Beam Position Monitors: How to Meet the Specifications of Most-Recent Accelerators

Glenn Decker
Advanced Photon Source
Diagnostics Group Leader
September 18, 2013

Overview

- Beam stability requirements
- Pickup Electrodes / Sensors
- Electronics / Data Acquisition / Processing
- B(PM)^2

Beam Stability Performance Requirements

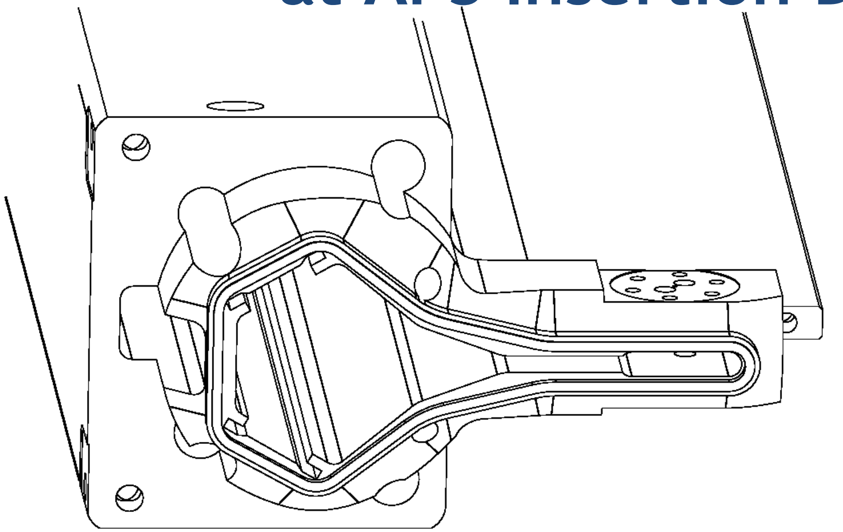
Facility	Stability Requirement (microns rms)	Bandwidth
Cornell ERL	0.3	1 kHz
LCLS-II FEL	< 1.0	60 Hz
E-XFEL	3.0	> 1 kHz
SwissFEL	< 1.0	50 Hz
APS upgrade	0.4 / 0.8	200 Hz / 1 kHz

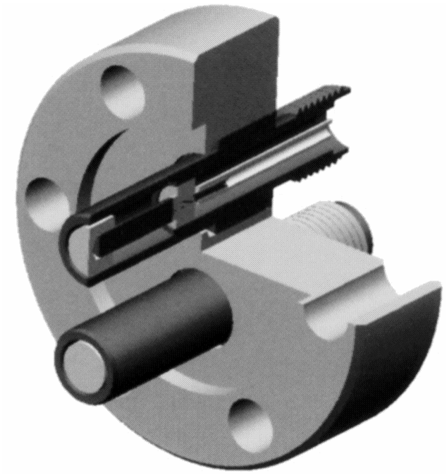
Beam Stability Performance Goals In Detail

