The European XFEL Beam Position Monitor System

Conceptual Design Report

Rev. 1.00

June 15, 2010

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			references in text. Added button ADC section. Added control and timing system section contents. Compressed all images to reduce document size. Corrected BPM specification table to values of 8/2009 meeting.
0.20	14.6.2010	Nölle	Most changes of rev. 0.19 accepted, some not or modified.
0.21	14.6.2010	Keil	Minor changes and smoothing of phrases.
1.00	15.6.2010	Nölle	Version with all comments and change requests included. Will serve as basis for CDR documents.

Table of Contents

1 High Level Description

(Author: Keil/Nölle)
(Check: Decking)

These documents describes the conceptual design of the Beam Position Monitor (BPM) System for the European XFEL [1]. The system will provided in-kind by a collaboration of

- Paul Scherrer Institut, Villigen, Switzerland
- CEA, Saclay, France
- DESY, Hamburg, Germany

The system will consist of about 450 BPMs. Three types of button BPM pickups and three types of cavity BPM pickups will be used in order to fulfil the requirements at different locations in the accelerator. The processing of the pickup signals will be done by a modular electronics system, providing a common interface to other accelerator subsystems like control, timing and interlock systems.

In this collaboration DESY will provide the mechanics of the BPMs, except for the re-entrant cavity BPMs. PSI will provide the complete electronics, firmware and embedded software, except the RF front end electronics for the re-entrant cavity BPMs. CEA will provide the mechanics and the RF front end for the re-entrant cavity BPMs.

The intent of this conceptual design report is to give a basic overview of the concepts, functionality, requirements and interfaces of the BPM system. All values quoted in this report reflect the current, preliminary status of requirement and performance estimations as well as prototype test results in the ongoing development process of BPM and other accelerator subsystems. While the respective values for the final BPM system may differ in order obtain an overall optimum of performance, cost, development time, the present status and results still allow to motivate the chosen conceptual design approach and demonstrate its feasibility.

2 Requirements/Interface List

(Author: Decking/Nölle/Keil)

Aspect/Interface Name	**Task**	**Interface to**	**Workpackage/ Coordinator**	**In Charge**	**Comment**
High level specifications	BPM System	Beam Dynamics	MLC	Decking/Limberg	Basic Machine Properties
BPM performance specification	BPM System	Beam Dynamics	MLC	Decking/Limberg	Specifications of the BPM performance
Lattice/BPM quantities	BPM System	Beam Dynamics	MLC	Decking/Limberg	Location, type and overall numbers of BPMs
Cold BPM	Cold BPM Mechanics	Cold LINAC	CLC	Weise	Make sure, the interfaces inside the cryo-module are compliant to the design of the cryo-module
BPM Electronics	BPM Electronics	Internal	WP-17	Schmidt-Föhre	Check Electronics Concept
EMI	BPM Electronics	EMI	WP-39	Kapitza	Make sure the electronics is compliant to EMI requirements
BPM Mechanics	BPM Mechanics	Internal	WP-17	PSI	Check the Mechanics Concept
Orbit walk off interlock	BPM Electronics	MPS	MLC	Decking, Kaukher/Staack/ Karstensen	BPMs provide an interlock signal, when beam walks off.

Remote Administration of BPMs	BPM Electronics	Control System	WP28	Rehlich	Make sure, that BPM electronics can be accessed remotely, even from Switzerland
System diagnostics, self tests, calibration procedures	BPM Electronics	Control System	WP28	Rehlich	Make sure build in test and calibration routines can be accessed
BPM panels, orbit displays, orbit server	Control System	BPM System	WP28	Rehlich	Make sure, the required software is available at start-up
Timing	Control System	BPM Electronics	WP28	Rehlich	Make sure, the BPMs get correct timing, i.e. triggers/events and ADC clocks as specified in ref. [2], chapter 3.
Time Stamps	Control System	BPM System	WP28	Rehlich	Make sure the BPM data gets correct time stamps
Performance Requirements at start-up	BPM System	Commissioning	MLC	Decking/Limberg	Define start-up performance and perspectives
Radiation Shelter	BPM Electronics	Technical Infrastructure	TC	Hott	Make sure, the required sheltered areas are available and the shelter is sufficient
Radiation Level Supervision in Shelter	BPM Electronics	Diagnostics	WP17	Nölle/Kaukher	Make sure that the integrated dose is measured in sheltered areas
Vacuum requirements	BPM Mechanics	Vacuum System	WP8/WP19	Lilje	BPMs have to be compliant to the vacuum specifications

Particle Cleanliness	BPM Mechanics	Vacuum System	WP19	Lilje	BPMs have to be compliant to the particle cleanliness requirements in the warm beam transfer lines
Particle Cleanliness	BPM Mechanics	Module String Assembly	WP09	Matheisen	Cold BPMs have to be compliant to the particle cleanliness requirements of the module string
Assembly and Alignment	BPM Mechanics	Tunnel Installation/ Survey and Alingnment	WP32/WP33	Meyners/Prenting	Make sure, support structures with required accuracy are provided and alignment is checked.
Assembly	BPM Mechanics	Girder/support systems	WP32/TC	Meyners/Pflüger/Hott	Make sure, the vibration properties of the supports are appropriate. Appropriate means, the integrated support motion up to 0.01 Hz must be smaller than ¼ of the BPM resolution averaged of the bunch train.
Assembly and Alignment	BPM Mechanics/ Cold BPM	Cold Quadrupole	WP11	Brück	Make sure, the interface between cold quad and BPM is provided with agreed tolerances
Assembly and Alignment	BPM Mechanics/ Precision BPM Undulator	Undulator System	WP71	Pflüger	Make sure, the undulator BPM fits to the intersection

Crate/Rack Installation	BPM Electronics	Technical Infrastructure	TC	Hott	Make sure the environmental conditions and infrastructure in the shelters tunnel is compliant to the requirements, given by the BPM electronics ref. [2].
Cabling of BPM (Cold)	BPM Mechanics	Module Assembly	WP3	Jensch	Agree on type, length and treatment of cable and connectors inside the cryostats.
Hybrids box near cryomodule	BPM System	Technical infastructure	TC	Hott	Make sure the hybrids box can be installed near the cryomodule.
Cabling of BPM (Undulator)	BPM System	Undulator System	WP71	Pflüger	Make sure the undulator signals of two intersections can be passed within a length of 6 m to the electronic cabinets (ref. [2])
Cabling of BPM	BPM System	Technical Infrastructure	TC	Hott	Make sure the cables from the BPMs to the sheltered area for the electronics are compliant to the requirements, given by the BPM electronics ref. [2].
RF Reference clock signal	BPM electronics	Technical Infrastructure/Reference Frequencies	TC/WP02	Hott/Schlarb	Make sure that the low-phase-noise RF reference clock signal for the BPM electronics

					is compliant ref. [2]..
Cold feedthroughs	BPM Mechanics	Module Assembly	WP3	Jensch	BPM have to be compliant to the test procedure for cold feedthroughs
Cold feedthroughs	BPM Mechanics	Cryo Infrastructure	MKS/WP45	Petersen	Make sure, the cryo infrastructure is available for acceptance test of the feedthroughs within schedule

3 Requirements

(Author: Keil/Nölle/Decking)
(Check: Decking)

This chapter summarizes the main requirements to the BPM system.

3.1 Basic Machine Properties

(Author: Keil/Nölle/Decking)
(Check: Decking)

The BPM system has to measure the beam position[1] within the XFEL facility. It will be designed according to the beam properties of XFEL, given in the table below:

Table 1: Specification of beam properties for the XFEL

Parameter	Value	Unit
normalized projected emittance	1-2	mm mrad
typical beam sizes (RMS)	20-200	µm
bunch charge	0.1-1	nC
bunch spacing	≥222	ns
macro-pulse length	≤600	µs
number of bunches within macro-pulse	1 - 3000	
bunch pattern	arbitrary	
maximum macro-pulse repetition rate	30	Hz

3.2 Scope

(Author: Keil/Nölle/Decking)
(Check: Decking)

This document covers the entire BPMs in the cold parts of the LINAC, the standard BPMs in the warm beam transfer lines, as well as precision BPMs for the undulators and critical locations in the warm beam transfer lines, including their electronics.

[1] In the context of E-XFEL bunch position means the measurement of the postion of a single electron bunch.

Table 2: BPM quantities currently planned for XFEL.

BPM Type	Required Number
Standard BPM	228
Cavity BPM: Undulator	117
Cavity BPM: Beam Transfer Line	12
Cold BPM	104

3.2.1 Exception

The BPMs to be used in the dispersive sections of the bunch compressors are of a very special type. They are excluded here. These systems are part of WP18. The dedicated low-latency BPM electronics for the Intra-Bunchtrain Feedback is also excluded here. It is part of WP16.

3.3 Specifications by Beam Dynamics

(Author: Decking)
(Check: Extern?)

The following specifications for the BPM performance are given by the beam dynamics work package. The values in the table below are coarse worst-case (i.e. demanding) estimates that were used to select suitable BPM types for the different parts of the machine. The specifications will be adapted during the ongoing development process of the BPM system as required for an optimal balance of performance, production cost, and development time, in order to obtain a BPM system on budget and on schedule that not only provides the necessary performance to commission and operate the XFEL, but also provides – where possible with negligible cost and development effort - added value that is not mandatory but beneficial for machine commissioning and present or possible future machine operating modes.

Table 3: Specification for the XFEL BPMs

	#	Beam Pipe Diameter	Vacuum length	Type	Single Bunch Resolution (RMS)	Averaged RMS Resolution over 1000 bunches of identiccal trains	Drift per 1 deg C, min 0.1 µm	Operation range for maximum resolution	Operation range providing reasonable signal at <= ¼ Q_{max}	Linearity	x/y Crosstalk	Charge Dependence for dQ = ±5%	Bunch to Bunch Crosstalk	Transverse Alignment Tolerance (RMS)	Pipeline Latency
		mm	mm		µm	µm	µm	mm	mm	%	%	±	µm	µm	µs
Gun BPM	3	40.5	100	Button	100	10	10	± 3.0	± 10	5	1	100	10	200	1E4
Standard BPM	219	40.5	200/[2] 100	Button	50	10	10	± 3.0	± 10	5	1	50	10	200	1E4
Standard BPM	6	100	200	Button	100	10	10	± 5.0	± 20	10	1	100	10	200	1E4
Cold BPM	102	78	170	Button/ Re-entrant	50	10	10	± 3.0	± 10	10	1	50	10	300	1E4
Cavity BPM Beam Transfer Line	12	40.5	255	Cavity	10	1	1	± 1.0	± 2	2	1	10	1	200	1E4
Cavity BPM Undulator	117	10	100	Cavity	1	0.1	1	± 0.5	± 2	2	1	1	0.1	50	1E4
IBFB[3]	4	40.5	255	Cavity	1	0.1	1	± 1.0	± 2	1	1	1	0.1	200	0.5

3.4 Technical Requirements

(Author: Keil/Nölle/Decking)
(Check: Extern??)

The following technical requirements have to be fulfilled:

- All BPMs have to measure single bunch beam position and charge. The charge measurement is not the main aspect and needs not to be that precise. (Preferably with a charge noise and drift of 1-10%, value to be determined during the development phase).

[2] The standard BPM will be available in a flanged version and to be welded to the beam pipe, in cases the usual 200 mm version is too long.
[3] The IBFB BPM is mechanically identical to the cavity BPM: beam line.

- The BPM electronics shall provide an interlock signal for the machine protection system if the beam position exceeds a programmable upper limit (within the operation range for maximum resolution). The interlock latency will be <10µs. The RMS noise and drift of the position information to be used for the interlock will be higher than for the regular position signals due to the low latency, with an RMS noise and drift of <100µm for the cavity BPMs and <500µm for the button and re-entrant BPMs.
- All BPMs have to provide two trigger modes, self-triggered and externally triggered, which can be selected remotely through the control system. The nominal specifications are only reached in externally triggered mode where all requirements for trigger jitter, clock phase noise etc. as specified in ref. [2] are met.
- The Button BPM electronics has to allow for installation of the BPM with horizontal and vertical orientation of the electrodes as well as for an installation rotated by 45°.
- Administration of the BPM boards has to be possible remote controlled. The access has to be supported by the control system.
- BPM data has to include a timestamp (provided by the control system), that allows precise correlation with other data on a bunch to bunch basis.
- All system diagnostics, self tests and automated self-calibration features supported by the BPM system have to be accessible remotely via the control system interface where this is feasible and necessary.
- For the technical and beam commissioning, the XFEL control system has to provide all functionality and infrastructure required to perform the relevant commissioning tasks, including:
    - Synchronized readout, and archiving of all relevant BPMs: position and charge vectors, ADC and relevant diagnostics data for each bunch train
    - Visualisation of the BPM information, including
        - X, Y Position of the bunches along the bunch train
        - Orbit display of the Positions of bunch n along the machine (n to be chosen by the operator)
        - Orbit Display of the "averaged orbit" over the bunchtrain
    - Read/write access to all relevant BPM system parameters and settings
    - Network access and infrastructure that allows PSI to access the maintenance interface of the BPMs in order to update BPM system firmware/software and reboot or diagnose BPM systems remotely.

3.5 Requirements at Machine Start-up

(Author Nölle/Keil)
(Check Decking)

The BPMs have to be operational right at the beginning of beam commissioning in the relevant section, however with relaxed performance requirements. The nominal performance has to be reached after the XFEL has provided the necessary machine performance and infrastructure required for BPM beam commissioning for an integrated duration of 6 months.

3.6 Radiation Shelters

(Author: Nölle)
(Check: Hott/Negodin)

The XFEL has to provide sufficiently shielded installation locations for the BPM electronics that allow the use of standard electronics components in order to reach the desired electronics lifetime of 20 years without radiation damage. Effects like single event upsets have also to be suppressed to tolerable levels.

The estimate of the radiation dose in the electronics shelters is 8 Gy/10 years[4]. XFEL will provide a system to trace the integrated dose in these shelters. This will allow detecting hot spots beforehand, and allows countermeasures before damaging the electronics. One local detector per shelter is foreseen.

3.7 Vacuum System

(Author: Nölle)
(Check Lilje)

All vacuum components have to be compliant to the XFEL vacuum specifications, published by DESY MVS:

- http://edmsdirect.desy.de/edmsdirect/baseline.jsp?edmsid=*1383041
- Vakuum 005/2008, General DESY UHV Guidelines for Vacuum components
- N. Mildner et al., Specifications for the Vacuum Sections of the European X FEL, current draft, 2.1 / Mar. 7, 2010
- MVS und ZM, Qualitätssicherung bei der Entwicklung und Fertigung vonVakuumkammern, 11/2009

All parts have to be delivered with a well documented leak test and mass spectrum.

