PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Volker Schlott   on behalf of the E-XFEL project team at PSI

Swiss In-Kind Contribution to the European XFEL Project – Beam Position Monitor System and Intra-Bunchtrain Feedback

Swiss In-Kind Contributions to the European XFEL Project

BPM System and Intra Bunchtrain Feedback

- Short Introduction to European X-FEL Project
- IK-Contributions, Project Partners and Work Distribution
- Status and Update on BPM System Components
  - Pick-Ups
  - Electronics
- Status and Update on Intra Bunchtrain Feedback

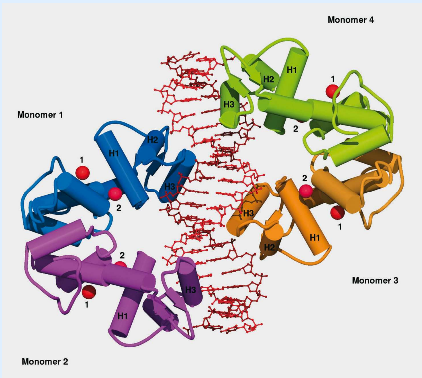
Introduction to the European XFEL Project – Scientific Impact

European XFEL is the 1st large scale XFEL user facility in Europe aiming for…:

- … hard X-rays at 1 Ångström wavelength (12 keV photon energy)
- … ultra-short photon pulses of < 100 femto-seconds
- … highest peak brilliances > 10^{13} photons per pulse (several tens of GW)

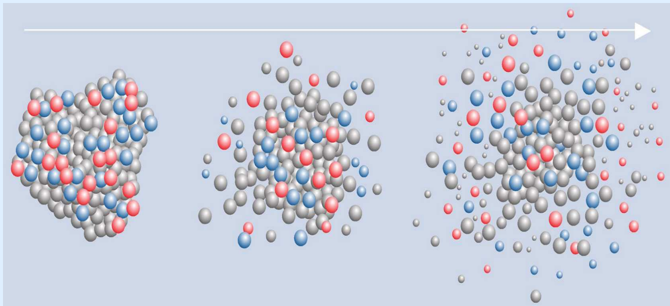
Some Examples of Research Areas

Protein-Crystallography



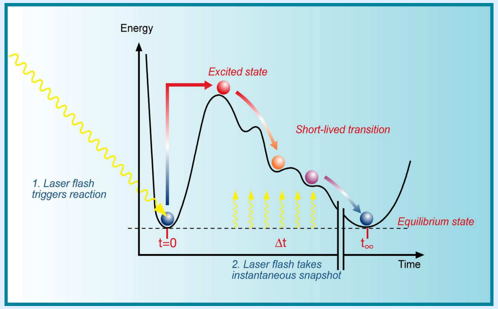
using the high number of photons to investigate large, multi-protein DNA complexes, which are hard to crystallize

Explosion of Bio-Molecules



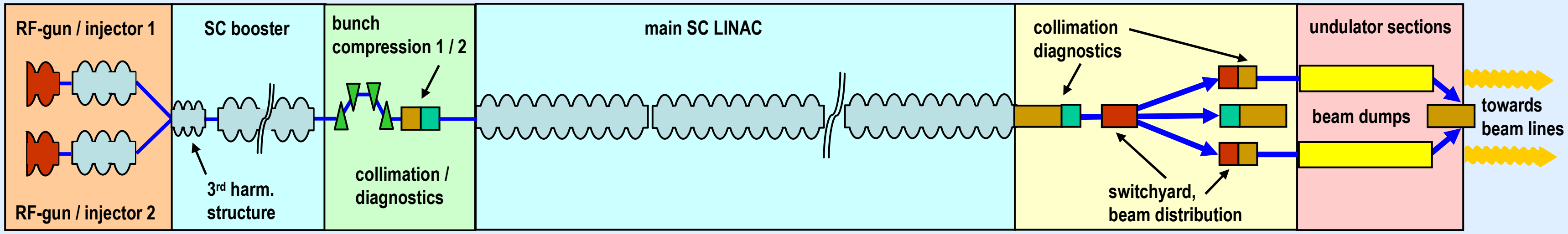
using the high number of photons and the ultra-short X-ray pulses to decipher the 3D structure of biomolecules and the functional processes at the molecular level

„Femto-Chemisty“



using ultra-short X-ray pulses and precise timing to „film“ chemical reactions and mechamisms at the atomic level with pump-probe techniques

Introduction to the European XFEL Project – The Facility



A 1.7 km long superconducting linear accelerator, provides:

… an electron beam energy of 17.5 GeV

… long bunchtrains of up to 3000 electron bunches with 200 ns bunch to bunch spacing at 10 Hz repetition rate

… flexible beam distribution to several undulator lines for X-ray generation (0.1 – 6 nm)

700 m of undulators (3 SASE & 2 spontaneous radiators) divided in 5 beamlines

… requiring **micron level electron beam stability** for stable SASE operation

Two user end-stations per beamline requiring:

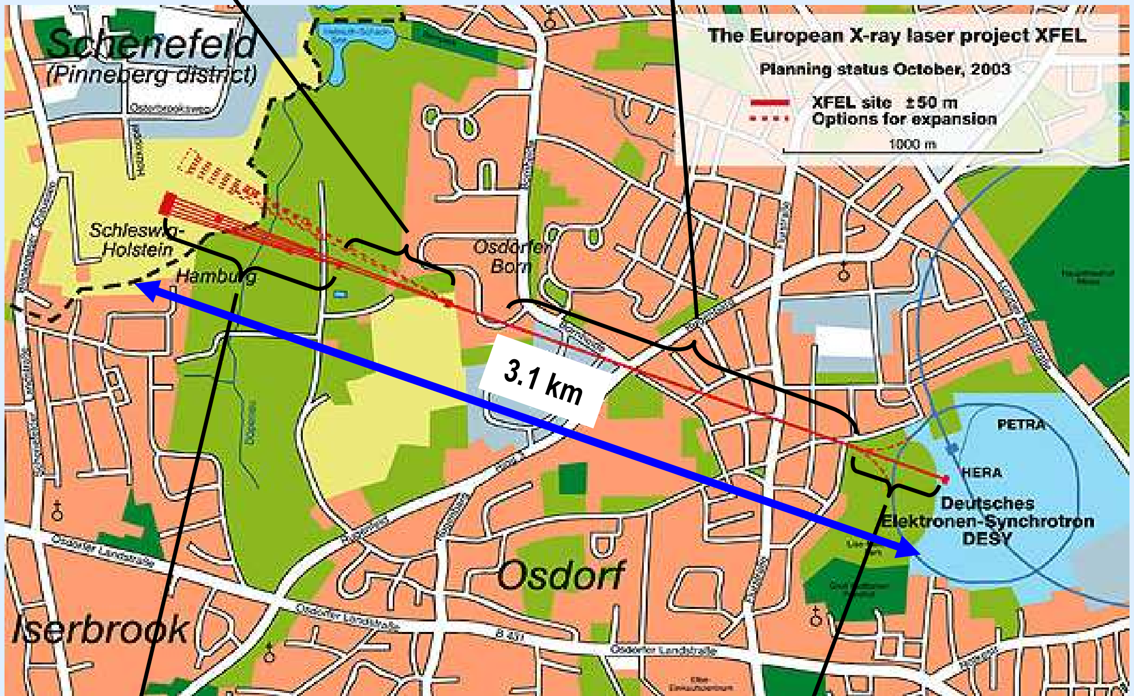
… newly developed X-ray optics for withstanding high heat load