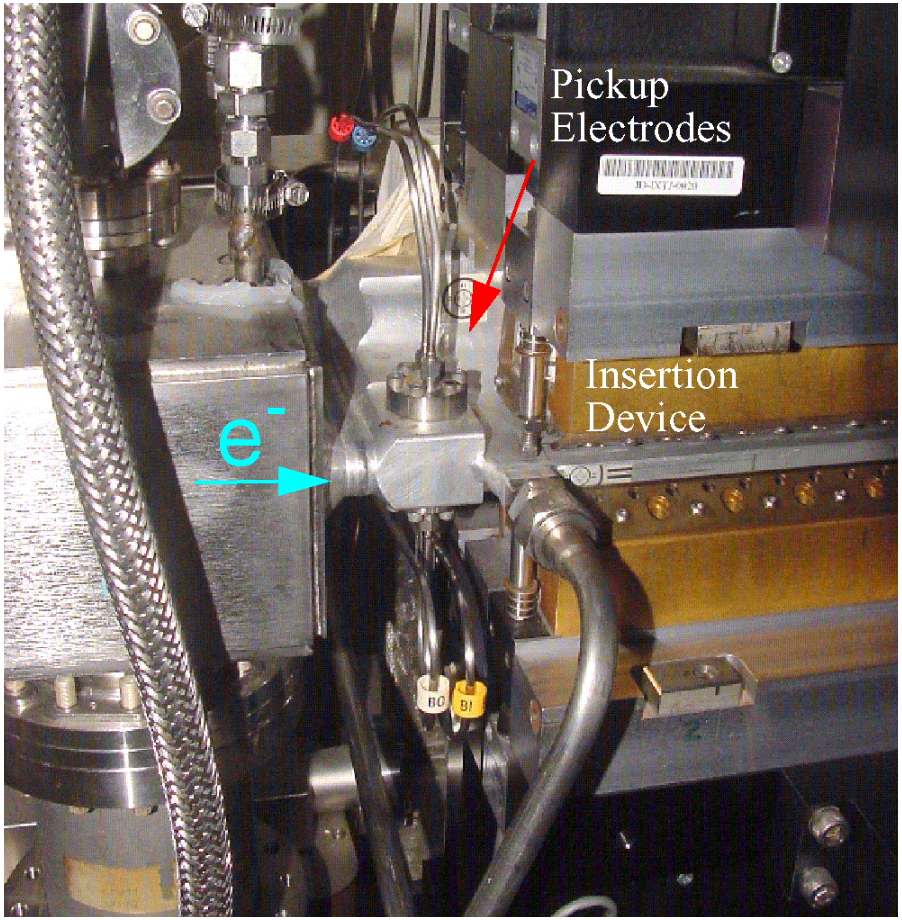
- Requirements for the APS Upgrade are

		RMS Motion (0.1-200 Hz)		Long term (1 week, rms)	
Horizontal	Now	5.0 μm	0.85 μrad	7.0 μm	1.4 μrad
	Upgrade	3.0 μm	0.53 μrad	5.0 μm	1.0 μrad
Vertical	Now	1.6 μm	0.80 μrad	5.0 μm	2.5 μrad
	Upgrade	0.42 μm	0.22 μrad	1.0 μm	0.5 μrad