3.8 Particle Cleanliness

(Author: Nölle)
(Check Lilje/Matheisen)

Since XFEL is a superconducting accelerator, all BPMs close to the cold cavities have to be assembled according to particle cleanliness requirements. Their final design has to pass a review by the responsible XFEL Workpackage (cold BPM: WP09/WP08, warm beam transfer line WP19).

The tightest requirements apply to the BPMs inside the accelerator modules. Here an ISO4 environment (clean room class 10) is required.

The BPMs installed in the injector and in the bunch compressors have to be cleaned and assembled according to ISO5 (clean room class 100) requirements. This is true

[4] **21st October 2009**: 234. XFEL Meeting,E. Negodin: Dose measurements and radiation protection measures for electronics in the XFEL tunnels

also for a safety section after the cold linac[5]. All machine sections following this safety section will have no requirements on particle cleanliness.

WP17 will provide the parts cleaned. This might require access to the DESY cleanroom infrastructure. Particle cleanliness will be checked by spot tests during the assembly process in the clean rooms.

3.9 Assembly and Alignment Concept

(Author: Nölle)
(Check: Lilje, Meyners, Prenting, Brück, Decking)

The alignment tolerances of the BPMs are given by table 3.

Except of the undulator section, the BPMs will get no alignment marks. The precision has to be guaranteed by the supports of the BPMs, and will be checked during the assembly process of girders and preassembly units. In case of the cold BPMs this support is given by the flange of the adjacent cold quadrupole. The alignment tolerance is given by dowel pins aligning the BPM body to the mechanical axis of the quadrupole.

The undulator BPMs will serve as the fix points of an undulator intersection, and thus get alignment marks for the alignment of the entire intersection.

3.10 BPM Electronics Interfaces and Infrastructure Requirements

(Author: Keil/Nölle)
(Check: Hott, Negodin, Rehlich, Schlarb)

Ref. [2] describes the requirements of the BPM system with respect to the E-XFEL tunnel infrastructure (power, temperature, space,...), including a description of cabling requirements (e.g. cable lengths) as well as signal properties of the cables (with respect to the physical layer). The BPM electronics will be located in a separate stand alone crate. It has interfaces to the timing system, to receive timing information, to the control system, to deliver bunch by bunch orbit data, as well as charge data. These interfaces are defined together with the control system, and the counterpart will be provided by the control system.

The cavity BPMs, both 3.3 GHz types as well as the re-entrant-cavity BPMs, require low-phase-noise reference clock signals from the master frequency distribution of the E-XFEL. The bunch synchronous frequency of 216 2/3 MHz has to be provided at each of these BPM crates. Power level, drift, phase noise and beam arrival time jitter specifications can be found in table 3-4 of ref. [2].

A further interface is foreseen to the machine protections system, in order to detect beam orbit walk offs. This interface will be defined by the MPS team, and the MPS provides the cabling and receiving interface for this information.

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[5] The current assumption is, that this length is about twice the „action length“ of a fast acting valve and about 30 m.

As described in ref. [2], an Ethernet interface for customisation and maintenance is required. This will be a standard optical network connection, which cabling and network infrastructure to be provided by the machine infrastructure. It has to be accessible from PSI and CEA.

The BPM electronics has to be installed in areas with suitable radiation shielding and temperature stability, with a distance to the BPM pickups that allows reaching the maximum cable length from pickup to BPM electronics as specified in ref. [2].

4 System Description

(Author: Nölle/Keil)
(Check: Decking, Rehlich, extern)

This chapter provides a conceptual description of the technical solution to fulfill the requirements defined in chapter 3.

The goal of the XFEL BPM system is to design and construct a modular system covering the requirements of the XFEL in the different parts of the machine.

Different types of BPMs will be used. The standard BPM will use button electrodes, providing a rather simple, robust and cost efficient solution. A cold button BPM pickup is especially developed for the environment inside the accelerator structures. Its feedthroughs have to operate at about 4 k and have to withstand cool down and heating cycles without mechanical failure. For positions, where higher precision is required cavity BPMs will be used. This type is foreseen in three different variants: A dual resonator type with 10 mm inner beam pipe diameter that will be used in the undulator intersections (Cavity BPM: undulator), another dual-resonator version with 40.5 mm inner beam pipe diameter (Cavity BPM: beam transfer line), to be installed at critical locations in the warm beam transport system, as well as a re-entrant single-resonator cavity BPM that is suited for the cold environment of the accelerator modules.

The modular design concept of the E-XFEL BPM electronics maximizes the number of common hardware, firmware and software components for the different E-XFEL BPM types. The analogue front-ends are specific for the different BPM types (cavities, re-entrant cavities and button BPMs), with a common FPGA-based digital back-end board ("GPAC" = Generic PSI ADC Carrier) for all BPMs. Due to the modular design concept, the different BPM types of the E-XFEL share a large part of common FPGA firmware and embedded software, with a common generic interface to other accelerator subsystems like control, timing, interlock and intra-bunchtrain feedback systems.

The picture below shows a BPM unit, with a common housing that contains the electronics for either 4 button type BPMs or 2 cavity or re-entrant cavity BPMs.

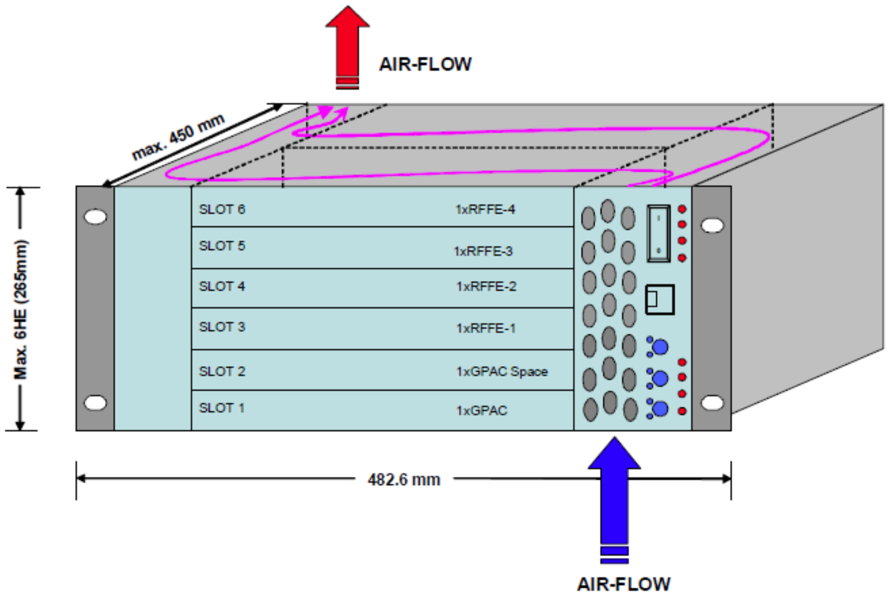


Fig. 1: Schematic picture of an XFEL BPM electronics unit. Each unit will either serve 2 cavity BPMs or 4 button type BPMs. Connection to the control system is provided by multi-gigabit fibre optic links.

4.1 BPM Mechanics

(Nölle/Lipka/Vilcins)

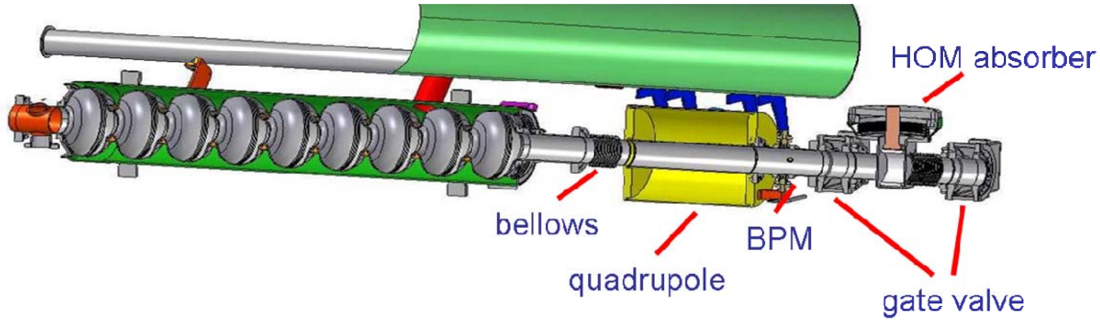
The "standard" BPM for the warm beam transfer lines will be of the button type. It will be available in two versions: A flanged version, and a version that can be welded into the beam pipe. The "precision" BPM pickups will be dual-resonator cavities based on an SCSS design [4][5], with a frequency of 3.3 GHz for the relevant mode of each resonator. Two versions will be provided, one for the undulator sections with a 10 mm beam pipe and with the standard 40.5 mm beam pipe for other warm beam pipe locations. The latter version will be able to be installed in particle free environment (ISO5/CC100)

4.1.1 Cold BPMs

(Nölle/Simon)

In the modules two types of BPMs will be used; Button BPM and re-entrant cavity BPM. The re-entrant cavity BPMs (30% of the cold BPMs) have the potential for higher resolution and will be distributed in groups of 4 equidistantly in the LINAC.

The BPMs in the accelerator or cryo modules will be located at the end of the module. They will be connected to the cold magnet package, and followed by a gate valve and the HOM absorber.



Independent of the type of BPM they will have a common mechanical interface. The length is fixed to 170 mm. The beam pipe diameter will be 78 mm. The inner surface of the beam pipe is copper plated. Fixed flanges of the cavity flange type will be used on both sides. Bolts have to be inserted from the side of the BPMs for both flanges.

The alignment of the BPM will be done by dowel pins with respect to the cold magnet. No individual alignment of the BPM in the module is planned; no alignment marks on the BPM are foreseen.

4.1.1.1 Feedthroughs for Cold BPMs

(Nölle/Vilcins)

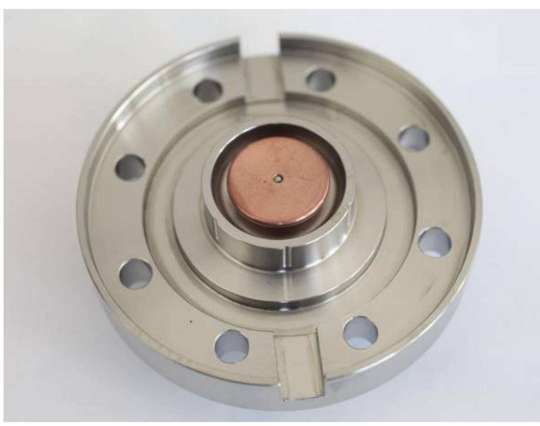


Fig. 2: Picture of a cold BPM feedthrough prototype, left of the button BPM, right of the re-entrant cavity BPM

The cold button BPMs [6] use custom made feedthroughs. During the R&D phase they have passed cryogenic tests, performed in the test cryostat 3 at DESY. Each item had to withstand 10 cycles to liquid He temperature and back to room temperature. The cycles took 30 min, each. During the cycle the vacuum pressure was monitored continuously. The number of 10 cycles is due to the assumption, that in the lifetime of the XFEL about 10 cool down and warm up cycles will be required.

All the BPM feedthroughs passed this test successfully.

For the series production all feedthroughs have to pass a special cryogenic acceptance test as a part of the acceptance tests. It consists of 3 cycles from room temperature to 4 k in a test cryostat flooded with liquid He. The 3 cycles will be followed by a leak check. This test will require the test infrastructure of DESY, about 400 feedthroughs have to be tested in two or three batches.

4.1.1.2 Cold Button BPM

(Nölle/Vilcins/Lipka)

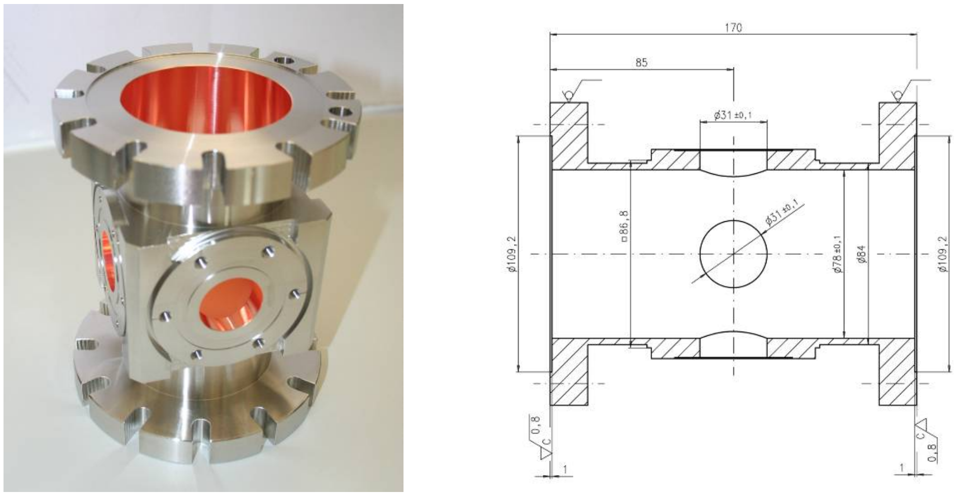


Fig. 3: Photograph and drawing of the recent prototype of the cold button BPM.

The cold button BPM consists of a precisely fabricated 4 way cross for the installation of the feedthroughs. In order to have a precise fitting to the magnetic axis of the adjacent quadrupole, the body is produced out of a single block. The flanges of the beam pipe are slotted to ease the mounting in the clean room. For the feedthroughs also a 40 mm cavity type flange was chosen.

In order to achieve high signal level a button diameter of 20 mm was chosen. The button material will be copper, in order to have high electric conductivity. The specifications of the feedthroughs emphasize the application in cryogenic environment. The mechanical design was checked by means of FEM analysis, performed in a study by the company Novicos[6].

With copper plating of the body and copper as the button material the heat load of the BPM at the highest possible beam power of the accelerator (3000 bunches, 30 Hz) is estimated by means of numerical simulation to be 78.7 mW. This includes the higher order mode losses in the BPM travelling from the accelerator to the higher order mode absorber nearby and losses due to the BPM itself. The maximum temperature at the button was calculated to be 11.4 K with the body connected to 4 K level. In this case the temperature gradient at the isolator of the feedthrough is 1.9 K. These temperatures and especially the gradient over the ceramics are estimated to be uncritical.

