THE BEAM DIAGNOSTIC INSTRUMENTATION OF PETRA III

K. Balewski, A. Brenger, H.-T. Duhme, V. Gharibyan, J. Klute, K. Knaack, I. Krouptchenkov, G. Kube, T. Lensch, D. Lipka, J. Liebing, Re. Neumann, Ru. Neumann, G. Priebe, F. Schmidt-Foehre, H.-Ch. Schroeder, R. Susen, S. Vilcins-Czvitkovits, M. Werner, Ch. Wiebers, K. Wittenburg
Deutsches Elektronen Synchrotron DESY, Hamburg, Germany.

Abstract

The former electron and proton preaccelerator PETRA at DESY is currently reconstructed and will be converted into a high brilliant storage-ring-based X-ray source called PETRA III [1]. Commissioning of the machine is scheduled for January 2009. PETRA III will operate at 6 GeV electrons or positrons with 100 mA stored current and a design emittance of 1 nm rad. Top-up operation is planned right from the beginning to reduce changes in heat-load and thermal drifts to a minimum,. Suitable beam diagnostic instrumentation and machine protection systems have to be established to guarantee the low emittance, sub-micron beam stability and save machine operation. To ensure a very high availability of the beam in top-up mode, injector and pre-accelerator diagnostic systems are refurbished as well. This paper presents a complete overview of the instrumentation and their latest developments to achieve these requirements.

INTRODUCTION

PETRA III will be a new high-brilliance synchrotron radiation source at DESY. The 6 GeV storage ring is on track to deliver the most brilliant storage-ring-based X-rays to users in 2009. The construction activities started in July 2007 when HERA went out of operation after 15 years of delivering high energy physics data. The 2.3 km long accelerator is completely redesigned, including the total rebuilding of one-eights of the storage ring where 14 undulators (incl. 5 canted) in 9 straight sections were installed. A new 300 m long experimental hall covering this octant with 14 independent beamlines (+ one diagnostic beam line) was recently build. In order to provide vibration-free conditions for the experiments the experimental hall rest on 99 piles of 1 m diameter that reach 20 m deep into the ground and a massive floor which consists of a 1 m thick monolithic slab of steel fiber enforced concrete. The remaining 7/8 of the storage ring are currently refurbished. Two damping wiggler sections were installed to achieve the designed low emittance of 1 nm rad. The vacuum system together with the beam position monitors (BPMs) was completely redesigned. PETRA III will run with a beam current of 100 mA (upgrade to 200 mA foreseen). Typically up to 100% of the ring circumference is filled with bunches of 8 ns distance (optional 2 ns) of nearly identical charge (N = $5\cdot10^9$ $e^{+,-}$/bunch ± 10%) but other bunch patterns are possible. The bunch length will be 100 ps immediately after injection and 40 ps for stored beam.

In the following the beam diagnostic instrumentation of PETRA III will be described in detail.

BEAM POSITION MONITORS (BPMS)

PETRA III will be equipped seven different pickup types; their properties are summarized in Table 1. A total of 227 BPMs is foreseen, one BPM per standard FODO-cell and additional BPMs at the locations of insertion devices. The BPM-system has to serve for two major tasks resulting in different operational modes and requirements:

1) Machine commissioning and development: Single turn, single pass capability to acquire beam positions is required for:

-of the non-stored first turn and

-of each of consecutive turns

In these turn-by-turn operation modes the resolution requirement is relaxed (50...100 μm).

2) Orbit feedback and observation: In standard user operation the beam orbit of the stored beam has to be kept constant with respect to the reference (golden) orbit. All BPMs have to be squeezed to their maximum performance in terms of resolution (1/10 of the 1σ beam width) and reproducibility. To achieve this, the bandwidth of the BPM-readout can be reduced to 300 Hz and averaged position measurements of many turns will be acquired. In addition the BPM system has to provide position data with a frequency of about 130 kHz (turn by turn) to feed the fast orbit feedback system. Even at that bandwidth the resolution of a BPM must not exceed 50 μm.