BPM Pickup Electrodes at APS Insertion Device Source Points





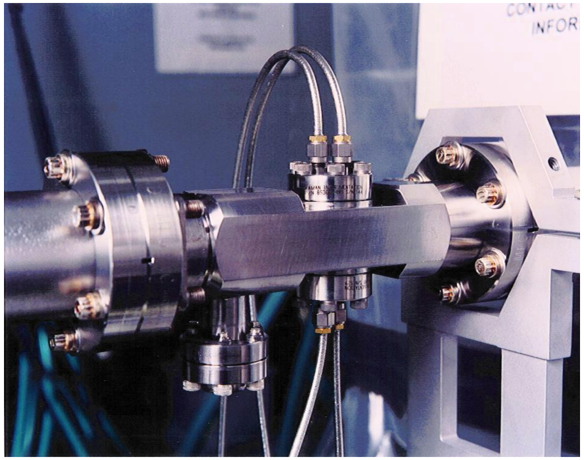


4 mm-diameter buttons w/ 1-cm horz. separation, 7.5 mm vert. gap

Other BPM Pickup Electrodes

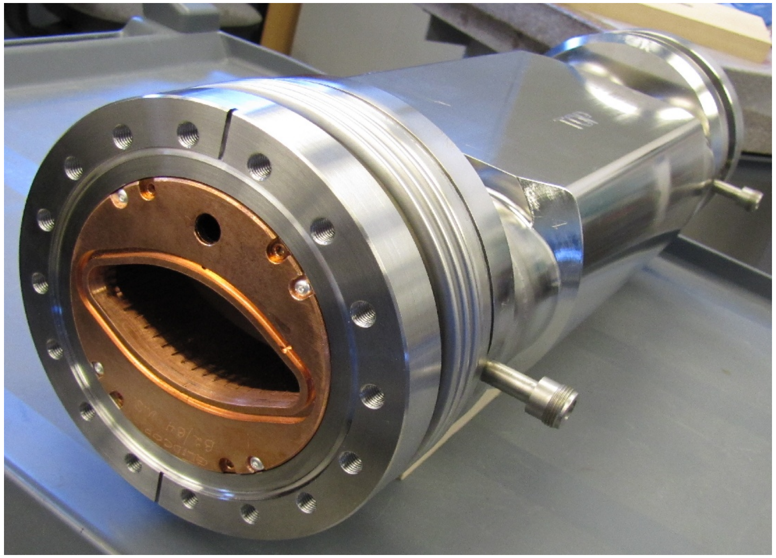
Cold E-XFEL Button

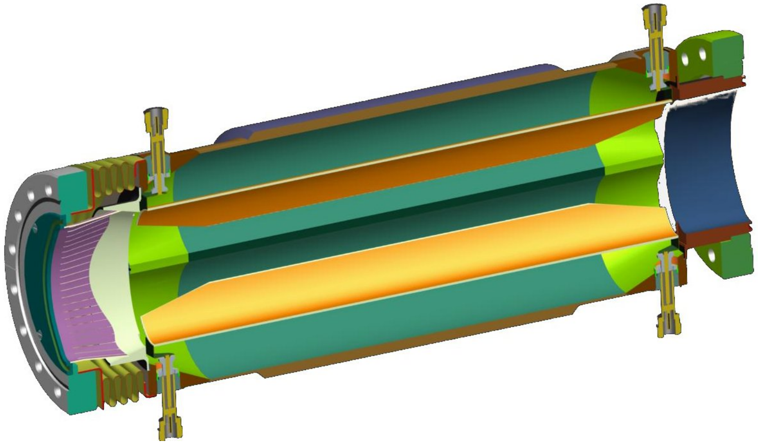
Warm E-XFEL Button



4-mm button application,
Rotated Geometry,
4 mm vertical aperture
APS LEUTL

Stripline Pickup Electrodes / Kickers*

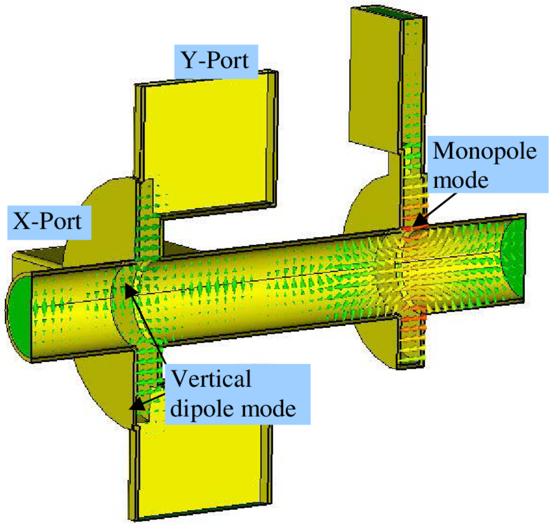


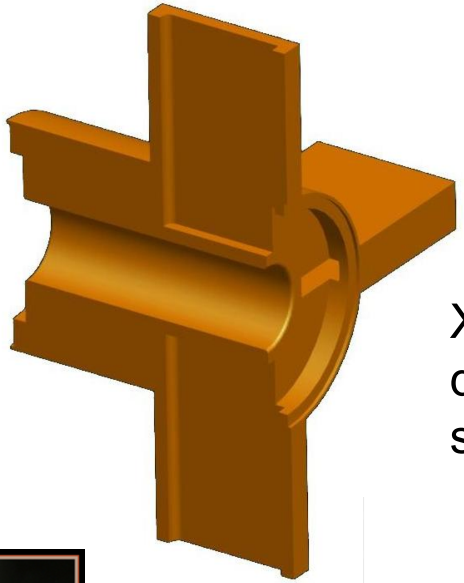


- Strongly-couples to the beam
- Commonly used for broadband multibunch feedback systems
- Signal comes out of the upstream end when used as a pickup
- Power goes in at the downstream end when used as a kicker
- Typical length is a quarter wavelength of the central frequency of interest