4.1.1.3 Reentrant Cavity BPM

(Simon)

[6] Fa. Novicos GmbH, Hamburg, "Festigkeitsananlyse einer neuen UHV Durchführung"

The reentrant cavity BPM pickup is composed of a coaxial mechanical structure, arranged around the beam pipe, forming a coaxial line which is short circuited at the downstream end. Passing through the cavity, the beam excites electro-magnetic fields (resonant modes), which are coupled by four feedthroughs to the outside: two of them determine the horizontal position (X position) and two others the vertical position (Y position). The dimensions of the system are: Gap 8 mm, coaxial cylinder 170 mm in length to satisfy the constraints imposed by the cryomodule, 78 mm for the beam pipe and 152 mm in diameter.

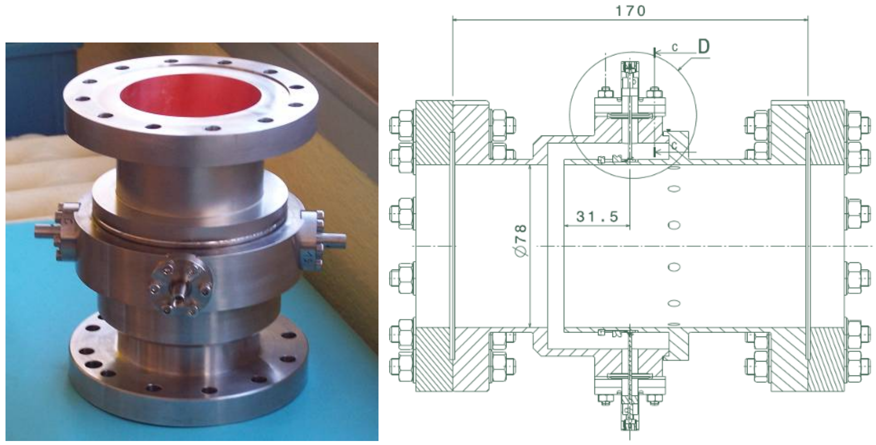


Fig. 4: Photography and drawing of the re-entrant cavity BPM.

The main RF measurements (frequencies, Q_l and shunt impedance) are presented in the following table but can shift gently according to the machining and the mounting of the cavity. The monopole mode signal is proportional to beam charge and does not depend on the beam position, contrary to the dipole mode signal which is proportional to the product of beam charge and distance of the beam from the centre axis of the monitor.

Table 4: RF Properties of the re-entrant cavity BPM.

Eigen modes	**F (MHz)**	Q_{ext}	**R/Q_l (Ω) at 5 mm**	**R/Q_l (Ω) at 10 mm**
Monopole mode	1255	23.5	12.9	12.9
Dipole mode	1724	59	0.27	1.15

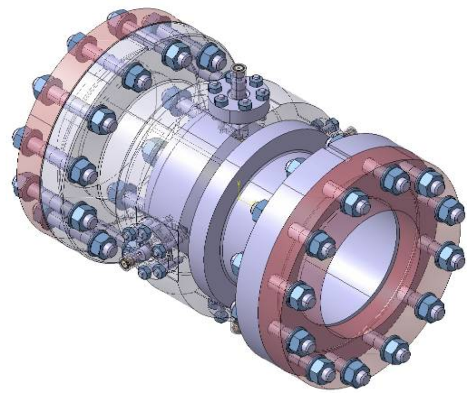


Fig. 5: 3D model of the re-entrant cavity BPM.

The re-entrant BPM pickup is composed of 2 parts which are welded together by an electron beam. Flanges are manufactured in the same blocks to reach the desired alignment tolerances. The material of the cavity is stainless steel 316LN. In order to avoid hydrogen out-gassing, a heat treatment at 950 °C for 2 hours is applied to the BPM cavity body. Each part has to be delivered with a material certificate, documented leak test and mass spectrum.
As the BPM is designed to be used in a clean environment, twelve holes of 5 mm diameter are drilled at the end of the re-entrant part for a more effective cleaning.
To reduce the cryo-losses, a 12 µm thick copper coating is deposited on the inner beam pipe. Then, a heat treatment at 400 °C is done to check the copper surface and test the contact of copper and steel.
The fixing of the antenna tips to the inner diameter of the cavity over coupled the cavity. For each antenna, a copper-beryllium RF contact is welded to the inner cylinder of the cavity to ensure electrical conduction between the feedthrough inner conductor and the cavity, providing a magnetic coupling loop. A Conflat flange CF16, which is a combination of stainless steel, molybdenum and alumina Al2O3 ceramic brazed, is used to assemble the feedthroughs to the cavity. The antennas fulfil the conditions of Ultra High Vacuum (UHV) and cryogenic tests.
The necessary handling steps, responsible WP, groups performing the different steps are listed in the following table:

Table 5: Fabrication steps of the re-entrant cavity BPM.

	Topic	**Respon-sible WP**	**Carried out by**
1	Firing of steel 950°C for 2 h	WP-17	CEA/Saclay
2	Machining of 2 parts of body	WP-17	Company
3	Machining of feedthroughs	WP-17	Company
4	Cleaning of feedthroughs and 2 parts	WP-17	CEA/Saclay
5	Cu coating of 2 parts	WP-17	Company
6	Heat treatment to check copper coating	WP-17	CEA/Saclay
7	Welding of RF contacts and EB welding of 2 parts	WP-17	Company
8	Electrical Measurements*	WP-17	CEA/Saclay
9	Cleaning, leak check and residual gas spectrum of	WP-17	CEA/Saclay

	BPM body		
10	Transport of feedthroughs and BPM body to DESY	WP-17	CEA/Saclay
11	Cold test, leak check and residual gas spectrum of feedthroughs	WP-17	MDI/MVS
12	Particle cleaning of BPM body and feedthroughs	WP-17	MVS
13	Leak check of BPM body	WP-17	MVS
14	Residual gas spectrum of BPM body	WP-17	MVS
15	Transport to clean room hall 3	WP-17	MVS

* Usually simple tests for correct impedance are sufficient; the first units should be checked with a network analyzer.

4.1.2 Warm Cavity BPMs

(Nölle/Lipka/Vilcins/Siemens)

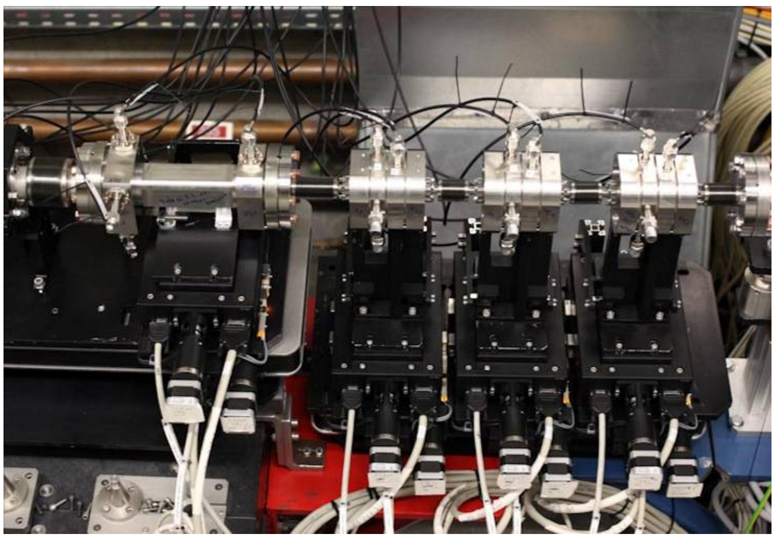


Fig. 6: BPM test facility in FLASH, with 4 cavity BPM prototypes: 3 of the undulator and one of the beam transfer line type. All BPMs are mounted on precision translation stages.

The precision BPMs will be cavity BPMs based on the ideas of the SCSS design [4][5], consisting of a reference and a dipole cavity. Therefore, charge, offset and also the sign of the displacement can be extracted out of the signals of the two cavities. Two types with different inner beam pipe diameter are required, 10 mm for the undulator sections and 40.5 mm for the standard warm beam transfer lines. For both types a frequency of 3.3 GHz and a loaded Q of about 70 was selected for both resonators. This allows using the same electronics for both pickup types. The material for both types is stainless steel in order to achieve a low Q especially for the monopole mode of the position cavity and thus to prevent cross talk between consecutive bunches and related instabilities of the beam.

4.1.2.1 Cavity BPM: Undulator Type

(Lipka/Vilcins/Siemens)
(Check: Lilje, Pflüger)

The cavity BPM consists of 3 discs, brazed together to form two resonators, a dipole and a reference resonator. Waveguide slots are attached to the dipole resonator that couple only to the dipole mode and suppress the monopole which usually limits the performance of the BPM electronics. The dipole signal is coupled out via the antennas in the waveguide slots. The coupler for the monopole signal of the reference resonator is located directly in the cavity. For both cavities a magnetic coupling is used which provides a robust transmission of signals and a fixed contact in the body. The feedthroughs are welded on the body. Due to the low quality factor, acceptable tolerances of the resonance frequencies and the magnetic coupling this cavity BPM can be reached without tuning.

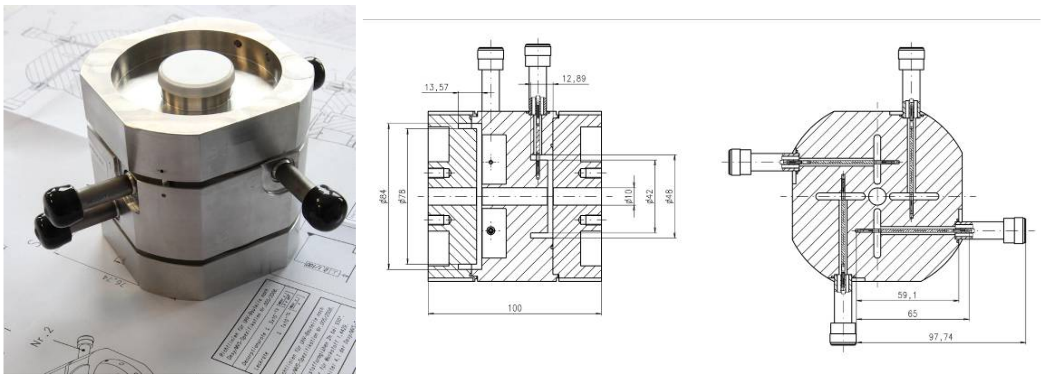


Fig. 7: Undulator cavity BPM. On the left hand side a prototype is shown. The drawings on the right hand side show the inner geometry of the BPM.

Table 6: Parameters of the undulator cavity BPM dipole resonator. The uncertainties for the resonance frequency and loaded quality factors allow to reach the desired overall BPM system performance by using a suitable RF front-end electronics design.

f_L / GHz	3.30 ± 0.05
Q loaded	70 ± 10
BW / MHz	47
Orthogonal coupling	-31.5 dB @ 3.3 GHz
Offset due to monopole mode @ 1 nC	1 µm
Offset due to beam angle @ 1 nC	0.95 mm dx,y/dz
Thermal noise (for BW)	11 nm @ 0.1 nC
Sensitivity V/(nV mm)	2.87

The signals of the monopole mode and beam angle signals in the dipole cavity have 90 degrees phase shift with respect to the beam offset signal. The impact of these undesired signal component on the BPM performance can thus be reduced by using a phase-sensitive detection method in the electronics.

In the undulator the beam pipe diameter is 10 mm. Therefore a compact design of the cavity BPM with a length of 100 mm meets the requirements of -100dB crosstalk between the two cavities.

4.1.2.2 Cavity BPM: Beam Transfer Line Type

(Lipka/Vilcins/Siemens)
(Check: Lilje, Prenting)

This cavity BPM for the beam transfer lines has similar properties as the undulator type. The main difference is the larger inner beam pipe diameter of 40.5mm, resulting in slightly different electro-magnetic properties and a larger distance of the two resonators to reach the desired -100dB crosstalk between them. Furthermore, the feedthroughs are flanged and not welded to the body. This simplifies particle free cleaning, since this BPM will also be used in sections with ISO5 particle cleanliness specification.

Fig. 8: Picture of the prototype of the beam transfer line cavity BPM type.

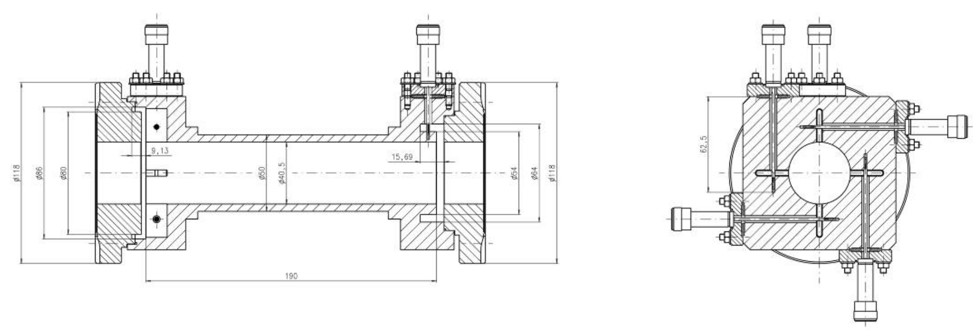


Fig. 9: Design drawing of beam transfer line cavity BPM type, showing its inner geometry. Left: Longitudinal cut along the two cavities. Right: Transverse cut close to the dipole resonator at the position of the feedthroughs, showing the coupling slots and antenna contacts.

Table 7: Parameter of the dipole resonator of the beam transfer line cavity BPM type. The uncertainties of the resonance frequency and loaded quality factors match the requirements of the front-end electronics.

f_L / GHz	3.30 ± 0.05
Q loaded	70 ± 10
BW / MHz	47
Orthogonal coupling	-27.5 dB @ 3.3 GHz
Offset due to monopole mode @ 1 nC	4 µm
Offset due to beam angle @ 1 nC	15.7 mm dx,y/dz
Thermal noise (for BW)	13 nm @ 0.1 nC
Sensitivity V/(nV mm)	2.46

The influence of the beam angle is larger compared to the undulator cavity BPM because of the larger effective length of the cavity (effective length consists of resonator length and tube diameter). This signal has a 90 degree phase offset to the beam offset signal too. Therefore a phase sensitive detection can minimize this influence.