All tasks are foreseen to be fulfilled with the LIBERA Brilliance BPM electronics from Instrumentation Technologies. A number of test measurements were performed in advance [2] to ensure, that the required specifications [3] will be covered by LIBERA. It was demonstrated that already the LIBERA Electron meets the required specifications and the new LIBERA Brilliance exceeds them. However, three parameters were discovered to be critical, namely 1) the temperature drift of LIBERA, 2) the bunch pattern dependence of the position readout and 3) the maximum input voltage of the channels:

1) A dependence on the bunch pattern was observed with LIBERA Electron, but LIBERA Brilliance should eliminate this behaviour. If there will be still a considerable dependency for extreme bunch patterns, it is planned to generate different "golden orbits" for certain fillings.

2) The temperature drift of 0.2 μm/°C allows operating LIBERA only in air-conditioned surroundings. Therefore all racks will be concentrated inside temperature

Location (number) -Chamber profile-	Chamber size [mm] (Button Ø [mm])	Required resolution σ (μm) vert.; hor.	Ultimate res. σ (μm) vert; hor.	current limits [mA]	Monitor const. k: vert.; hor.
Old octants (108) -elliptical-	80 x 40 (11)	10 ; 10	0.5 ; 0.5	8 – 100	16.9 ; 17.7
New octant (44) -octagon-	80 x 38 (11)	0.5 ; 2	0.5 ; 0.5	8 – 100	16.8 ; 17.5
Next to undulators (16) -elliptical-	66 x 11 (11)	0.3 ; 2	0.15 ; 0.15	4 – 100	5.26 ; 5.26
Canted undulator (5) -elliptical-	57 x 7 (4)	1 ; 1			2.34 ; 7.19
Straight sections (26) -round-	Ø 94 (15)	10 ; 10	1.0 ; 1.0	10 – 100	33.3 ; 33.3
Damping wiggler (26) -racetrack-	120 x 30 (11)	5; 5	0.5; 0.35	7 – 100	12.0 ; 16.4
Damping Wigglers (2) -octagon-	60 x 26 (11)	5; 5			10.24 ; 14.41

Table 1. Properties of the beam position pickups installed in PETRA-III and orbit resolution requirements at certain locations at a bandwidth of BW=300 Hz. The ultimate limits can be expected from the tightest requirement of a resolution of 0.5 μm for the new octant (taking into account the monitor constants). The lower beam current limit for which the ultimate resolution is valid is a result of the pick-up geometry, respectively the coupling to the beam. The Turn by Turn (TBT) position resolution is acquired by LIBERA Brilliance at a bandwidth of B = 0.3 ·130 kHz = 39 kHz. The accuracy requirements for the TBT measurement are relaxed from those in table 1. Since the resolution is proportional to 1/sqrt(B), the resolution requirements of 50μm (1 σ) are fulfilled.

stabilized cabins and in the new octant near the undulators (± 1 ^{o}C for both).

3) For the estimation of the signal levels at the LIBERA crossbar switch (limiting element), the transient signal at the input of the module was calculated for the various position monitors [4]. Beam offsets in the order of some mm (depending on the pickup type) resulted in amplitudes exceeding the allowed input amplitude of 80 V. Therefore additional 10 dB attenuators are foreseen. However, large beam excursions will still result in too high voltages and a nonlinear behaviour of the readout is expected. Such large beam offsets should be avoided when defining “golden orbits”. To avoid measured orbit drifts due to different heating of the attenuators, they will be mounted thermally coupled on a solid metal board directly in front of the LIBERA input connectors. Calculations have shown that signals of reasonable small beam intensities are still in the useful range of the LIBERA electronics. More detailed specifications of the BPM readout system can be found in [3].