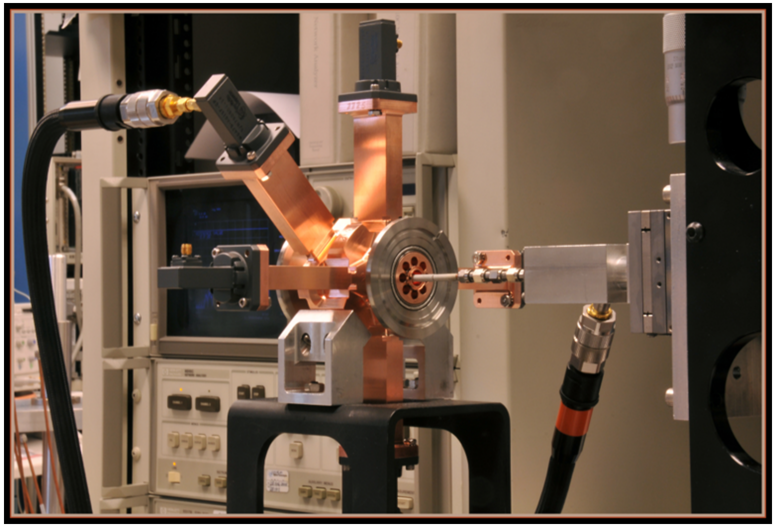
*Google Glen Lambertson stripline pickups kickers