… newly developed detector systems allowing ultra-fast data acquisition

Introduction to the European XFEL Project – The Site

beam distribution and undulator sections

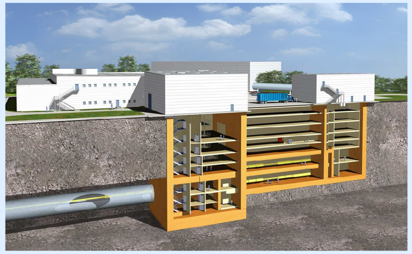
20 GeV main LINAC



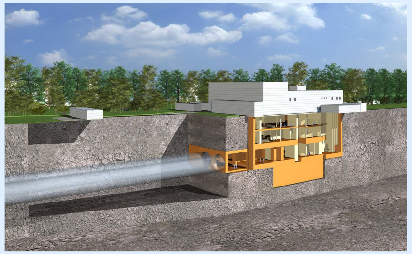
beam line front ends and experimental stations

500 MeV injector complex at DESY site

Injector Building @ DESY



Beam Distribution Building



Main Experimental Building

Introduction to the European XFEL Project – Site & Status

Injector Building @ DESY Bahrenfels

Beam Distribution @ Osdorfer Born

Experimental Building @ Schenefeld

The European XFEL Accelerator Tunnel - Construction Work has been finished by 01. March 2012)

Introduction to the European XFEL Project – Organization

- **14 countries** support the construction and operation of the European XFEL
- the realization of the project is organized through a company: **E-XFEL GmbH**
- the project is structured in **50 work packages** combined into **six groups**
- the partner countries typically contribute **in cash (~ 33%)** and **„in-kind“ (~ 67 %)**
- the principle of **„in-kind contributions“** assures…:

  … that the project profits strongly from the expertise of the accelerator labs and science groups in the partner countries

  … that the partner countries profit from the technical developments and scientific opportunities of the project

- **PSI contributes** „in-kind“ and in collaboration in 3 major fields of expertise:

  … electron **beam position monitors (BPM)** and **fast beam orbit stabilization (IBFB)**
  … **pixel detector** development
  … contributions to various **scientific experiments** (not presented in this talk)

Stability Requirements for Stable Accelerator and SASE Operation

→ single bunch position resolution in accelerator and transfer lines…: 50 µm *

→ single bunch position resolution in undulator sections: 1 µm *

→ high resolution BPMs in transfer lines and IBFB BPMs: 1 µm *

* for extended bunch charge range: 20 pC to 1 nC

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

[1] warm button: flanged version & welded version (where flanged is too long)

BPM System and Intra Bunchtrain Feedback – Deliverables

BPM System (E-XFEL WP 17) consists of…:

… pick-ups: cold and warm buttons for *„standard BPMs"*
cold re-entrant and warm dual resonator cavities for *„high resolution BPMs"*

… electronics: BPM type specific RF front ends for signal conditioning
only two types of A/D converters for digitization
generic processor boards for data processing and transmission
mainly generic firmware & software for system integration

Intra Bunchtrain Feedback System (E-XFEL WP 16) consists of…:

… high resolution BPMs: for bunch-by-bunch beam position measurement

… stripline kickers: for high bandwidth (intra bunchtrain) correction of beam offsets

… electronics and FW: for high speed data processing, data transfer and application of correction algorithms

… beam optics: for efficient integration of IBFB in EXFEL accelerator lattice

Work Distribution between Project Partners

modular BPM system with common “generic“ digital back end and software / firmware

PAUL SCHERRER INSTITUT

→ overall BPM and IBFB system design and lead of BPM collaboration
→ BPM electronics development and fabrication
→ BPM firmware / software development and control system integration
→ IBFB system design, simulations and beam optics optimization
→ IBFB electronics, kicker concept and amplifier development
→ IBFB correction algorithms and control system integration
→ BPM system and IBFB commissioning

DESY

→ BPM pick-up development and fabrication
→ IBFB integration in E-XFEL accelerator lattice
→ IBFB stripline kicker fabrication
→ BPM and IBFB infrastructure, installation and integration in E-XFEL facility

cea

→ cold “re-entrant BPM“ pick-up design and fabrication
→ “re-entrant BPM“ RF front end design, fabrication and commissioning

The Project Teams and Main Competences

- Boris Keil → Project Leader
- Markus Stadler → RF-Engineer
- Daniel Treyer → RF-Engineer
- Markus Roggli → HW-Engineer
- Robin Ditter → Technician
- Martin Rohrer → Mech. Engineer
- Goran Marinkovic → FPGA-Engineer
- Waldemar Koprek → FPGA-Engineer
- Raphael Baldinger → Technician
- Carl Beard → Physicist
- Hisham Kamal Sayed → Physicist
- Volker Schlott → IK Coordinator

and strong support from PSI Administration and Infrastructure Departments

- Dirk Nölle → WP-17 Leader
- Silke Vilcins → Mech. Engineer
- Maike Siemens → Mech. Engineer
- Dirk Lipka → Physicist
- Winnie Decking → WP-16 Leader

and strong support from DESY Accelerator and Infrastructure Departments

- Claire Simon → Electrical Engineer
- Pascal Contrepois → Mech. Engineer

and strong support from CEA Accelerator and Infrastructure Departments

Standard BPM Pick-Ups – Cold and Warm Buttons (DESY contribution)

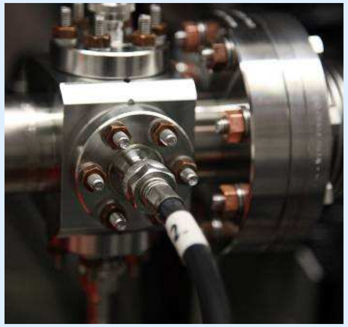
Cold Button BPM Pick-Ups

- 78 mm beam aperture
- signal level and spectrum match simulations and electronics requirements
- production readiness review passed
- qualification process: pre-series BPM blocks different companies
- next step: series order of feedthroughs

Warm Button BPM Pick-Ups

BPM Block and Feedthrough

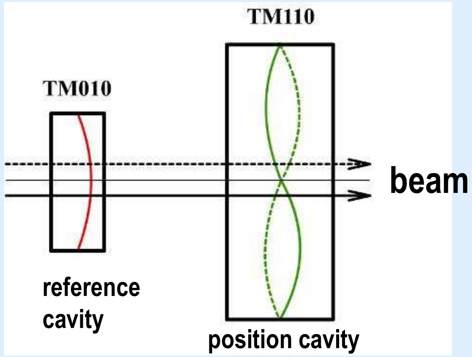
BPM Installation in FLASH



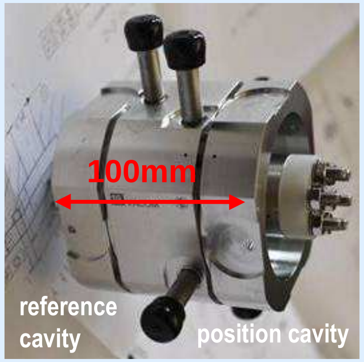
- 40.5 mm beam aperture
- beam tests with prototypes at FLASH and PSI
- production readiness review in preparation
- qualification process: contacts with companies
- performance: position resolution 3x better than cold BPMs at low charges (aperture 2x, button size 1.5x)