Movement detection

The position and movement of the pickups at critical locations will be measured with respect to the ground floor, respectively girder. All pickups in the new octant are attached to a “High Frequency Movement Monitor” (HF-MOMO) which determines pickup movements with a resolution of << 1 μm, based on the measurement of the distance between 4 terminated (50 Ω) striplines (two per plane) and a stiff solid wire of 2 mm diameter. The wire is mounted on a fork which is firmly connected to the ground or girder by a massive support. It is part of a matched 145 MHz λ/4-resonator and the striplines pickup this HF-signal. The 4 signals are processed like usual BPM signals to determine the position of the wire inside the pickup (monitor constant k = 3.0). The bandwidth of the system is about 1 Hz, sufficient to observe long term drifts. 4 ADCs (80 kHz, 16 bit) are attached to the 4 striplines, 16 monitors are multiplexed so that each monitor has a repetition rate of 16 s. The gap of the sensors limits the sensitive area to 8 x 8 mm^2, the linear response is in the range of ± 2mm in each plane. The readout electronics gives access to the ADC raw data to enable FFT analysis of measured frequencies.

The supports of the HF-MOMOs near the undulators are made from carbon fibers, designed for zero thermal expansion although the complete new octant (tunnel) will be temperature stabilized to 0.1 ^{0}C.

BEAM CURRENT MONITORS

Fast current transformer (FCT): A wide-band In-Flange FCTs with a bandwidth of 1.75 GHz (Bergoz) will measure the individual charge of each stored bunch. This measurement defines the required individual charge for the topping up injection. A resolution of < 1 μA/bunch with an analog bandwidth of 500 MHz (to meet the optional 2 ns bunch spacing) is intended. Its readout is performed by a scope type Wave-Runner 104Xi (LeCroy) with a sampling rate of 10 GS, a bandwidth of 1 GHz and 8 bit resolution. An average of about 50 turns of each bunch is displayed in the control room and sent via Ethernet connection to the control system. Two customized elliptical FCT (BW=800 MHz) are located in the injection area to determine the injection efficiency by comparing with the current in the pre-accelerators.

DC current transformers: The very high resolution measurement of the DC current will be performed by three parametric current transformers (PCT, Bergoz) reused from PETRAII and HERAe and upgraded by the company. Experiences from HERA with this type of monitor showed a resolution of σ <<1 ‰ (absolute: 3 μA of 61.7 mA) [1] which is sufficient for the top-up operation of PETRA III. The readout is performed by a high precision DVM (Type HP 3458A with 16 - 24 bit resolution depending on sampling rate), connected to the Bergoz back-end electronics. The DVM averages over defined number of turns.

EMITTANCE

X-Ray Diagnostic Beamline

An x-ray diagnostics beamline will be located at the end of the new octant. Synchrotron radiation (SR) from a bending magnet with critical photon energy of 20.907 keV and a total emitted power of 6.96 kW is produced in the central field. The x-ray part of the emitted radiation will be used to image the beam spot onto a high resolution CCD camera system. Imaging will be performed with two interchangeable x-ray optics: A high resolution compound refractive lens (CRL) system (≈ 2 μm resolution) and a pinhole camera system for lower resolution standard operation (≈ 20 μm resolution). The CRL is made of 31 individual beryllium lenses, stacked behind each other in a very precise (1 μm) support fixed by a laminated spring. The pinhole consists of a 0.5 mm thick tungsten blade with a circular hole of 20 μm. In order to switch between they have to be moved ± 5mm in vertical direction by a stepper motor. Both optical systems are water-cooled, and two additional absorbers are installed in the photon path. The beamline has a vacuum system which is separated from the machine vacuum by a CVD window

For improvement of the spatial resolution a water cooled monochromator crystal (Si 311 in Laue geometry) will be used which is located 8.78 m behind the x-ray optics. At the nominal photon beam energy of $\hbar\omega$ = 20 keV the Bragg angle amounts 10.912^0.