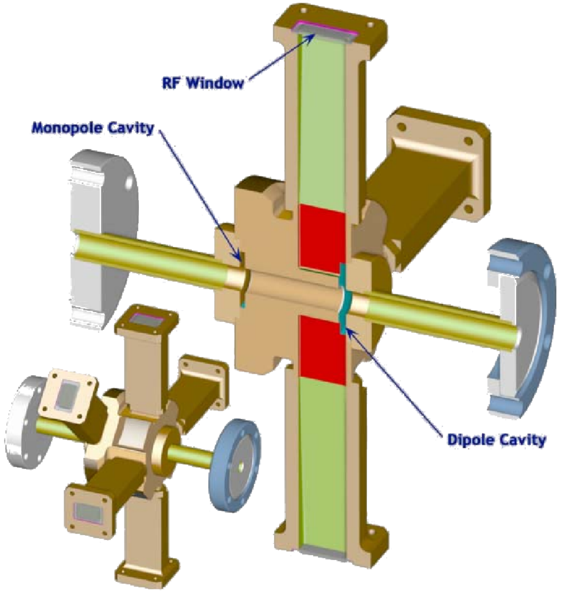
LCLS Cavity Beam Position Monitors





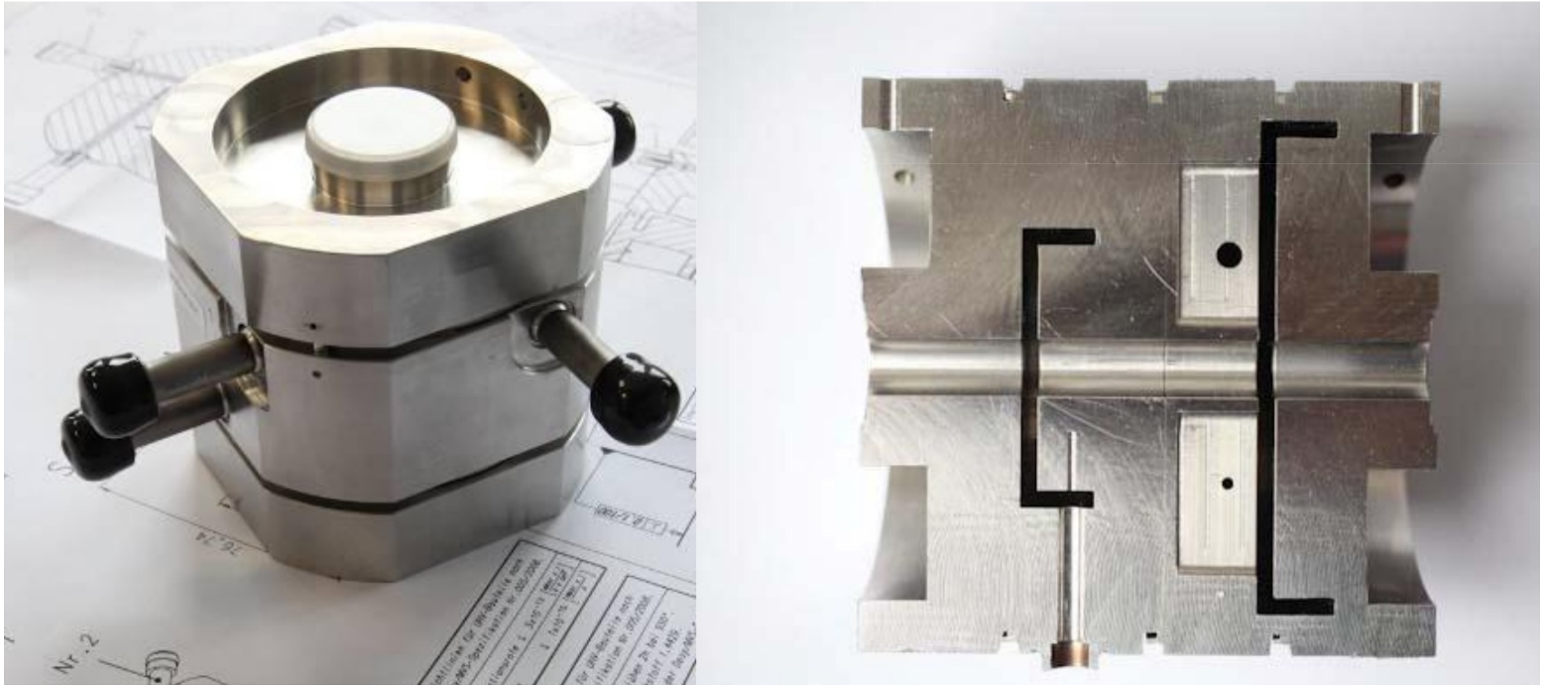
X-Band copper cavity demonstrated < 500 nm single-shot resolution*





*Stephen Smith et al., PAC'09

Shintake-Style Cavity Beam Position Monitors



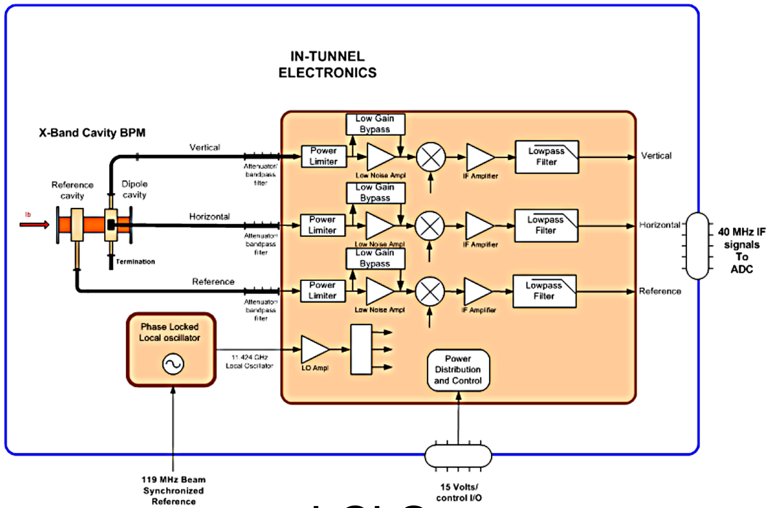
S-Band Steel Cavity developed for E-XFEL
-Demonstrated < 200 nm single-shot resolution*