High Resolution BPM Pick-Ups – Dual Resonator Cavity (DESY contribution)

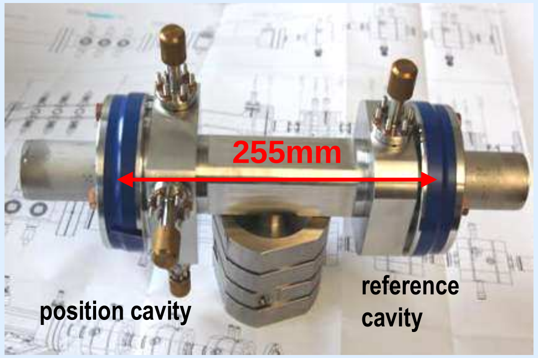
Cavity BPM Design Principle



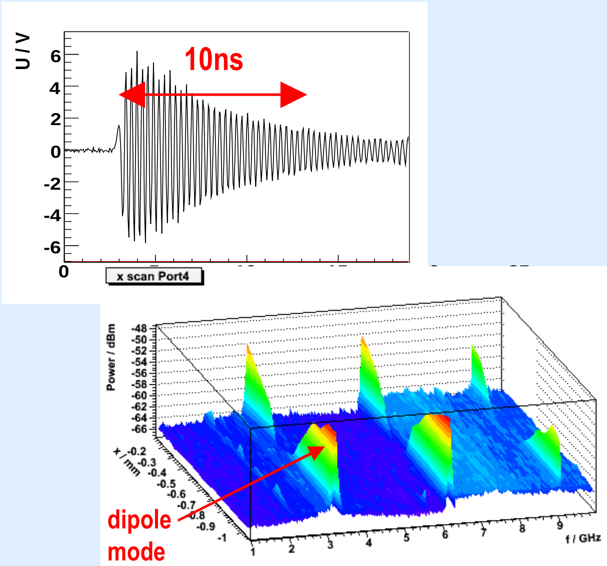
Undulator Cavity BPM Prototype



Transfer Line Cavity BPM Prototype



Beam Tests at FLASH



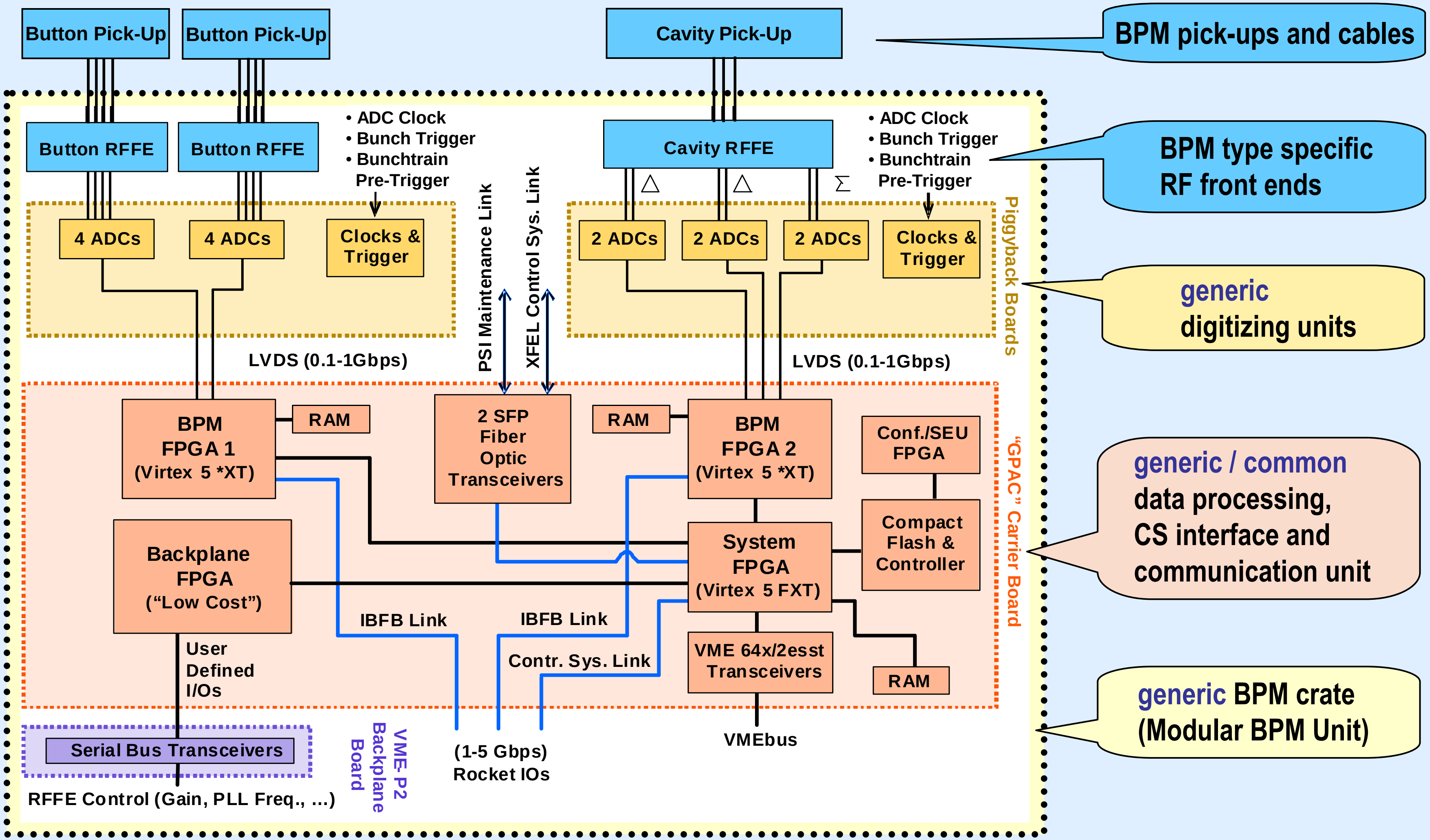
Design Considerations and Status

- 10 mm beam aperture for undulator cavity BPM
- 40.5 mm beam aperture for transfer line cavity BPM
- common resonance frequency at 3.3 GHz → same electronics
- „low Q“ design to allow 200 ns bunch spacing

- prototypes installed in FLASH and SwissFEL Test Injector
- lab and beam measurements agree with simulations

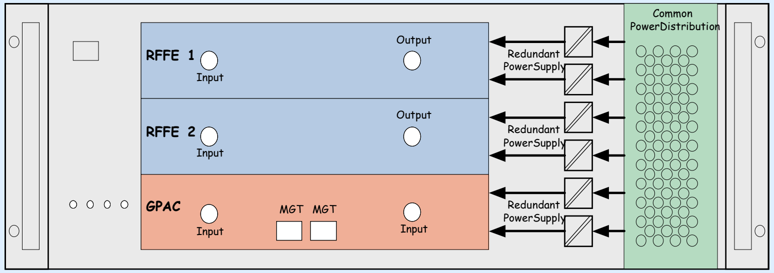
- qualification process: pre-series of cavity body and cavity body „ok“ from different companies
- production readiness review passed → start series production

