Beam-based Accelerator Modeling and Control, 9th Beam Instrumentation Workshop, Cambridge, AIP Conf. Proc. 546, p.23, 2000.
6. Y. Chung, G. Decker and K. Evans, Proc. 1993 U.S. Particle Accel. Conf., p.2263, 1993.
7. P. Rojsel, Nucl. Instr. Meth. A, **343**, 1994.
8. H. Koziol, "Beam Diagnostics for Accelerators", CAS,CERN 94-01, January, 1994.