4.1.3 Standard BPMs (Warm Button BPMs)

(Nölle/Vilcins)
(Check: Lilje, Meyners)

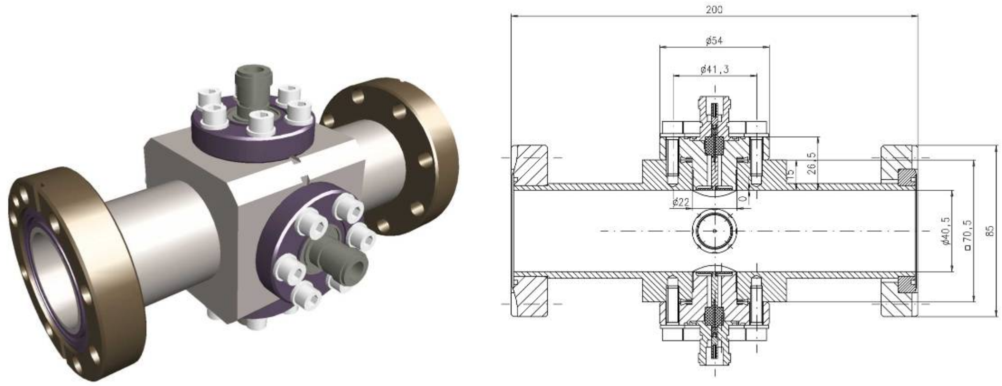


Fig. 10: Current design draft for the standard beam transfer line BPM. The right drawing shows a longitudinal cut through the BPM.

The standard BPMs will be of the button type. Its pickup will consist of a precisely milled central block, allowing for precise positioning of flanged feedthroughs (CF25). Such a block can either be extended with some beampipes and flanges on both sides (XFEL-CF50 type), as shown in Fig. 10, or can be welded to bigger chamber sections. For the flanged case the length of the pipes left and right from this body are chosen such that screws can be inserted from the side of the BPM pickup.

The non particle free sections start about 30 m after the last module of the main LINAC.

Remark on Gun BPMs: These BPMs will be based on the design of the standard BPMs, but they will be welded to the beam pipe due to the limited space in the gun section.

4.1.3.1 Standard BPMs for Non Particle free Sections

(Nölle/Vilcins)
(Check: Lilje, Meyners, Decking)

Due to synchrotron radiation, mainly an issue at the high energy, it is proposed to install the electrodes for these BPMs at +/- 45° angle with respect to the horizontal plane.

4.2 BPM Electronics

(Author: Keil)
(Check: Schmidt-Foehre)

The BPM electronics follows a modular design concept in order to maximize the number of common hardware, firmware and embedded software components for the different BPM types in the E-XFEL. The electronics is a 19’’ rack unit called MBU (modular BPM unit). Depending on the BPM type, each MBU contains 2-4 BPM-specific RF-front end modules and a common generic FPGA-based digital back-end module with two ADC mezzanines that digitize the RF front-end output signals. An MBU can either contain four button BPM RFFEs or two re-entrant or undulator/beam transfer line cavity BPM RFFEs, or a combination of these types, e.g. two button plus one cavity RFFE.

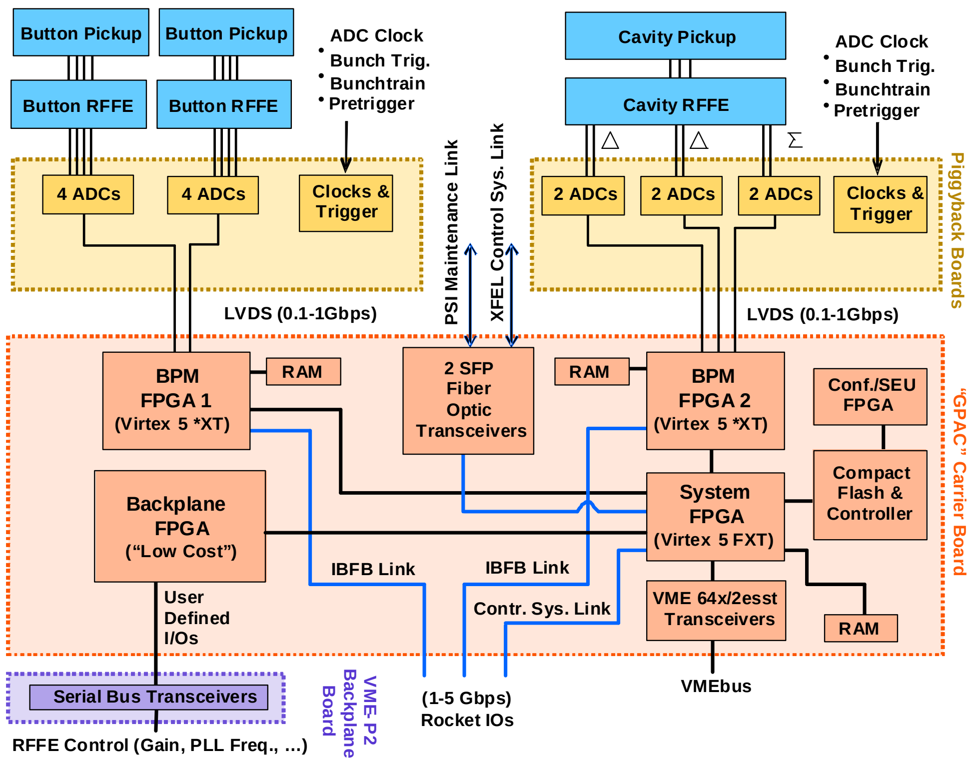


Fig. 11: BPM electronics system architecture.

Fig. 11 shows a block diagram of the E-XFEL BPM electronics system architecture. The BPM RFFE electronics receives RF signals in the multi-GHz range from the pickups and converts them to a sufficiently low-frequent pulse of typically some 10ns length that can be sampled by high-resolution ADCs on two mezzanine ("piggyback") cards which are plugged onto the GPAC board. In case of the E-XFEL cavity BPMs each mezzanine contains six 16-bit ADCs running at typically 160MSample/s. One such digital back-end can thus handle 2 cavity BPM RFFEs or 4 button BPM RFFEs. The ADC data is sent to the FPGAs on the GPAC board via a high-speed connector, using LVDS signals to minimize ground currents and interference noise.

4.2.1 RF Front End Electronics

(Author: Keil, Simon)
(Check: Schmidt-Foehre)

The E-XFEL will have three different RF front-end (RFFE) electronics types:

- 3,3GHz cavity BPM RFFEs (the RFFE is identical for undulator and beam transfer line cavity BPM types).
- Re-entrant cavity BPM RFFEs.

- Button BPM RFFEs.

4.2.1.1 Undulator and Beam Transfer Line Cavity BPMs Electronics

(Author: Keil)

The concept for the E-XFEL 3.3GHz precision cavity BPM electronics is based on the system diagram shown in Fig. 12. It consists of an RF front-end (RFFE) that uses IQ down conversion in order to convert the 3.3 GHz pickup RF signals to base band IQ signals that are sampled by ADCs and processed on an FPGA-based digital carrier board.

After being excited by the bunches of the electron beam, the cavity pickups deliver exponentially decaying signals that are band-pass filtered in order to separate the desired monopole and dipole mode from other modes. The desired modes have a frequency of 3.3GHz in the position (dipole) and reference (monopole) cavity. The magnitude of the reference cavity signal is proportional to the bunch charge only, whereas the position signals in the x (horizontal) and y (vertical) plane are proportional to the bunch charge times the beam position displacement from the beam pipe centre in x-direction for one output coupler port and the y-direction for the other port, respectively.

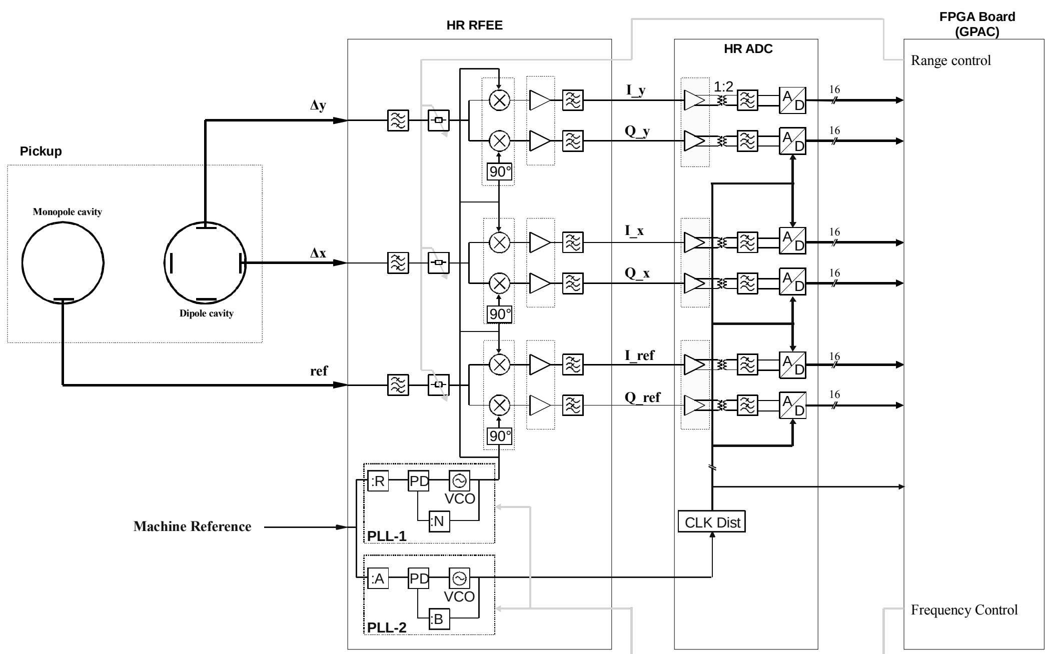


Fig. 12: Cavity BPM system concept, consisting of cavity pick-up, RF front-end electronics, ADC- and digital back-end signal processing board "GPAC" (Generic PSI ADC Carrier).

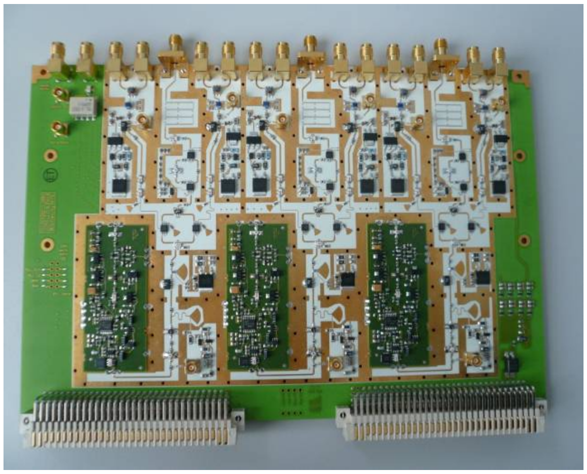
After IQ down conversion and low-pass filtering, the I and Q output signals of the RFFE consist of one pulse for each bunch, with a pulse length that depends on the output filter bandwidth. The beam displacement (from the center) in x-direction is calculated by evaluating an equation of the form

$$\Delta x = k \cdot \frac{\sqrt{X_I^2 + X_Q^2}}{\sqrt{R_I^2 + R_Q^2}}$$

Equation 1: Precision BPM position calculation.

k is a constant depending on the cavity BPM characteristics and X and R are properties of the x- and reference-channel pulses, respectively. The properties evaluated have to be proportional to the original pick-up signal. Useful properties are the peak amplitude of the pulse, the pulse energy (in which case the above equation has to be modified slightly) or the value of the pulse-integral over time. For optimal noise performance of the undulator BPM electronics it is advantageous to have a lower RFFE output filter bandwidth and thus longer pulses. This allows to minimize the position noise due to the reduced noise of the sampled signal per ADC sample and the larger number of ADC samples that can be used and averaged.

The construction of a first prototype was finished in 2009. Laboratory and beam tests showed good initial performance and confirmed the conceptual studies that have been done prior to prototype design. Tests with a single prototype E-XFEL undulator cavity pickup in the SLS linac where the pickup signals were split to two electronics already showed sub-micron resolution [1]. Noise correlation tests with arrays of 3-4 pickups at FLASH and the SwissFEL test injector at PSI are planned in order to investigate the impact e.g. of pickup fabrication or alignment tolerances, mechanical vibrations or environmental noise on the BPM performance.



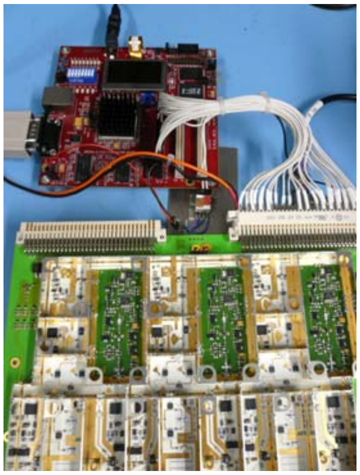


Fig. 13: Cavity BPM RFFE prototype electronics (screen cover removed). Right: Lab test setup, using a commercial FPGA board as provisional interface to the digital components on the RFFE (programmable PLLs etc.).

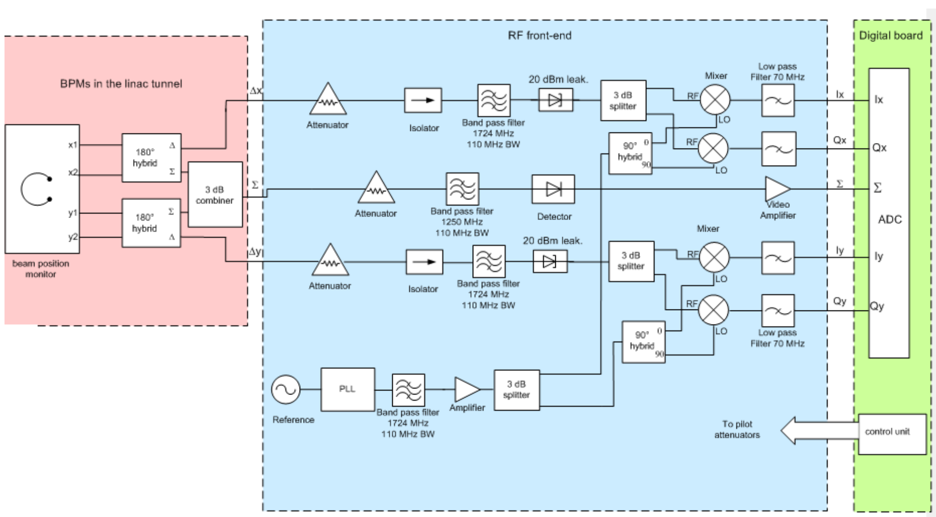
The design of the first RFFE prototype will however be altered for the next version in order to reduce the noise level and to adapt the electronics to the various test environments at which the system is planned to be tested. Noise (and therefore accuracy improvement) can be achieved using a lower noise IF amplification stage as a first priority and additionally by reducing input stage losses as a second priority, with an expected improvement of 4dB. Further noise reduction is also possible by using cables with less attenuation between pickup and RFFE. The present RFFE prototype supports two gain ranges, 0.1nC to 0.3nC and 0.3nC to 1nC, with the noise increasing nearly inversely with the charge in each range. Further noise reduction is therefore also possible by increasing the number of gain ranges.