BPM Electronics – Modular Concept for all BPM Types (PSI Contribution)

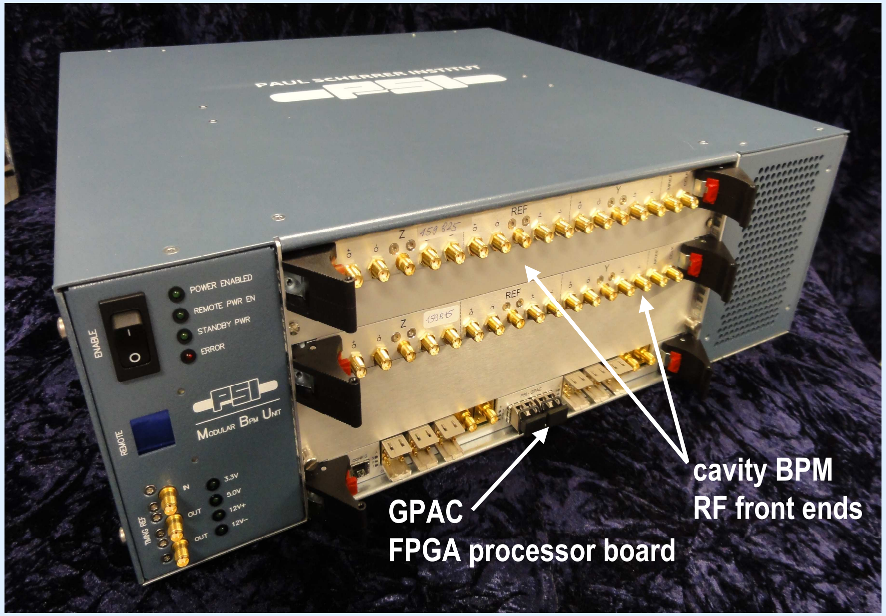


BPM Electronics – Modular BPM Unit (PSI Contribution)

MBU Schematic Layout



MBU Prototype (fully assembled for two undulator cavity BPMs)

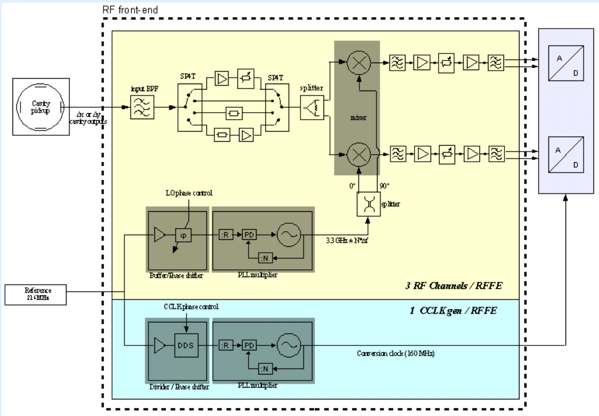


Design Considerations and Status

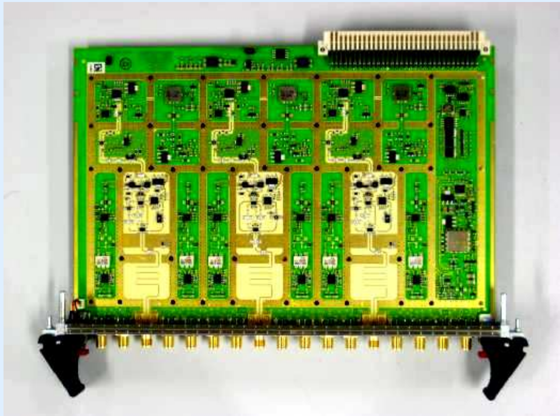
- 19“ housing including
  power supply, fans, temperature control…
- contains: 4 button BPM RF front ends or
  2 cavity BPM RF front ends
  1 common digital back end FPGA processor board (GPAC)
  2 ADC mezzanine boards
- prototypes fabricated → MBU used for beam tests
- next step: finish production readiness review

BPM Electronics – Undulator Cavity BPM RF Front End (PSI Contribution)

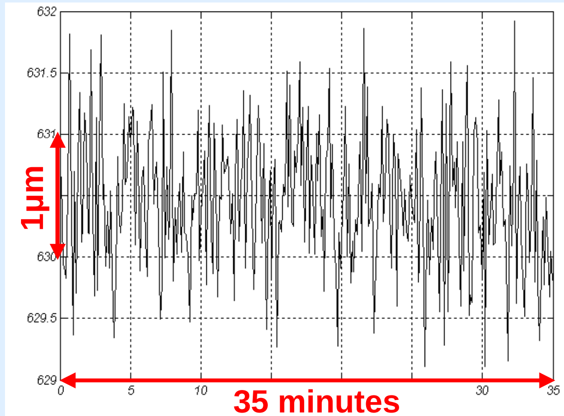
Schematic of Undulator Cavity BPM RFFE



Undulator Cavity BPM RFFE Prototype Board



Performance Tests with Beam at PSI

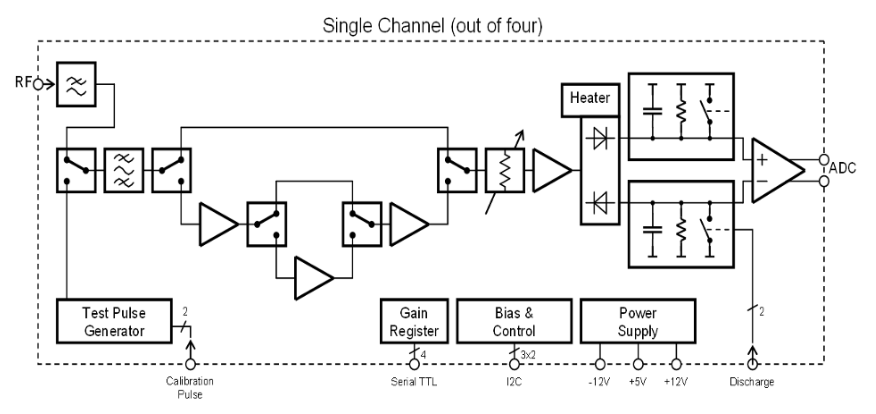


Design Considerations and Status

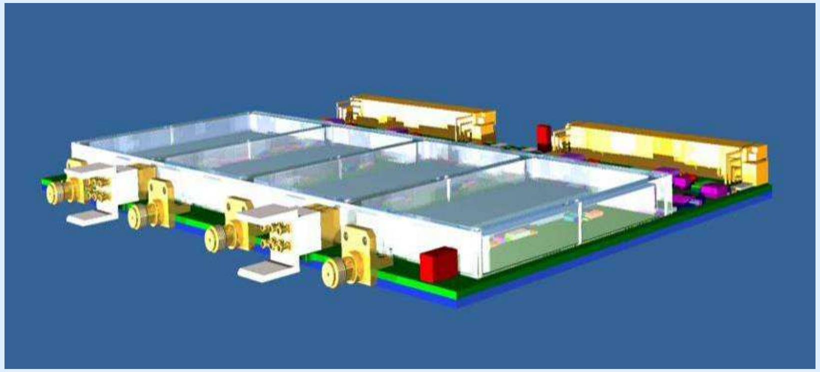
- IQ demodulation of 3.3 GHz cavity pick-up signal to baseband
- 4 gain ranges (> 20 dB) to cover all E-XFEL operation modes (1 nC – 20 pC)
- 3 programmable LOs (phase and frequency) and on-board ADC clock synthesis
- 1st version (2010) → 0.35 – 0.75 µm RMS noise @ 0.1 – 1 nC
- 2nd version (2011) → active temperature stabilization, solid RF shielding, more gain ranges…
- next steps: lab and beam tests at FLASH and SwissFEL Test Injector ongoing
  final cavity RFFE version by end of 2012
  production readiness review and CFT for series production in 2013