The detector system (Hamamatsu AA50 beam monitor) will be installed about 68 cm away from the monochromator crystal outside of the vacuum system. It consists of a 10 μm thick LSO scintillator screen together with a microscope optics and a progressive scan interline chip CCD camera (Hamamatsu Orca C4742-80-12AG). The Peltier-cooled camera allows variable exposure times from 10 μsec up to 4200 sec. A remotely controlled filter wheel with molybdenum foils will be used together with different absorbers in order to adjust the incoming intensity and photon energy and to avoid saturation of the camera.

Optical Beam Line

For the main purpose of measuring the bunch lengths, an optical beam line is under construction. It uses the radiation from a standard dipole magnet. A mirror will extract the optical part of synchrotron radiation from the dipole and an optical relay system will guide the light to an experimental hut outside the tunnel. In the beginning it is foreseen to perform measurements of the bunch length with fast optical elements like streak camera or Avalanche Photo Diodes (APD). To be prepared for the measurement of the beam size in the optical regime as well, all optical elements are designed and proven to be as precise as possible (peak to valley wavefront aberration of λ/20 at λ=632 nm).

Laser wire scanner

A laser wire scanner is built to measure the beam emittance and its coupling. The laser itself is placed in a hut 6 m above the PETRA tunnel. A commercially available pulsed Nd:YAG laser capable of delivering 7.5 MW light pulses at 20 Hz is installed to produce high power light (532 nm). The laser system is injection seeded to eliminate mode-beating and to enable fast scans. The laser light will be transported from the laser hut to a vertical and horizontal optical table positioned around the cross chamber. Both tables are equipped with scanning, focusing and diagnostics optics.

A light polarization based, fast splitting technique will be applied. A Pockels cell at the laser hut allows pulse by pulse splitting of the laser beam to enable horizontal and vertical scans. Left/right helicity pulses made by the Pockels cell reach the tunnel and are converted into horizontal/vertical polarisations by a quarter wave plate followed by a Glan-laser prism-splitter. This prism guides laser pulses with vertical/horizontal polarization to different scanning arms (one for each plane). Each scanning arm will contain a bending transverse Pockels cell for scanning and a lens to focus the beam down to a laser spot size of about 5 μm.

A vacuum chamber with an outlet in the next dipole allows a safe transport of the scattered photons with few hundred MeV energies into the detector. The photon detector is a tungsten-scintillator sandwich with 2 segments to allow vertical position detection. The whole setup will allow a complete 2D transverse scan in about 30 s within a few percent accuracy [5].

MACHINE PROTECTION SYSTEM

PETRA III will be equipped with a ring-wide Machine Protection System (MPS) which will dump the beam in case of equipment failures, critical temperatures or too large beam offsets. One or more MPS crates are located in each of the 8 "old" PETRA halls. Each crate houses an interface to a field bus (SEDAC), a MPS-Controller (MPSC) and 1 to 10 Alarm-Input-Modules (MPSA). Each MPSA can sample up to 16 alarm inputs. Alarms might come from the BPMs (LIBERA interlock output), the temperature system (> 1500 PT100 sensors), from the vacuum pumps and valves, from the HF-system, from the power supplies, etc. The alarm-inputs can be enabled and disabled by software or automatically by predefined conditions. Certain conditions like low beam currents, large undulator gaps will disable individual inputs to allow machine studies without interference with the MPS.

Especially the beam current is directly connected to a special module to make the MPS independent from any network connection. The live-value of the current monitor (PCT) is always checked by test-pulses through a special test winding in the monitor. Various alarm conditions can be logically combined in one module

All crates are connected with an optical fibre dual loop (redundancy) via the MPSC. This loop synchronises all crates to the same beam turn. In case of an alarm the corresponding MPSC activates the dump and the post mortem trigger which is distributed to all other crates by the optical fibre loop. The dump trigger is connected to the RF-system which will stop to deliver power to the beam and the beam will be lost within ≈ 4 ms. The delay of the dump trigger with respect to the alarm does not exceed 100 μs. Two massive pieces of metal will also be driven into the beam pipe to ensure no survival of the beam (delay ≥ 100ms). A faster dump kicker (1 turn) triggered by the MPS is foreseen at a later stage. The MPS will keep the information of the channel which delivered the first alarm to simplify the search for responsible candidates. A post mortem trigger will be available at each crate to enable post mortem analysis of connected subsystems (e.g. BPM system, RF-system, etc).