It is also planned to include at least one more gain range in the next RFFE version by using a switch able microwave amplifier in the RFFE input stage that increases the sensitivity at low beam charge, and to have a variable gain stage in the IF section, in order to keep the ADC input signal as large as possible and thus fully exploit the ADC resolution over the full range of beam charges and cavity pickup signal level tolerances that are estimated to be as high as ±15% due to mechanical manufacturing tolerances. Furthermore, the next RFFE prototype will have on-board temperature sensors and a reduced sensitivity to external temperature variations.

4.2.1.2 Re-entrant BPM

(Author: Simon)

The signal processing of the re-entrant BPM uses a single stage down conversion to obtain Δ/Σ. As shown below, the difference Δ and sum Σ signals are obtained from a passive 4-ports 180° hybrid which will be installed in a box mounted at the side of the cryomodule. Each coupler is connected to each pair of opposite antennas and transmits the signals to the radio-frequency front end electronics via some 30 m long semi-rigid cables. The Radio-Frequency front-end (RFFE) electronics is based on a Printed Circuit Board (PCB) with surface mount components. Because of the low external quality factor, the single bunch response of the cavity has to be broadened before its acquisition.



Re-Entrant BPM signal processing electronics.

On the Δ channel, the rejection of the monopole mode, which does not depend on the beam position, proceeds in three steps:

- A mode symmetry based rejection with a hybrid coupler having an isolation better than 20 dB.
- A frequency domain rejection with a band pass filter centered at the dipole mode frequency.

- An in phase/quadrature-phase (I/Q) demodulation of the dipole mode signal. A reference signal, from the linac machine system is combined with a phase locked loop (PLL) to generate a local oscillator (LO) signal to the mixers around the dipole mode frequency.

The Σ signal, which is proportional to the beam charge, is measured by a direct detection using a Schottky diode detector. This signal is used to normalize the Δ signal. This normalization is made by the digital carrier board in order to provide a fast position interlock, with the possibility to read also the Δ and Σ signals as well as ADC raw data by the control system e.g. for diagnostics purposes.
On each channel, the gain is adjusted thanks to variable attenuators to avoid saturation from ADCs in different operating modes of the accelerator.
The RFFE output Σ signal and Δ I/Q IF signals Ix, Qx, Iy and Qy are delivered to ADC mezzanines on the digital carrier board (both provided by PSI) via differential 50ohms lines. These signals are pulses of around 40 ns length, with a nearly Gaussian shape and amplitudes up to +/- 1.25V.
The phase of the ADC sample clock will be adjusted to the input signals in order to get correct measurements of a pulsed signal and determine the peak values of the outputs signal from the RFFE.
More details on this electronics are described in ref. [3].

4.2.1.3 Button BPM

(Author: Keil)

In 2009, PSI reviewed, tested and improved a button BPM electronics prototype that has been developed by DESY. It employs time-domain multiplexing of the electrode signals (a.k.a. “Neumann principle”), low pass filtering and peak detection, followed by A/D conversion and post processing. Based on the results of these tests, a 2nd prototype is presently being constructed by PSI. Due to its simplicity and proven performance, the analogue part of this prototype will be based on low pass filtering and peak detection. A peak detector bypass with a pulse shaping filter will also support direct sampling. A block diagram of the PSI BPM electronics is shown in Fig. 14.

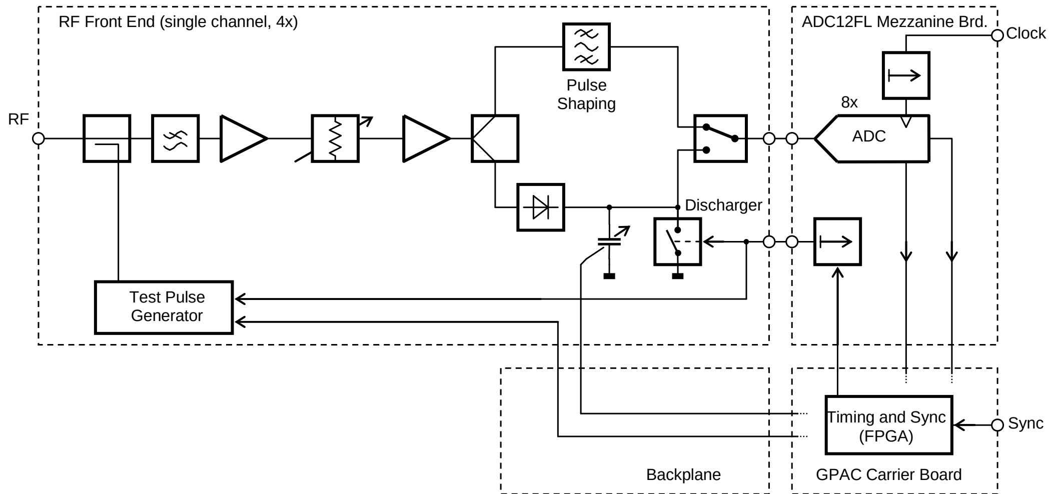


Fig. 14: Button BPM electronics concept.

The design contains four analogue channels, allowing processing all four electrode signals per pickup individually. However, the timing of signals and discharge pulser is fast enough to also enable multiplexing multiple electrode signals on the same analogue channel by an external TDM network (Neumann principle), thus allowing to compare experimentally the performance of both approaches. In front of the peak detector, the RF bandwidth is limited and the potentially interfering 1.3 GHz E-XFEL machine RF is suppressed. A variable attenuator adjusts the analogue gain depending on the beam charge. The balanced peak detector employs a biased microwave diode. To calibrate the nonlinearity and temperature drift of the diode peak detector, a test pulse generator is included. Making the peak detector's droop rate variable allows to operate in two modes: a) High droop rate prevents signal pile-up when turning off the discharger; b) low droop rate allows jitter-insensitive sampling but requires the discharger. For self triggering the BPM when machine timing is not known, e.g. during accelerator commissioning, mode a) can be used. For higher performance, mode b) is selected after aligning the discharger timing.
The first PSI prototype for the final button BPM RFFE is presently being designed. First tests are scheduled for the 2nd half of 2010, using a test pulser as well as triple button BPM pickup arrays at FLASH and the SwissFEL test injector to characterize the electronics.

4.2.2 ADC Mezzanine Boards

4.2.2.1 Cavity BPM ADC Mezzanine Board

(Author: Keil)

In 2009, a first prototype of the cavity BPM ADC mezzanine board has been designed and fabricated. Low noise and low channel to channel crosstalk on a relatively small board space were the main design challenges.

Key features:

- 6 Channel 16-bit low-noise ADC board; 160MSa/s

- Mezzanine module for digital back-end FPGA carrier board (GPAC)
- Selectable input ranges: 1.5Vpp and 2.25Vpp
- Phase shifting for each channel: 0...2250ps in 150ps steps
- Temperature and DC offset and gain measurement on board
- Differential ADC inputs and clock
- High reliability, suitable for high volume production

One important goal of the development is the production of a robust BPM system requiring low attention and minimal maintenance while operational. Therefore the development process focuses on achieving maximum robustness and performance. A considerable effort is required to minimize the impact of environmental changes and aging.

In order to meet the specifications of speed, precision and economy simultaneously, only the latest-technology analogue to digital converters can be used, with speed in the range of 150-200MSample/s and 16-bit precision. The first mezzanine prototype uses the LTC2209 16-bit ADC from Linear Technologies with a maximum sample rate of 160MSample/s and a parallel LVDS interface to the GPAC. The high-speed 500-pin mezzanine connector of the GPAC and its FPGAs can handle parallel ADC interfaces with 500MSample/s and more, therefore the ADC type can even be upgraded to future faster ADC versions once they become available.

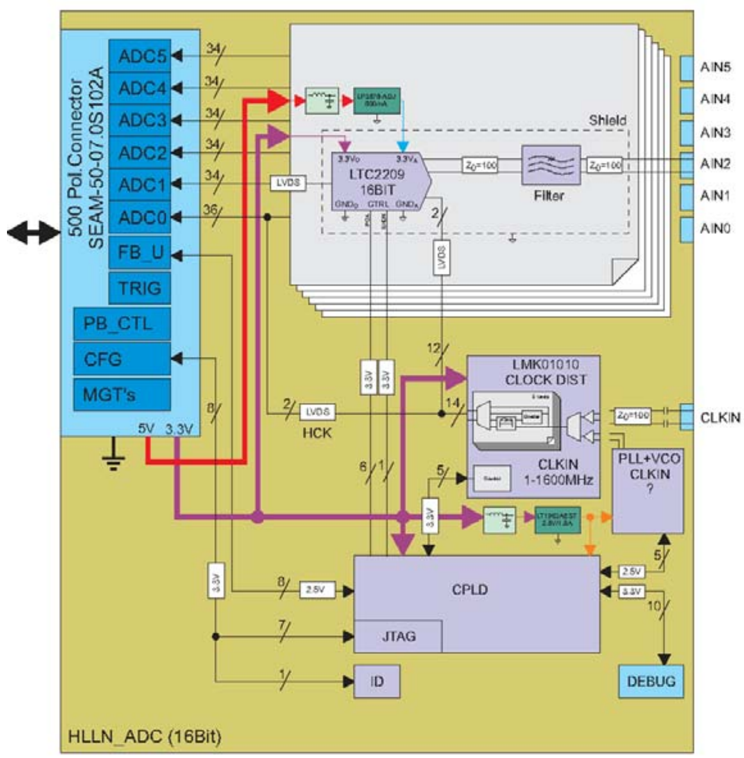


Fig. 15: Cavity BPM ADC mezzanine board block schematics.

The ADC mezzanine board has been successfully tested in combination with the cavity BPM RF-front-end, both in the lab and with a E-XFEL undulator cavity pickup installed for beam tests in the SLS linac [1].

4.2.2.2 Button BPM ADC Mezzanine Board

(Author: Keil)

The button BPM RFFE signals will be digitized by an ADC mezzanine, using same digital back-end (GPAC) board as the cavity BPM ADC mezzanine. The present prototype of the button BPM digitizer has 8 channels, thus allowing the individual sampling of the pickup electrode signals of two button BPMs with one mezzanine. The resolution of 12-bit (with >10 effective bits) allows to reach the desired position resolution, utilizing all available mezzanine IO pins. A maximum sample rate of 500Msps and a low ADC latency enable the control of the peak detector discharge circuit by real-time detection of beam signals in the BPM FPGA on the GPAC. Furthermore, the high sample rate allows the automated adjustment of the RFFE peak detector discharger timing based on an automated analysis of the sampled ADC waveforms in the FPGA. The wide ADC input bandwidth of more than one gigahertz allows for acquisition of input frequencies beyond the sampling rate. Particular attention has been paid to the ADC clock circuit: To facilitate testing of the button BPMs at various machines, the clock synthesizer can adapt to the synchronization signals of the following machines: E-XFEL, FLASH, SwissFEL, and SLS. This lead to the incorporation of a board crystal oscillator (for autonomous clocking), a phase-locked loop (for frequency multiplication), frequency dividers, and delay stages (for phase alignment).

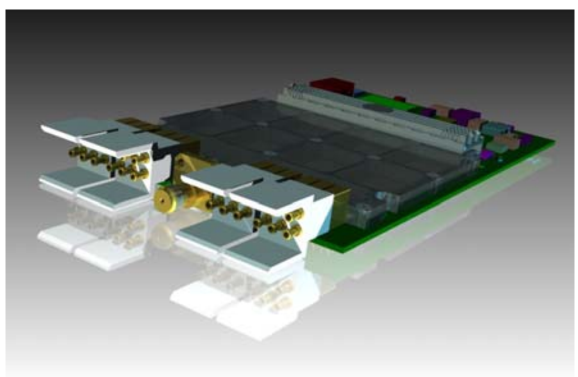


Fig. 16: 8-Channel 12-bit button BPM ADC mezzanine board

A first prototype of the ADC mezzanine has been designed, fabricated and successfully tested in the lab. The board has the same form factor as 6-channel 16-bit cavity BPM ADC mezzanine.

Key features:

- 8 Channel 12-bit ADC board; 500MSa/s
- Mezzanine module for digital back-end FPGA carrier board (GPAC)
- Input range: 2.45Vpp, differential
- Phase shifting for each channel: 0..2250ps in 150ps steps
- Temperature measurement on board
- Universal Clock Input stage: 1MHz...1.6GHz, selectable PLL, delays
- 4 Bidirectional LVDS channels on the front connector

4.2.3 Digital Back-End

(Author: Keil)

The Generic PSI ADC Carrier Board (GPAC) is a generic digital back-end for the different BPM types of the European X-ray FEL.

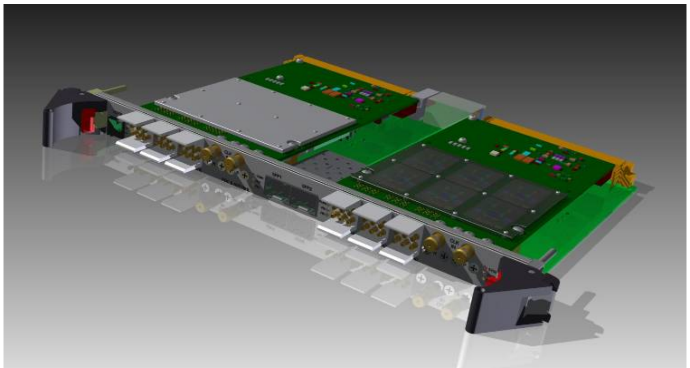


Fig. 17: Digital back-end (Generic PSI ADC Carrier "GPAC") of the E-XFEL BPM system, equipped with two undulator BPM ADC mezzanine modules.