E-XFEL BPM Electronics – Button BPM RF Front Ends

Schematic of Button BPM RFFE (single channel)



Button BPM RFFE Electronics Board Concept



Design Considerations and Status

Button RFFE

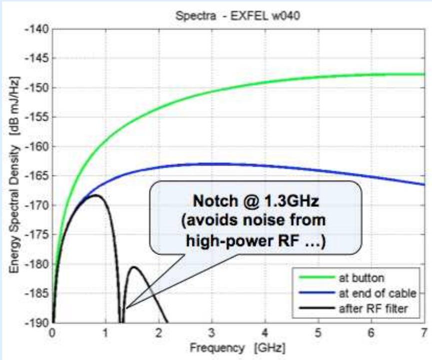
→ input filtering (bandpass and 1.3 GHz notch) avoids noise from high power RF and stretches button pick-up signal

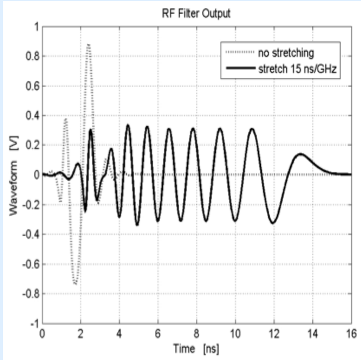
→ variable gain stage (> 40 dB) and online calibration pulser

→ peak detection with hold capacitor

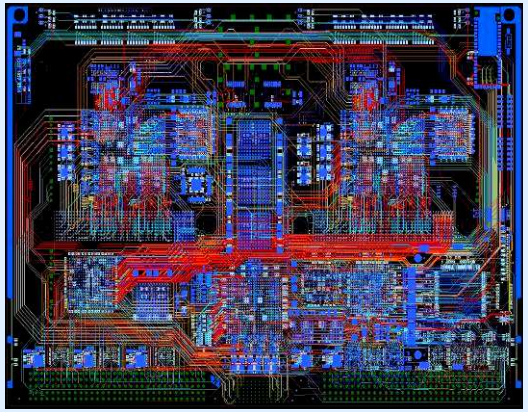
→ PCB layout ready, prototype in fabrication, beam tests early 2012

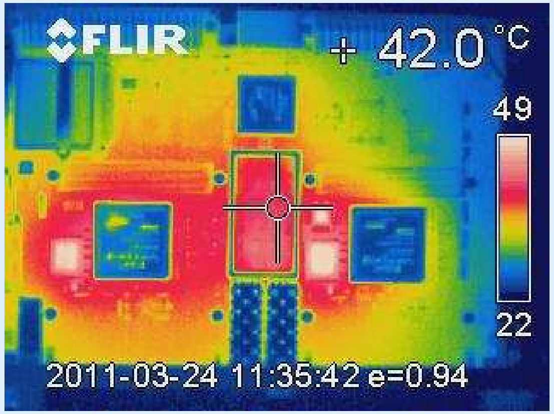
Button BPM RFFE Input Filtering





BPM Electronics – Digital Back End: GPAC FPGA Board (PSI Contribution)

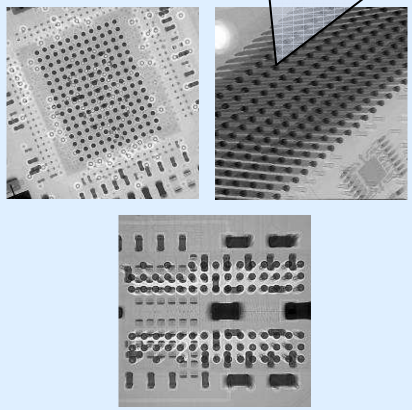




Design Considerations and Status

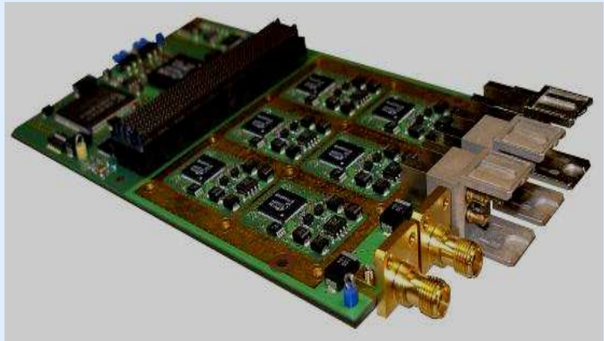
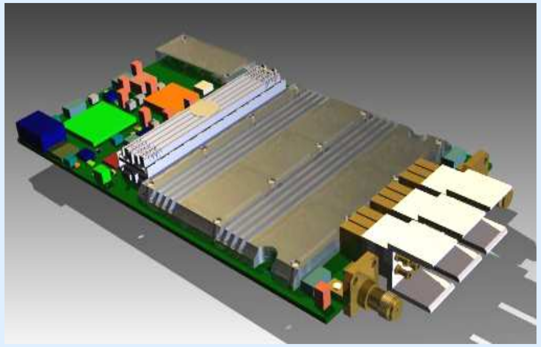
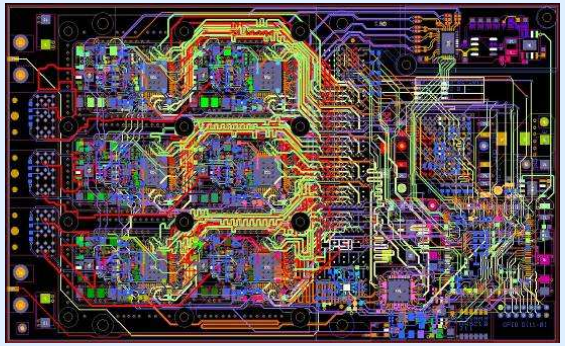
- common FPGA-based processor board for all BPM types
  - → allows the use of standardized ADC mezzanies
  - → allows the use of standardized FPGA firmware
  - → single and standardized interface to E-XFEL control system
- first prototypes mid 2010 → only few faults found and fixed
  - → extensive test runs were successful
  - → present focus on firmware / software
- next step: production readiness review

X-ray quality control (RAMs, connector)