ORBIT STABILIZATION, FEEDBACK AND TUNE

Orbit stabilization is the precondition for stable user conditions and it also prevents a blow up of the vertical emittance. The stabilization system has to suppress slow motions of the particle beam within time constants from several days to 300 Hz. The stability demand is about 10 % of the beam sizes, which is of the order of 4 μm for the horizontal and 0.5 μm for the vertical plane at the location of the undulators.

Slow orbit correction.

The slow orbit correction will be performed by the control system, based on the readout of the 220 BPMs. The LIBERA electronics are connected via Ethernet to the control system while its readout frequency is about 1 s for each. Singular Value Decomposition (SVD) is applied for simultaneous optimization of the closed orbit and the dispersion. Simulations have shown that the rms vertical dispersion can be kept below 5.0 mm in the whole ring. The maximum corrector strength needed is 0.5 mrad. The required resolution of the corrector power supplies has to be at least 16 bit. The slow orbit corrections will be performed with small horizontal and vertical magnets and backleg windings on selected magnets.

Fast Orbit Feedback System

The fast orbit feedback will reduce orbit distortion by about 20 dB at 50 Hz with a slope of -20 dB/decade. Its low frequency component does not overlap the high frequency range of the slow orbit feedback. Both systems will work independently. However it is foreseen to synchronize both systems at a later stage.

System setup: Each LIBERA brilliance box delivers 'raw' turn by turn position information to a signal combiner via their ultra fast rocket IO connector. 24 signal combiners are located near the BPM racks to which up to 15 LIBERA modules are connected. Each combiner generates a fast data stream into optical fibre lines (up to 200 MB/s synchronous data flow) which are connected in a star topology with a main processing unit. A second task of the signal combiner is the supply of timing signals e.g. machine clock and event triggers to the LIBERA front-ends. A main processing unit manages data collection, processing and distribution. The signal processing will be performed by using SVD and PID algorithms in FPGA technology. The output data stream is distributed (star topology) via fibre links to 82 digital power amplifiers (DPA) located in 12 racks. The DPAs have individual DSP based current controllers which are connected to 82 fast air coil correctors: 30 air coil magnets for each plane in the new octant and 11 for each plane in the seven old octants are designed. The DPA supplies have an average current of 10 A (max. 20 A). The frequency range spans DC to 1 kHz. The signal splitters, the main processing unit and all DPAs are accessible through standard USB interfaces by the orbit feedback server for control and maintenance. The whole setup is a complete end-to-end digital design with 16 bit resolution. A feed forward of mains frequency and its harmonics is also foreseen.

Multi Bunch Feedback Systems

The design current in PETRA III can only be achieved with the help of powerful bunch by bunch feedback systems. The required minimum bandwidth is 62.5 MHz (8 ns bunch distance).

Transverse feedback: The signals of two dedicated stripline beam position monitors are connected to an RF-front-end (in-house development) followed by a FPGA based signal processing board. It drives 4 feedback power amplifiers per plane (Bonn Elektronik, Type BSA 0125-250) with a frequency range of 9 kHz to 250 MHz and an output power of 250 W each. The amplifiers drive 4 stripline kickers (2 for each plane) which are designed and build in-house.