In contrast to the carrier board for the Intra Bunchtrain Feedback System it is targeting high-volume measurement applications like BPMs. Thus no DSPs are on board. Due to cost optimization for large production quantities as well as relaxed performance requirements smaller Xilinx Virtex-5 LXT/FXT and low-cost Spartan FPGA types are used. This results in a less complex layer stack and overall design of the printed circuit board.

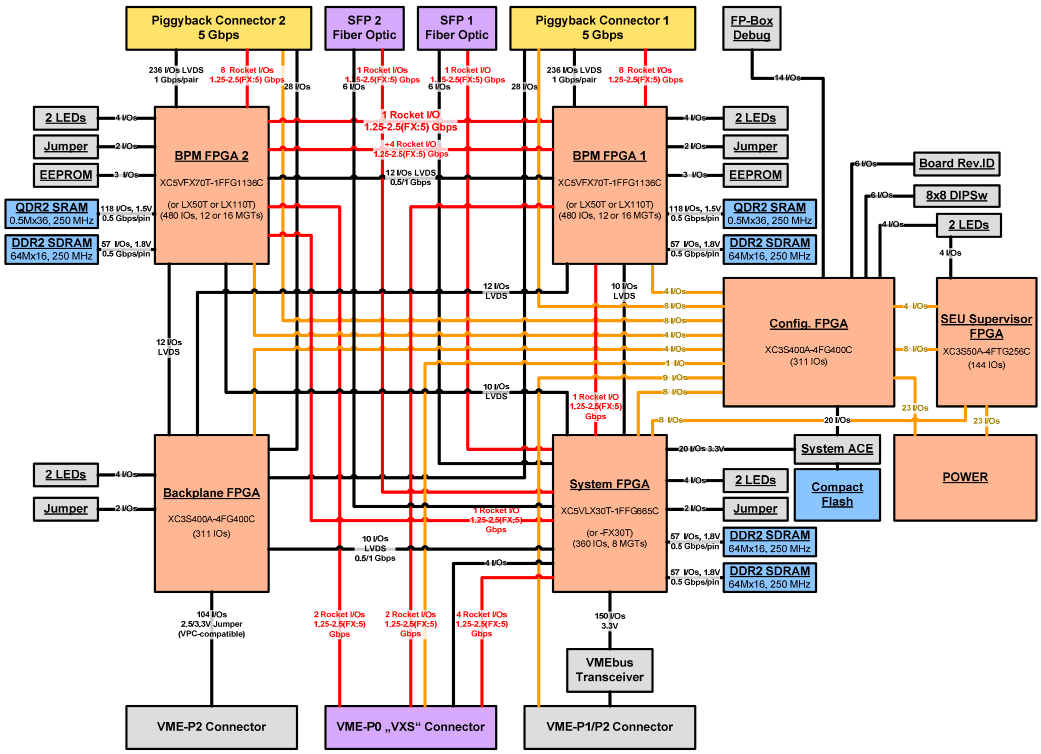


Fig. 18: Simplified schematics of the GPAC digital back-end board.

The block diagram of the GPAC is shown in Fig. 18. The tasks of the so-called "BPM FPGAs" include processing of the ADC data, calculation of the beam positions, periodic calibrations, manual or automatic adjustments of ADC clock delays, and storage of beam position waveforms as well as calibration data in external memories. Furthermore, these FPGAs control and adjust components in the RFFE like programmable attenuators, clock synthesis PLLs, DACs for offset adjustments etc. via low-speed serial links that are routed through the so-called "backplane FPGA" (a low-cost Spartan3 FPGA serving as a routing matrix) to the RFFEs.

The so-called "System FPGA" allows control system access of internal memories, registers and external RAMs of all FPGAs on the GPAC via multi-gigabit "Rocket IO" fiber optic links. These Rocket IO links are also used as maintenance interface or data exchange with other accelerator subsystems, like the transverse intra-bunchtrain feedback. The GPAC supports two Rocket IO links at the front panel, and up to 8 at the back side of the MBU, using a multi-gigabit connector at the GPAC backplane. All Rocket IOs interfaces use the SFP transceiver standard that allows flexible choice of physical layer, baud rate and protocol (the latter two can be selected via FPGA firmware). In addition, the GPAC also supports control system access via an optional low-cost VME64x or VXS interface, e.g. for beam tests of BPM electronics at VME-based accelerators at PSI or DESY.

External DRAMs for System and BPM FPGAs provide memory e.g. for embedded MicroBlaze or PowerPC processor program code. The DRAMs connected to the BPM FPGAs also allow long-term data logging e.g. of beam positions. The high-speed QDR2 SRAMs with their deterministic access timing (no refresh cycles needed) enable real-time storage of ADC raw data streams or access to calibration lookup tables that do not fit into the much smaller internal FPGA memory.

The GPAC boots the FPGA firmware and PowerPC software for System, Backplane and BPM FPGAs from a CompactFlash card that can be updated and modified remotely in the E-XFEL tunnel via the SFP based external interfaces. The CompactFlash may also serve as a disk drive for a Linux operating system running on the System FPGA to support remote maintenance and system diagnostics. The actual firmware and software boot process is handled by a smaller Spartan-3A FPGA ("Configuration FPGA") that loads its own firmware independently from an EEPROM, controls the power-up/-down sequence of numerous onboard voltage regulators, loads the firmware from the CompactFlash into the other FPGAs, and supervises power supply voltages and currents of the connected FPGAs.

During normal operation of the GPAC board, each FPGA is continuously performing a CRC check on its configuration bits, in order to prevent malfunction caused by bit flips due to single event upsets (SEUs) that may be induced by the radiation that occurs in the X-FEL due to beam loss of high-energy electronsbeam loss and related radiation background in the E-XFEL tunnel. Once a SEU is detected, the affected FPGA notifies the Configuration FPGA which then initiates the reconfiguration process of the affected FPGA depending on the actual board status. When the Configuration FPGA itself is affected by an SEU, another FPGA, the "SEU Supervisor FPGA" is taking over the control and performs a smooth reconfiguration of the Configuration FPGA, thus avoiding system operation interrupts. A compact maintenance connector on the GPAC front panel enables JTAG access to all FPGAs and also provides an additional RS232 serial port for lab tests and maintenance purposes.

4.2.4 Form Factor: Modular BPM Unit

(Author: Keil)
(Check: K. Rehlich, T.Hott)

The BPM hardware of the E-XFEL will be arranged in compact units called "MBU" (Modular BPM Unit). Each MBU consists of an RF-shielded housing that contains a power supply, fans, a GPAC with two ADC mezzanines, and either four button BPM RFFEs or two undulator or re-entrant RFFEs. In case of the undulator BPMs an active temperature stabilization scheme for the electronics will be applied in order to minimize the beam position drift and thus to fulfill the extremely challenging beam position measurement and stability requirements in the E-XFEL undulators. The MBU allows remote supervision of the power supplies, fans, temperatures and health status of the electronics modules for efficient remote diagnostics and system health monitoring of the BPM hardware in the E-XFEL tunnel that is not accessible during machine operation. Furthermore, the MBU will measure and regulate its overall power dissipation in order to minimize temperature variations in the accelerator tunnel.

GPAC and RFFEs are plugged onto a common backplane that provides power supply voltages as well as the required connectivity between the different modules. This backplane is a cost-efficient, application specific solution streamlined for reliability and low noise, with the functions needed for the safe and reliable operation of the BPM system. The undulator BPM electronics needs to be attached to the main RF frequency distribution of the accelerator in order to synthesize local oscillator frequencies for the IQ down-converters in the RFFEs that need to be synchronized to the bunch repetition rate and cavity pickup signals for highest performance.

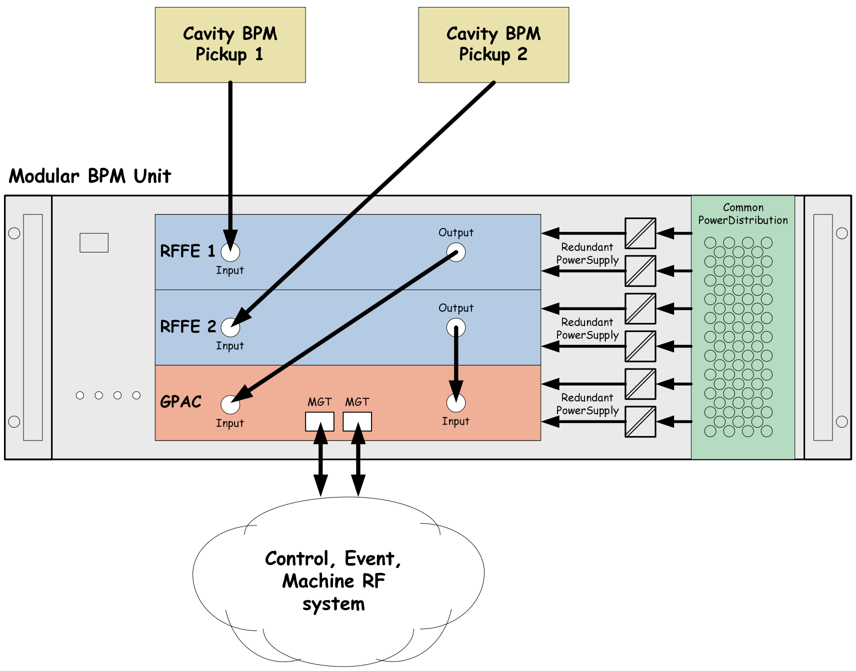


Fig. 19: Modular BPM unit "MBU" (simplified schematic).

Furthermore, all BPM electronics will receive bunch trigger and bunch train pre-trigger signals from the E-XFEL timing/event system via multi-gigabit Rocket-IO links or electrical signals (e.g. TTL) routed to the GPAC via the MBU backplane or the SFP front panel connectors. Furthermore, the MBU supports SFP fiber optics transceivers attached to the backplane (in addition to two transceivers at the GPAC front panel) in order to connect external accelerator subsystems like IBFB, low-level RF systems or X-ray BPMs to the GPAC via the multi-gigabit Rocket IO links of multi-gigabit backplane connector.

4.2.5 Additional Features of the BPM Electronics

4.2.5.1 Charge Information

(Author: Nölle/Keil)
(Check: Decking)

The BPM electronics will deliver a bunch by bunch charge signal. This signal will be deduced from the monopole modes of the cavity type BPMs or from the sum signal for the button type BPMs.

4.2.5.2 Interlock Signal in case of Beam Walk-off

(Author: Nölle/Keil)
(Check: Decking)

The BPM electronics will deliver a fast interlock signal, in case the beam exceeds some given threshold. The latency of this signal with respect to the beam will be less than <10µs. The RMS noise and drift of the position information to be used for the interlock will be higher than for the regular position signals due to the low latency, with an RMS noise and drift of <100µm for the cavity BPMs and <500µm for the button and re-entrant BPMs.

A MPS (interlock system) interface will be provided at the back side of the MBU, with the signal being controlled by the GPAC. The connector and signal type to be used needs to be specified to PSI by the MPS team.

4.3 Cabling of BPMs

(Nölle)
(Check: Hott)

Installation of the signal cables will be provided as a central service by the XFEL Company. The costs for the cables are charged to WP-17.

In general all cables have to be connected to the feedthroughs without any stress. Therefore, short light weight patch cables are used to well fixed patch panel. From this point the thicker low loss cables are used to bring the signal to the electronics racks. For internal cabling of the racks also patch panels and cables are used. Exceptions are the undulator and warm beamline cavity BPMs where flexible ¼'' cables directly connect the BPM pickups with the electronics in order to minimize reflections and achieve highest performance for the undulator BPM system.

The cabling of the BPM electronics must meet the requirements specified in ref. [2] where cable types, locations, signal properties and other requirements (e.g. max. length) are specified.

4.3.1 Cold BPM

(Nölle)
(Check: Decking, Rehlich, Hott)

The cold BPMs will be used in the Linac sections only. The electronics will be installed in shielded rack areas inside the tunnel. These racks will also be used by other customers. The machine infrastructure foresees such rack area at the end of each RF station. In these areas the cables of 4 BPMs, two from modules upstream and two from modules downstream, will be collected. This gives a maximum cable length of about 30 m for the BPMs in this section.

The fibre connections to the control system will be provided by WP17.

4.3.1.1 Cabling inside the Cryostat

(Nölle/Knaack)
(Check: Jensch)

The cables of the cold BPMs will be produced together with the HOM absorber and probe cables by WP06 (paid by WP17). Installation will be done by WP03 (module assembly). The production will follow the same procedures for aging of the cables, as specified for all cables inside the module. A double shielded cable (Suhner K03252D-06) with corresponding connectors, qualified by WP03, will be used. The length of the cable will be roughly 2.5 m.

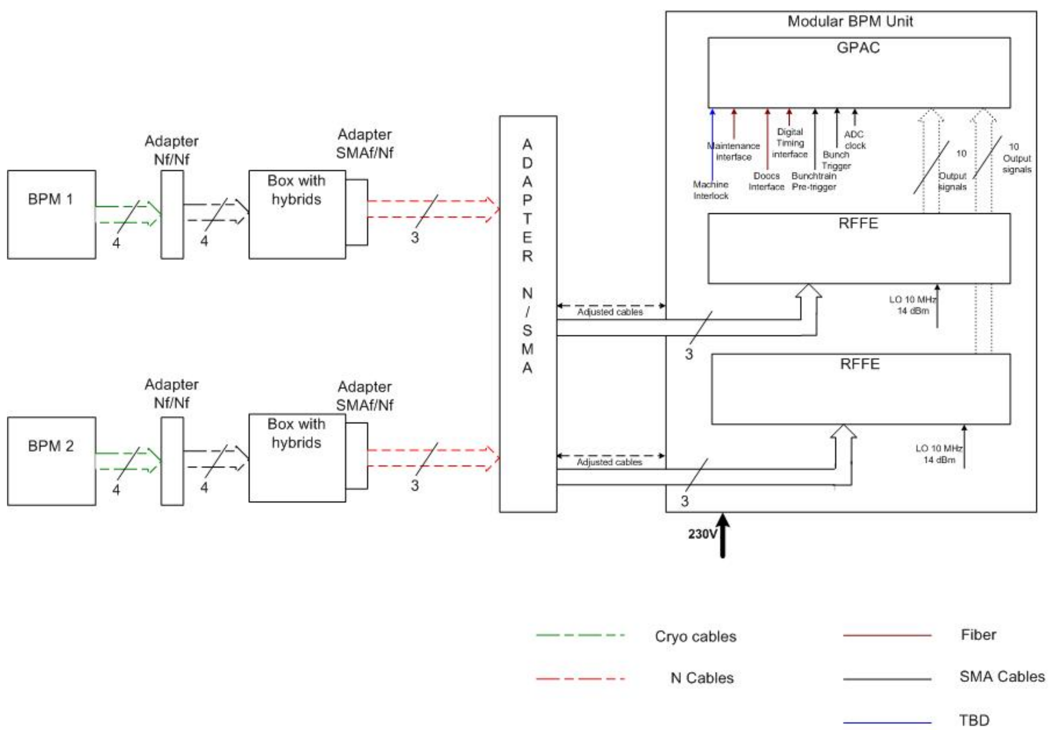
The cables and connectors are charged to WP17, the flange in the module is charged to WP03.