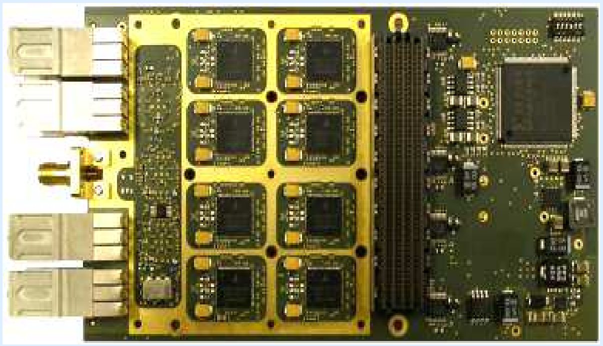
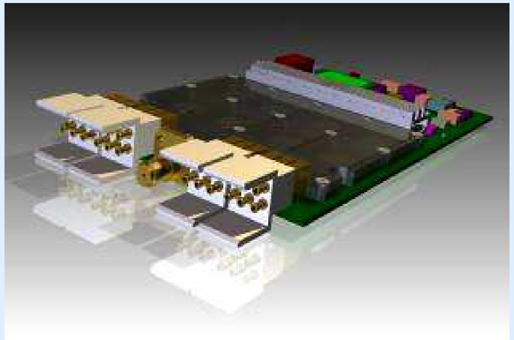
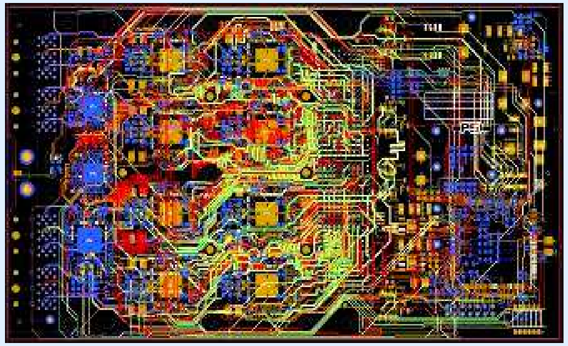


BPM Electronics – Cavity & Button BPM ADC Mezzanines (PSI Contribution)

Cavity BPMs: 6-channel, 16-bit, 160MSamples/s → fabrication and performance tests "ok"

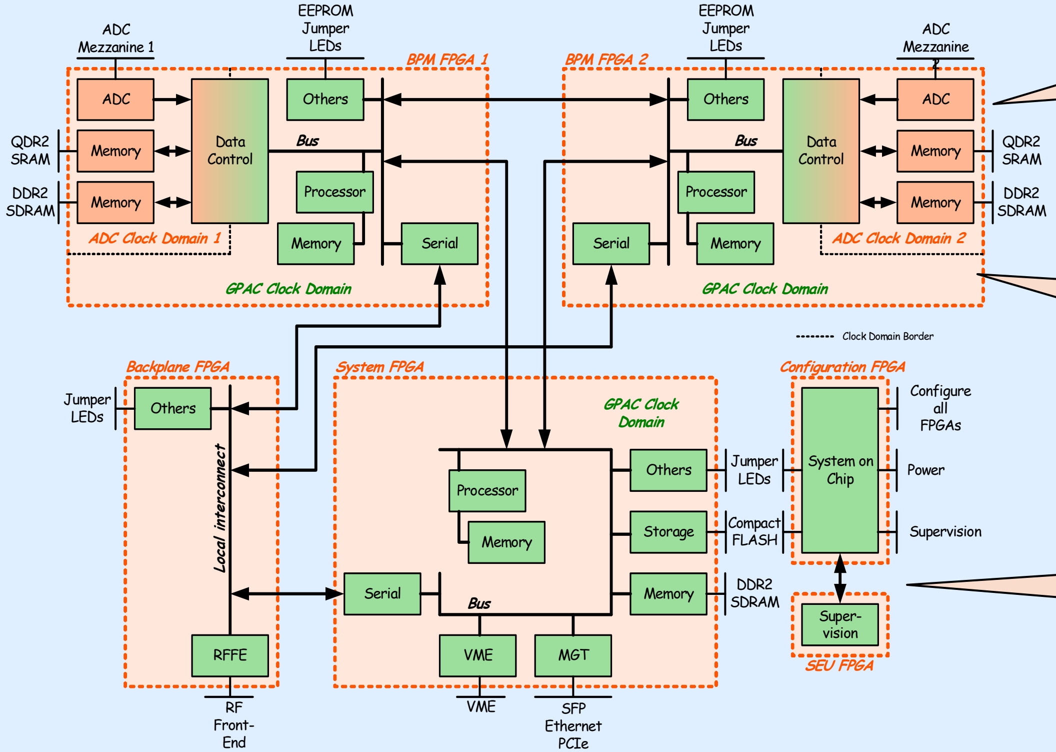




Button BPMs: 8-channel, 12-bit, 500MSamples/s → fabrication and performance tests "ok"

Both ADC types: differential coax inputs, 150 ps step clock phase adjustment per ADC.

BPM Electronics – FPGA Firmware / Software (PSI Contribution)



Cavity BPM: storage of ADC waveforms in RAM working at 2GByte/s for complete bunchtrains

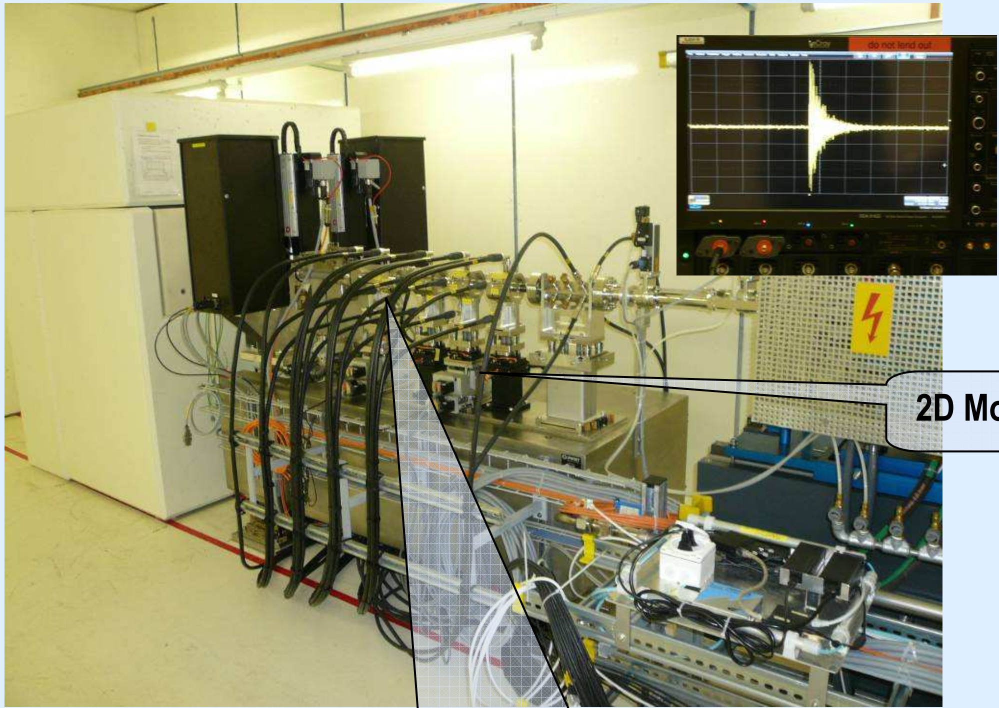
Data Processing: beam position calculation in FPGA to be implemented (so far off-line on PC)

CS Interface: partially implemented will be used for long-term beam tests at FLASH and PSI