Longitudinal feedback: The signals of 4 buttons of a beam position monitor are combined to give an intensity signal which is insensitive to the transverse beam position. The longitudinal signal chain consists of an RF-front-end and a digital signal processing board as for the transverse system. The kicker devices consists of 8 cavities (modified DAFNE cavity [6]). These are well tuned and damped to get the required bandwidth of 62.5 MHz. The centre frequency is 1375 MHz and double sideband modulation will be used. A later modification for 250 MHz bandwidth is possible by changing the tuning and damping of the cavities and using single sideband modulation at the same centre frequency.

Tune

The tune measurement is part of the transverse multibunch feedback system. It contains a digital signal generator to feed different kind of signals bunch-synchronized to the kickers. Single bunch as well as multibunch excitations can be performed. In the single bunch mode the number of bunches can be chosen while in multibunch mode the frequency of each mode can be adjusted. Different excitation schemes exist: 1) sinusoidal CW, 2) bursts with adjustable rate and length, and 3) bandwidth-limited "white" noise. Since the feedback systems will damp away any kind of excitation, the classical tune measurement can be performed only without feedback. However, a new idea of tune measurement with feedback will be tested at PETRA III: An adjustable broadband noise will be added to the RF front-end output (and therefore to the kickers). In the frequency response this will be seen as constant offset. At the tune resonance frequency a notch will appear due to the 180^0 phase shift of the feedback. These notches can be analyzed very precisely, even with running feedbacks and with a minimum of excitation. A detailed description of the system is in preparation [7].

X-RAY BEAM POSITION MONITORS

Blade-type x-ray BPMs obtain the information of the beam position from the halo of the undulator radiation. Their signals depend on the undulator gap and are strongly affected by stray radiation from bending and focusing magnets, making it not well feasible to use them in the photon beamlines for the experiments. To overcome these limitations an x-ray BPMs based on the ionization of residual gas was developed and tested. It uses the ions created by the x-ray beam in a small pressure bump of about 10^{-6} mbar. The ions are accelerated by a parallel electrical field towards a Micro Cannel Plate and an attached phosphor screen. This monitor type has the advantage of imaging the whole body of the beam so that the centre is well defined. Tests with a prototype at the ESRF showed a resolution of better than 5 μm. More details can be found in [8].

PREACCELERATORS

The PETRA III injector chain consists of the linear accelerator LINAC 2, the positron intensity accumulator PIA, the booster synchrotron DESY II and the interconnecting transfer lines. The whole chain is equipped with essential beam diagnostic instruments like BPMs, current monitors and screens:

LINAC2 is equipped with 5 BPMs, their readout electronics development started recently. The 3 GHz beam sub-structure needs a complete new type of readout electronics. The other pre-accelerators have a single bunch structure to provide filling and topping-up of PETRA III. The "Delay Multiplex Single Path Technique" is used to readout the beam position of the bunch. The technique was developed in 1978 for PETRA I by Ru. Neumann at DESY. An upgraded version will be used for the European XFEL [9].

All transfer lines, PIA and DESY II are equipped with in-house designed inductive current monitors (BW=150 MHz) to observe the bunch current behaviour in all stages of the filling of the PETRA III filling.

25 new designed phosphor screens (Ø 63.5 and 98 mm) are installed in the injector chain. They consist of a thin 8 μm Al screen covered with a thin layer of ZnS. The screens are viewed at 45^0 by commercial CCD cameras (radiation hard types in exposed areas) typically located about 800 mm below the beam inside a 50 mm thick lead shielding. The driving mechanism consists of a pressed-air cylinder to move the screen in and out, an electro-magnetic bar to allow the in-movement and a spring to ensure an automatic pullout of the screen in case of an air-pressure drop. Special screens are needed at the entrance and at the exit of the injection septum and one additional in PETRA III for observing the incoming beam. Their frameless screens consist of a 1 mm thick Al_2O_3 ceramic (66 x 38 mm) with a thin layer of ZnS. Special care is taken (by soft- and hardware) to avoid to move the PETRA-screen into a stored beam. The video signal treatment of the screens is described in detail in [10].

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