For the re-entrant BPM, a SMA Jack-Jack adaptor (Rosenberger 32K10A-K00L5) is inserted between feedthroughs and cables. The dielectric of this adaptor is PEEK and material of center and outer contacts is gold plated CuBe.

More detailed information can be found in [7].**Error! No bookmark name given.**

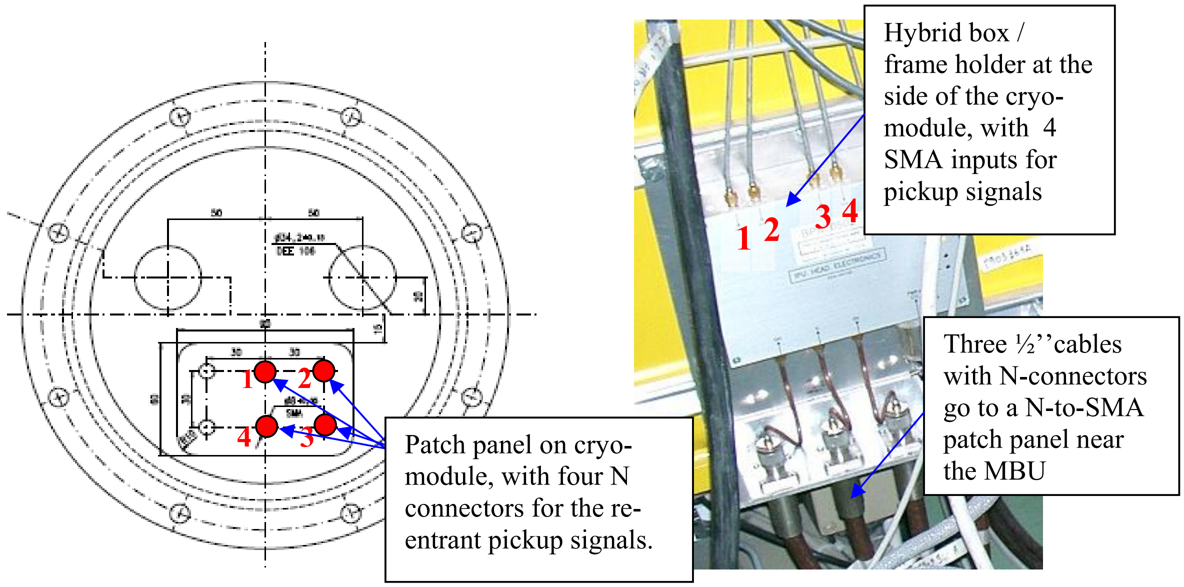
4.3.1.2 Cabling of Re-entrant Cavity BPM

A general cabling of the re-entrant BPM is presented below:



A patch panel with N connectors is installed on the cryomodule. Short cables from this patch panel go to an angle bracket where a box with hybrids, which generates three signals (one sum and two difference signals) from the four pickup signals, is mounted at the side of the cryomodule. From this angle bracket, via SMA-to-N connectors, 3 cables ½” with N connectors at both sides go to the 19’’ rack where the MBU is installed. Those cables are connected to a patch panel near to the MBU with other adapters N/SMA, to avoid a force on the MBU front panel. From this patch panel to the re-entrant RFFE in the MBU three ¼’’ SMA cables are required.

Connection between the reentrant RFFE and the ADC board is with SMA connectors on the RFFE side and differential Radiall connectors on the ADC side.



4.3.1.3 Cabling of Standard BPMs

(Nölle/Keil)
(Check: Rehlich, Hott)

The cables from the BPMs will be laid such that they end in a sheltered rack area inside the tunnel. The maximum length, length differences and other properties of these cables (to be provided by DESY) must meet the requirements specified in ref. [2] .The cables from up to 4 BPMs have to be collected at the location of a BPM unit.

The fibre connections to the control system will be provided by WP17.

4.3.1.4 Cabling of Cavity BPMs: Beam Transfer Line Type

(Nölle/Keil)
(Check: Rehlich, Hott)

The cables from the BPMs will be laid such that they end in a sheltered rack area inside the tunnel. The cable length should not exceed 10 m. The cables from up to 2 BPMs have to be collected at the location of a BPM unit. The cable will be provided by PSI. See ref. [2] for cable properties and requirements.

The fibre connections to the control system will be provided by WP17.

4.3.1.5 Cabling of Cavity BPMs: Undulator Type

(Autor: Nölle/Keil)
(Check: Negodin, Pflüger)

The cables from the BPMs will be laid such that they end in an electronic rack area in between to undulators. The cable length should not exceed 6 m. The cables from up to

2 BPMs have to be collected at the location of a BPM unit. The cable will be provided by PSI. See ref. [2] for cable properties and requirements.

The fibre connections to the control system will be provided by WP17.

4.4 Interfaces of the BPM System

4.4.1 Mechanical

(Nölle/Vilcins)

This section describes the interfaces to the machine infrastructure and other systems.

4.4.1.1 Vacuum System

(Nölle/Vilcins)
(Check: Lilje)

The specification of the vacuum requirements for the entire XFEL is published by the vacuum work packages:

- http://edmsdirect.desy.de/edmsdirect/baseline.jsp?edmsid=*1383041
- Vakuum 005/2008, General DESY UHV Guidelines for Vacuumcomponents
- N. Mildner et al.,Specifications for the Vacuum Sections of the European X FEL, current draft, 2.1 / Mar. 7, 2010
- MVS und ZM, Qualitätssicherung bei der Entwicklung und Fertigung vonVakuumkammern, 11/2009

The BPM mechanics has to be built compliant to these documents.

All vacuum components need to pass a review by the vacuum group in charge. This review is part of the PPR.

4.4.1.2 Particle Cleanliness of the BPM

(Nölle/Vilcins)
(Check: Matheiesen, Lilje, Lederer)

All cold BPMs have to be particle free according to ISO4 (clean room class 10).

The BPMs in the injector, the bunch compressors and up to 20 m after the cold LINAC have to be cleaned to fulfil ISO5 (clean room class 100).

Remark: Both types of the 3.3 GHz cavity BPMs are not suited for wet cleaning. They shall be cleaned by pump and purge. This procedure should be acceptable due to the low number of items in the particle free sections of the machine.

4.4.1.2.1 Accelerator Modules

(Nölle/Vilcins)
(Check: Matheisen/Jensch)

All cold BPMs have to be particle free according to ISO4 (clean room class 10).

WP-17 provides the cleaning of the BPM bodies and the feedthroughs prior to the assembly to the magnet in the cleanroom.

Details on the cleaning and mounting process have to be finalized. Prototype assemblies have shown that suitable procedures are known. DESY will provide the clean room infrastructure (MKS, MVS) and the access for the cleaning of the BPMs. WP09 will provide the material and tooling for the assembly of the BPM in the module string.

4.4.1.2.2 Particle Free Sections (Gun 2 Main Linac, plus 20 m after the LINAC)

(Nölle/Vilcins)
(Check: Lederer)

The button BPMs in these sections have to be particle clean according to clean room class 100.

WP-17 will provide the BPM bodies to WP-19 for cleaning in the DESY clean room facilities (MVS). Cleaning will be done by WP-19. The feedthroughs are cleaned separately by WP-17, and are mounted by WP-17 in the DESY clean room infrastructure. A final cleaning step by blowing Nitrogen and a particle count will be done by WP-17.

4.4.1.2.3 Non Particle Clean Sections: Beam Transport from Collimator to Dump

(Nölle/Vilcins)
(Check: Lederer)

In these sections no requirements on particle cleanliness hold anymore. This part of the machine starts 20 m after last module of the main LINAC.

4.4.1.3 Support and Alignment

(Author: Nölle/Vilcins)
(Check: Prenting/Meyners/Mildner/Pflüger)

Support and Alignment issues are different for different parts of the machine.

4.4.1.3.1 BPMs in the Cryo Modules (Cold BPMs)

(Nölle/Vilcins/(Kleen/Bandelmann))

Fig. 20: Picture of a part of the string of the PXFEL3 prototype cryo module. It shows a button BPM assembled between the gate valve and the cold quadrupole.

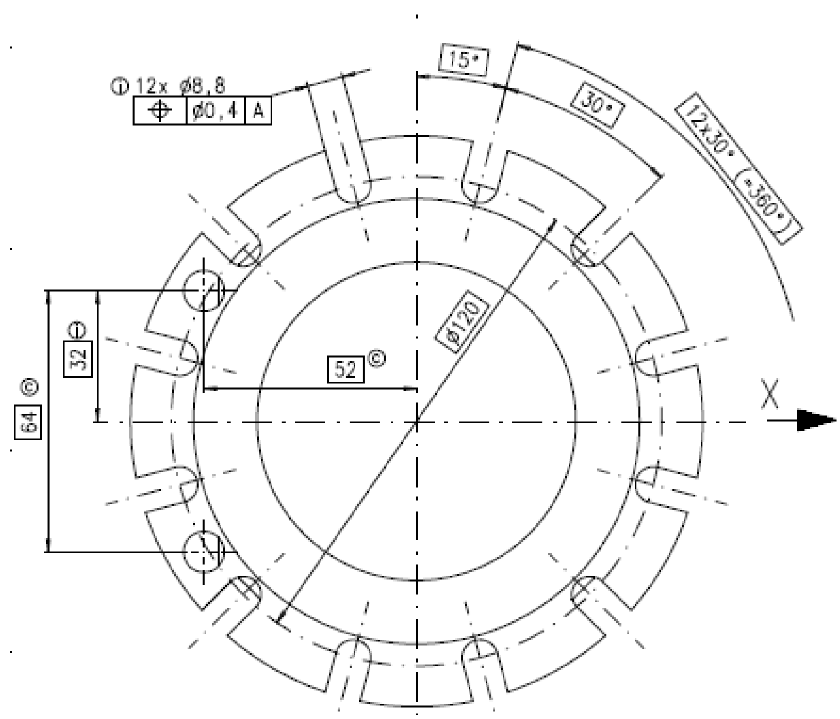


Fig. 21: View to the flange o the cold BPM. On the left hand side, one can see the two pinholes for the dowel pins for precise alignment of BPM and quadrupole. A more detailed drawing can be provided on request.

The precision of the alignment of the cold BPMs to the cold quadrupole is guaranteed by precise production of both devices. Using the basic hole/basis shaft principle the mechanical axis of the BPM and quadrupole will be matched to each other.

WP-17 provides all BPMs with the corresponding hole in the cavity flange. The dowel pins will be provided and mounted to the magnets by WP-11. All required screws, the sealings and also the tooling for the assembly are not provided by WP-17.

Details of the fitting of BPM and quadrupole can be found the design drawing (EDMS 910385)

4.4.1.3.2 BPMs in the Warm Beam Transfer Lines

(Author: Nölle/Vilcins)
(Check: Prenting/Meyners/Lilje)

For the XFEL the alignment tolerances of the vacuum system is not determined by the BPMs, but by the precision required to mount the special type of XFEL flange. Therefore, the girder system designed for the low energy parts of the machine fits to the alignment requirements of the BPM. In this part of the machine no further alignment marks are foreseen on the BPMs
In the high energy part of the machine, the density of components is smaller, so that girders will not be used. Currently, standard units are defined, consisting of quadrupole, BPM, steerer and a vacuum pump. Such a unit will also be assembled based on fabrication tolerances without special alignment marks on the BPM. Therefore no alignment marks are foreseen for the BPMs in the high energy and non particle free part of the machine.

The movements of the support structure at the BPM locations, integrated to the 0.01 Hz scale must not exceed ¼ of the BPM resolution, averaged of the bunch train.

4.4.1.3.2.1 Exception: Cavity BPMs: Beam Transfer Line

(Author: Nölle/Vilcins)
(Check: Prenting/Meyners)

The cavity BPMs of the beam transfer line type will get alignment marks, independent of their location in the machine. They have to be installed on adjustable supports. These supports have to provide precise alignment not only of the roll angle but also on the pitch and yaw angles. The latter is required to reduce the undesired beam angle signal component of the position cavity to a level that allows the electronics to reach the desired overall BPM performance.

4.4.1.3.3 BPMs in the Undulator Intersections

(Author: Nölle/Vilcins)
(Check: Prenting//Pflüger)

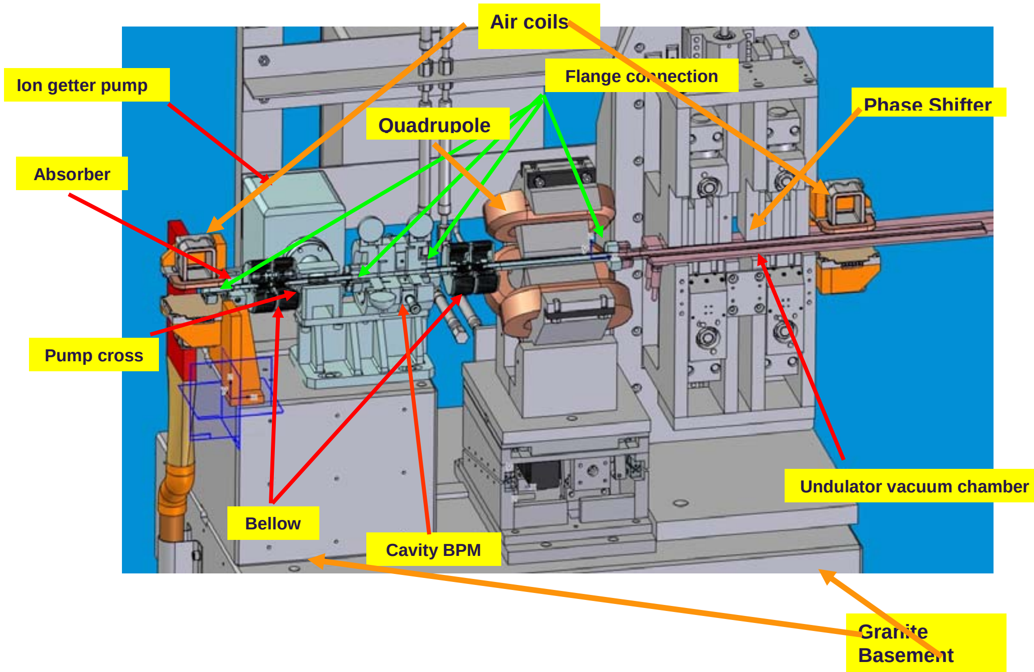


Fig. 22: 3D Overview of a standard undulator intersection.