Design Considerations and Status

- modular FPGA firmware / software design provides…:
  - → data processing and CS interface for all BPM types (cavity BPMs already implemented)
  - → saves firmware / software development time (MP) and eases future upgrades

E-XFEL & SwissFEL Cavity BPM Test Area @ SwissFEL Test Injector



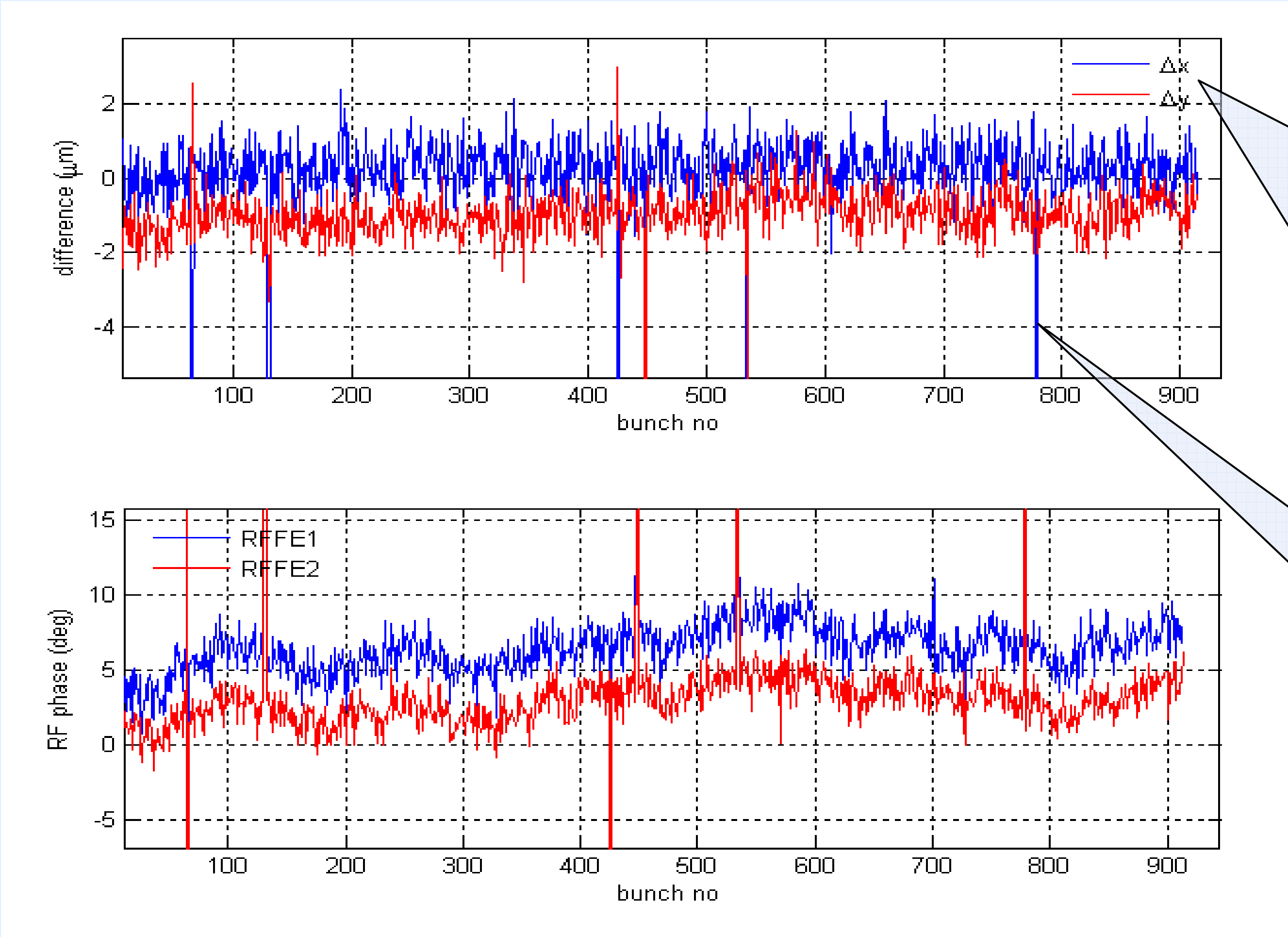
2D Mover

Three E-XFEL undulator cavity PU & one beamline cavity PU

E-XFEL cavity BPM electronics for 2 BPMs (works in MBU and standard VME crates)

Status: beam time for multi-BPM noise correlation after February 2012 shutdown

E-XFEL Cavity BPM Electronics: Latest Tests @ SLS Injector LINAC



Signal of one cavity BPM pickup split to two electronics:
~300nm noise
~500nm drift.
Drift will be reduced (phase feedback, I/Q imbalance calibration, ...)

Parasitic test during SLS operation: SLS top-up injection caused spikes (arrival time switched by N*2ns)

IBFB – E-XFEL Beam Stability Considerations (PSI and DESY Contributions)

Slow and medium term motions (< 30 μm)

- ground settlement, temperature drifts
- girder / magnet excitation by ground motion, cooling water, He flow…

Fast motions (few 100 μm)

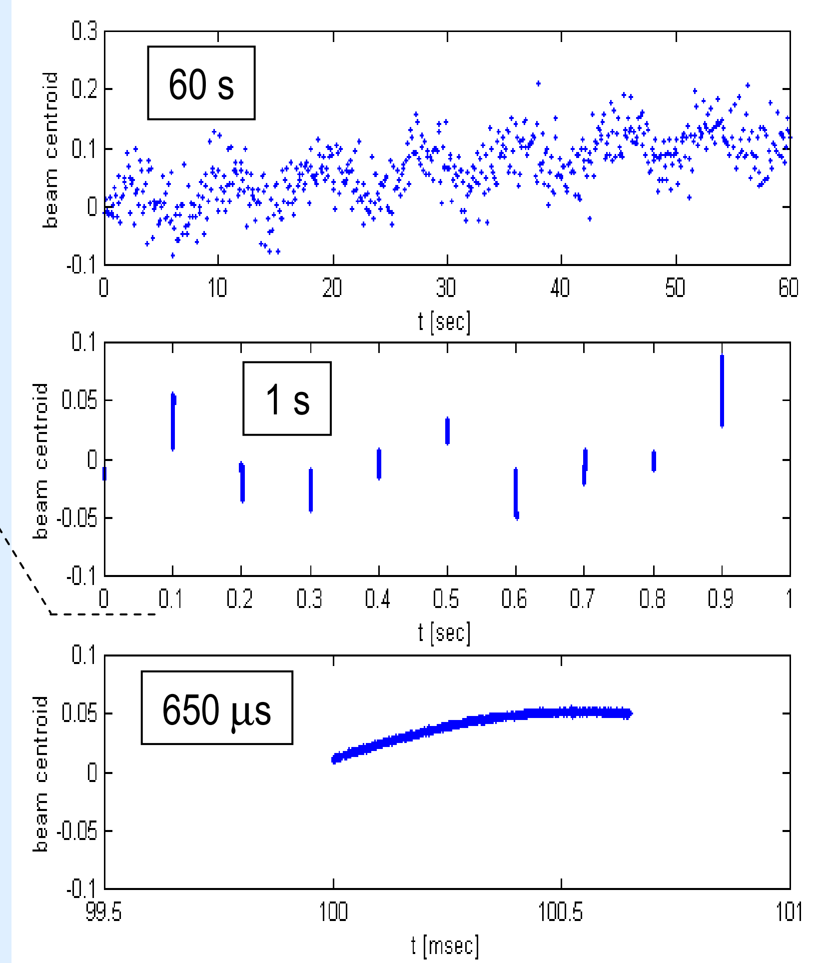
- switching magnets, power supply jitter
- RF transient, RF jitter
- photocathode laser jitter
- beam current variations
- long range wake fields

Leads to:

- beam centroid motions
- beam shape variations
- beam arrival time jitter

… affects SASE power and gain length !
… disturbs stable user operation !

examples of beam centroid motions (a.u.)