In the space between the single undulator segments so called undulator intersections will be installed. They consist of a phase shifter, a quadrupole, a BPM and some vacuum components. Due to the high accuracy on the orbit position in the undulator cavity BPMs are used in this place. They will be fixed rigidly to the granite support plate of the intersection. Alignment marks on the BPM serve as a reference for the position of the entire section.

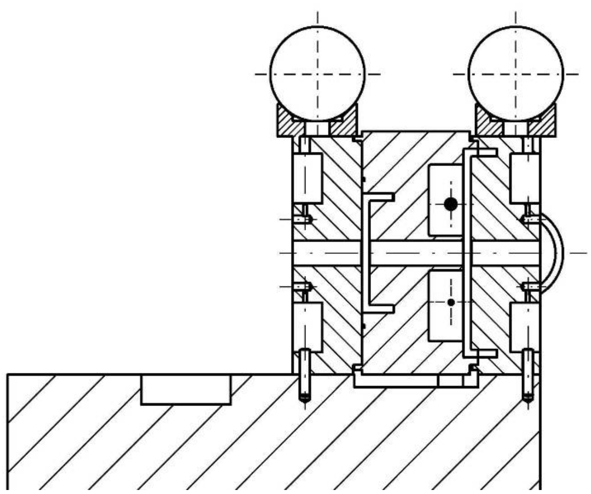


Fig. 23: Cut through a BPM and the holder for the undulator intersection. One can see two alignment marks on top of the BPM, an additional mark is located on height of the beam pipe towards the observer.

Before start up with beam the intersections will be aligned by the alignment group to a precision of +/- 200 μm (RMS). This initial alignment has to be improved by beam based alignment of the BPMs in the undulator section, resulting in a final alignment precision of 50 µm (RMS). This will require a relative readjustment of the intersection after the beam based alignment procedure. The need for an iterative adjustment or periodical adjustment cannot be excluded.

The movements of the support structure at the BPM locations, integrated to the 0.01 Hz scale must not exceed ¼ of the BPM resolution, averaged of the bunch train.

In order to ensure that mechanical movement due to temperature variations are within levels not disturbing the beam based alignment procedures, the temperature variations in the undulator tunnels must not exceed 0.2 °C peak-peak.

4.4.2 Electronics

(Nölle/Keil)

The interfaces of the PSI BPM electronics to other accelerator subsystems as well as the requirements of this electronics with respect to the tunnel infrastructure shall be compliant to ref. [2] which is provided by PSI/CEA as an attachment to this document.

The electronic racks are considered to be infrastructure of the machine, and are provided by the XFEL Company. Installation of the BPM units into these racks will be done by WP-17.

4.4.2.1 Control System Interface

(Author: Keil)
(Check: Rehlich)

The interface to the control system is provided via one of two SFP fibre optics Rocket-IO transceivers on the front panel that are connected to the so-called System FPGA of the digital back-end carrier board. The System FPGA supports control system access of internal memories, registers and external RAMs of all FPGAs on the GPAC. The physical layer of the control system interface is specified in ref. [2]. The communication protocol is determined by the FPGA firmware. It is planned to use a packet-based protocol that supports single word and burst read and write cycles to the above described memory and registers of the digital BPM back-end, with the back-end as slave and the external control system hardware as master. The packets will contain address, data (for write cycles), 32-bit CRC checksum and status bits (e.g. read/write flag, number of data words for burst cycles, etc.). Data integrity will be provided using a simple handshake mechanism.

The hardware and cabling required to read out the BPM units (MBU) is provided by the control system. No costs for this interface are foreseen in the BPM project.

4.4.2.2 Timing

(Author: Keil)
(Check: Rehlich)

Each BPM electronics requires a bunchtrain pre-trigger signal, a bunch trigger, and an ADC clock signal, to be provided as electrical signals at the back side of the MBU. The bunch trigger should only occur for bunches with nominal (i.e. non-zero) charge. Presently, SMA connectors are foreseen for these trigger and clock signals. PSI is flexible to use other connectors if desired by WP28 (e.g. a multi-pin connector), provided the respective connector and signal scheme is specified to PSI in due time.

In addition to these electrical timing signals, the MBU will receive the 1.3GBaud multi-gigabit optical timing system signal of the E-XFEL timing system via an SFP connector at the back side of the MBU. The physical layer of the timing interface of the BPM system is described in ref. [2]. The protocol of this optical timing system link needs to be specified to PSI in order to implement a suitable receiver module in the System FPGA firmware on the GPAC.

The control system should send the GPAC information about the expected bunch charge and bunch pattern as well as the desired BPM electronics trigger mode (external trigger or self-trigger) at least 5ms before the first bunch of the respective bunch train. In self-trigger mode, the bunch trigger will be ignored, and the first bunch with a charge above and adjustable level after the bunchtrain pre-trigger will be treated as bunch no. 1 of the train. In both trigger modes, ADC clock and bunchtrain pre-trigger are required. The delay of the bunchtrain pre-trigger should be adjustable at least in 100ns steps from 0-1ms before the 1st bunch of the train arrives at the respective BPM pickup, with a nominal delay value of 10µs. In internal trigger mode, the exact delay of the pre-trigger may be anywhere between 10µs and 50µs and the ADC clock phase may be arbitrary but needs to be constant with respect to the bunch arrival time. See ref. [2] for jitter, drift and pulse shape specifications.

After the bunch train has passed and the GPAC has processed the BPM data, the beam positions and charges can be read by the control system 10ms after the bunch train has passed.

4.4.2.3 Reference Frequencies

(Author: Keil, Lipka)
(Check: Schlarb)

4.4.2.3.1 Cavity BPMs

Each cavity BPM electronics unit requires an external highly stable RF reference clock, to be provided at the location of each electronics module. In order to allow tests at different accelerators (FLASH, SwissFEL test injector, E-XFEL) without changes of the clock synthesis unit, the electronics will accept reference frequencies in the range of 210 to 220 MHz. With this setup the electronics can be matched to the E-XFEL master frequency of 216.67 MHz. Details on level, drift and phase noise can be found in table 3-4 in ref. [2].

4.4.2.3.2 Reentrant Cavity BPMs

Each cavity BPM electronics unit requires an external highly stable RF reference clock, to be provided at the location of each electronics module. Details on level, drift and phase noise can be found in table 3-5 in ref. [2].

4.4.3 Control System Software

(Nölle/Decking/Keil)

The required firmware and on-board software[7] of the BPM electronics is provided by WP-17 (PSI). This includes also the interface and Linux server for maintenance access.

WP-28 provides the required software to access the BPM data, this includes the BPM server with the interface to the PSI BPM unit, as well as some basic software to display the data of a single BPM and overview panels to display the orbit in the machine. For the technical and beam commissioning, the XFEL control system has to provide all functionality and infrastructure required to perform the relevant commissioning tasks, including:

- Synchronized readout, and archiving of all relevant BPM position, charge, ADC and relevant diagnostics data for each bunch train
- Visualisation of the BPM information, either as
    - X, Y Position of the bunches along the bunch train
    - Orbit display of the Positions of bunch n along the machine (n to be chosen by the operator)
    - Orbit Display of the “averaged obit” over the bunchtrain
- Read/write access to all relevant BPM system parameters and settings
- Network access and infrastructure that allows to access the maintenance interface of the BPMs (using a 1000-base-X Ethernet SFP transceiver of the BPM electronics) in order to update BPM system firmware/software and reboot or diagnose BPM systems remotely, even from PSI and CEA.
- DOOCs also provides an API to access BPM data by MATLAB or C code.

5 Schedule and Project Plan

(Keil/Nölle/Simon)
(Check: Decking, Stakeholders)

From the MSPE plan of WP17 the following major milestones can be extracted for the BPM system:

01.07.2010	Conceptual design review BPM mechanics
01.10.2010	Production readiness review for the Cold BPM mechanics
01.10.2010	Production readiness review for the Undulator and Precision BPM mechanics
01.01.2011	Production readiness review for the Standard Button BPM mechanics
01.07.2011	Cold BPM pickups ready for module pre-series
01.10.2011	First Undulator BPM pickups ready for intersection assembly
01.01.2012	Warm BPM pickups ready for injector beam transfer line installation in clean room
01.01.2012	Warm BPMs (non particle clean) ready for vacuum installation
01.01.2012	First cold BPM pickups ready for module assembly

[7] Server software on the MBU processor unit.

01.04.2012	Technical design review (Buton BPM electronics))
01.04.2012	Cavity BPM pickup: beam line type ready for installation
01.07.2012	Production readiness review (PRR) the electronics pre-series, to be used for the injector
01.10.2012	Technical design review (Cavity BPM electronics)
01.01.2013	Production readiness review (PRR) for the main series of BPM electronics
01.03.2013	Injector BPM electronics delivered to XFEL
15.09.2013	Injector BPM installation and technical commissioning completed
30.09.2013	**First beam in injector**
01.01.2014	LINAC/undulator BPM electronics delivered to XFEL
15.07.2014	LINAC/undulator BPM installation and technical commissioning completed
31.07.2014	**First beam main LINAC**
31.12.2014	**First lasing SASE1 at 0.2nm**
01.07.2015	Beam commissioning completed, BPM specifications reached

6 Safety Analysis

(Keil/Nölle)

The mechanical parts of the BPMs are vacuum vessels with flanged, braised or soldered connections without any movable part. Materials used for these vessels are stainless steel, titanium, some copper plating. All materials used for braising and welding are compatible with the requirements of UHV.

The feedthroughs used for the BPS use ceramics as insulator and thus are ROHS free.

The BPM pickups have no movable parts, except of manual alignment possibilities in case of the beam transfer line type of the cavity BPM. Therefore, there is no danger for maintenance personnel. Standards concerning safety of the mechanics have to be specified by the E-XFEL company.

All cables will be halogen free. Heavy and stiff long distance cables will end on patch panels on both sides. Therefore, stress relief is provided minimizing the risk of damaging UHV feedthroughs and electronics boards.

The electronics has be ROHS free and compliant to standards to be defined by the E-XFEL company.

BPM signals are low power and low duty cycle, and there is no electrical risk for maintenance personnel. The BPM electronics uses a commercially available main power supply to convert the 230V AC mains to 12V and 5V DC voltages that are used by the different electronics modules. The 230V main power supply is installed inside the BPM electronics unit in a way that eliminates any risk of electrical shock. Fans inside the BPM electronics will be protected against accidental touching. The BPM electronics will be ROHS compliant.

7 Quality Assurance Plan

7.1 General

(Keil/Nölle)

Describe QA processes here

- Regular Collaboration Meetings with reports from the different tasks
- Discussion with external experts
- Reviews with external experts
- Beam tests with prototypes at FLASH and the PSI Injector facility
- Pre-series productions, performance and reliability tests in advance to procurement
- Selection of companies by quality audits and/or an "experience database"

7.2 Risk

- Failure in the series production of the cold feedthroughs: ceramics breaks during cryo tests. This can result in a delay of 6-12 months.

7.3 Mechanics

(Nölle)

Development of the BPM mechanics is based on many years of experience. The following quality assurance procedures will be applied:

- Careful prototyping of all items in internal workshops and industry.
- Beam tests
- 100% component tests for critical parts (feedthroughs)
- Pre-series productions in advance to procurement
- Acceptance tests
- Review processes (PPR for each individual BPM type)
- Selection of companies by quality audits and an "experience database"

7.4 Electronics

(Author: Keil)

The different modules of the BPM electronics are designed at PSI by an experienced group of BPM electronics experts that perform mutual, detailed reviews of circuit schematics and PCB layouts in order to eliminate any errors as early as possible in the staged design process. After the definition of specifications and requirements, a first prototype is designed, fabricated and tested to verify that the chosen conceptual design approach and technology allows reaching the final specifications on time and on budget.
The following design iteration will then result in a system with the final form factor, using fabrication technologies that are already suitable for large-scale series production. Furthermore, this design phase should either already reach the final specifications or come at least so close that the following pre-series design is guaranteed to fulfill all requirements of the final series version, with the possible exception of minor refinements and optimizations e.g. of series-production aspects (production time, costs, duration of tuning/adjustments etc.).

In addition to extensive lab and beam tests at PSI and DESY as well as detailed design reviews and quality control in all design stages, this approach should guarantee that the final series version fulfills all requirements with respect to performance, efficient series production, costs, schedule and maintainability. At each prototype stage, lab and beam tests of the electronics are performed.

The production quality for the series production is ensured by tight quality control of prototypes, pre-series and series versions. All PCBs are electrically tested, including impedance measurements of PCB traces where necessary. The soldering quality of the PCBs is sample-tested and optimized using X-ray analysis of critical soldering joints. Only companies that have demonstrated their ability to manufacture the electronics modules with the desired high quality are used for series production ("quality audits").

In addition, all prototypes, pre-series and series electronics modules will be tested using an automated test system developed by PSI. Digital inputs and outputs as well as memories are tested using various test patterns in a loopback configuration. Furthermore, the full functionality of each BPM electronics unit will be tested by feeding pickup-like signals into the RFFEs and checking if the beam position and charge calculated by the BPM electronics matches the expectations with respect to value, noise level and other relevant properties. Long-term beam tests of prototype and pre-series electronics modules at PSI and DESY accelerators (SwissFEL test injector, SLS linac, FLASH) will also be used to verify the desired performance under realistic environmental conditions.

Unique, remotly readable series numbers of electronics modules (e.g. RF front-ends, ADC mezzanines, GPACs) will allow to identify each module in the E-XFEL tunnel, allow monitoring its performance, correlating it with automated test measurements and related calibration data, and tracking the manufacturer and production date and lot.

8 References

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