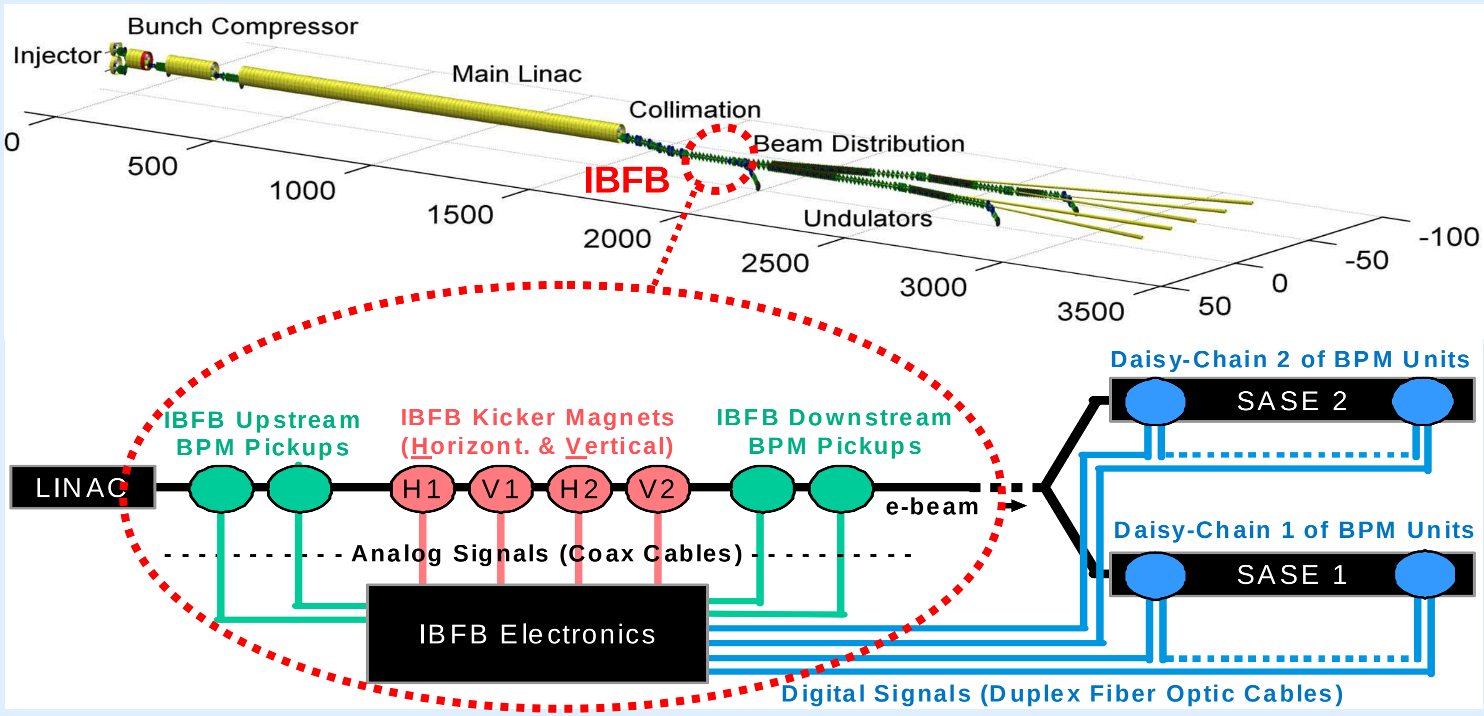
IBFB – Topology and Realization in E-XFEL (PSI Contribution)

A single IBFB will be located in front of the beam distribution section…:

… **high resolution beam pick-ups:** 3.3 GHz cavity BPMs with 40 mm diameter

… **low latency (≤ 1 μs) IBFB electronics** for beam position measurements, calculation of corrections and distribution of FB data

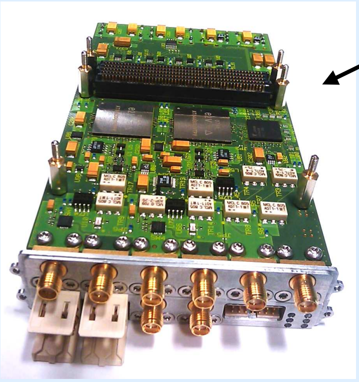
… **fast (high bandwidth) kickers and amplifiers** for applying orbit corrections to the beam



IBFB – Component Development and Status (PSI Contribution)

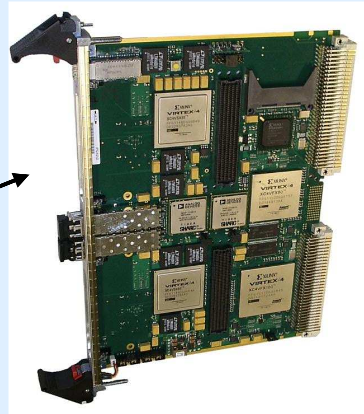
IBFB Beam Optics:
→ lattice design optimized for most efficient IBFB performance
→ reduction of IBFB correction kick strength

Status of IBFB Electronics

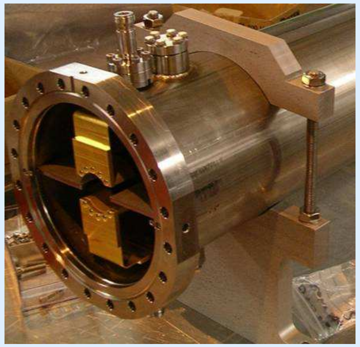


Two Stack Mezzanine Card
- low latency 4 channel, 12 bit, 500 MS/s ADC
- 14 bit 1 GS/s DAC

PDC Board
FPGA & DSP realtime processor and communication board (similar to GPAC processor board of BPM system)
basic firmware implemented



Status of IBFB Kickers and Amplifiers



IBFB Stripline Kicker
- length: 1 m
  bandwidth: > 50 MHz
- prototype installed and successfully tested at FLASH
- final version under design

Commercial Solid State Power Amplifier
- power: 2 – 8 kW
  bandwidth: 80 MHz
  < 30 ns latency
- final specs in preparation

BPM System and IBFB – Overall Status & Outlook

→ complete and compentent teams at PSI and collaborating IK partners established

→ great communication and team spirit between teams of IK partner institutes

→ BPM system and IBFB work in good progess and according to schedule

→ successful prototype tests for almost all BPM system and IBFB components

→ final iterations and production readiness achieved for time critical components in order to achieve E-XFEL project milestones (2016 fully operational facility)

thank you

for your interest and attention