*M. Stadler et al., IBIC'12

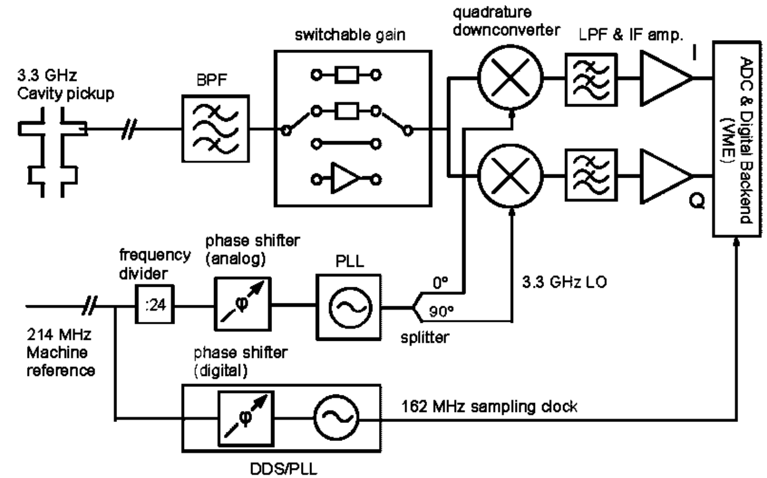
BPM Electronics

- Topologies
- Commercial
- In-house developed
- Hybrids

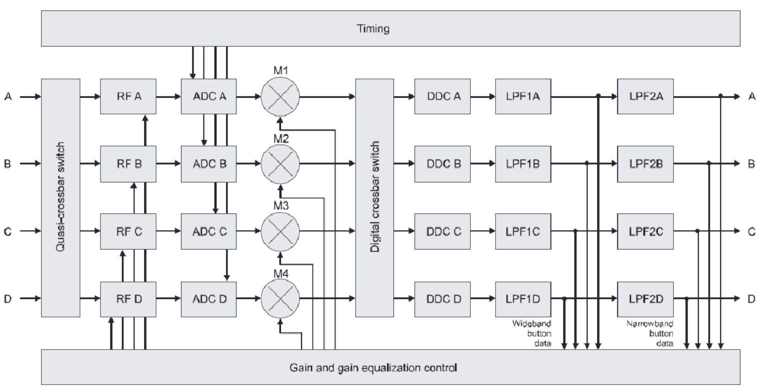
BPM Electronics Topologies



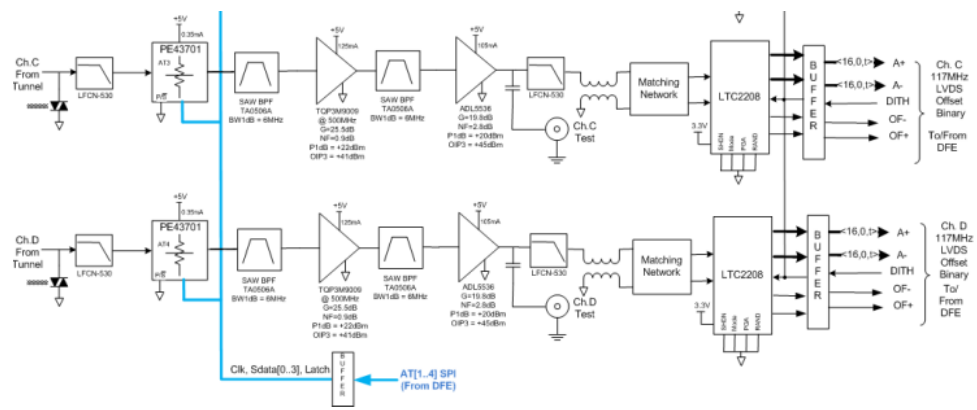
LCLS



ExFEL@SITF@PSI



I-Tech



NSLS-II

Commercial Solution

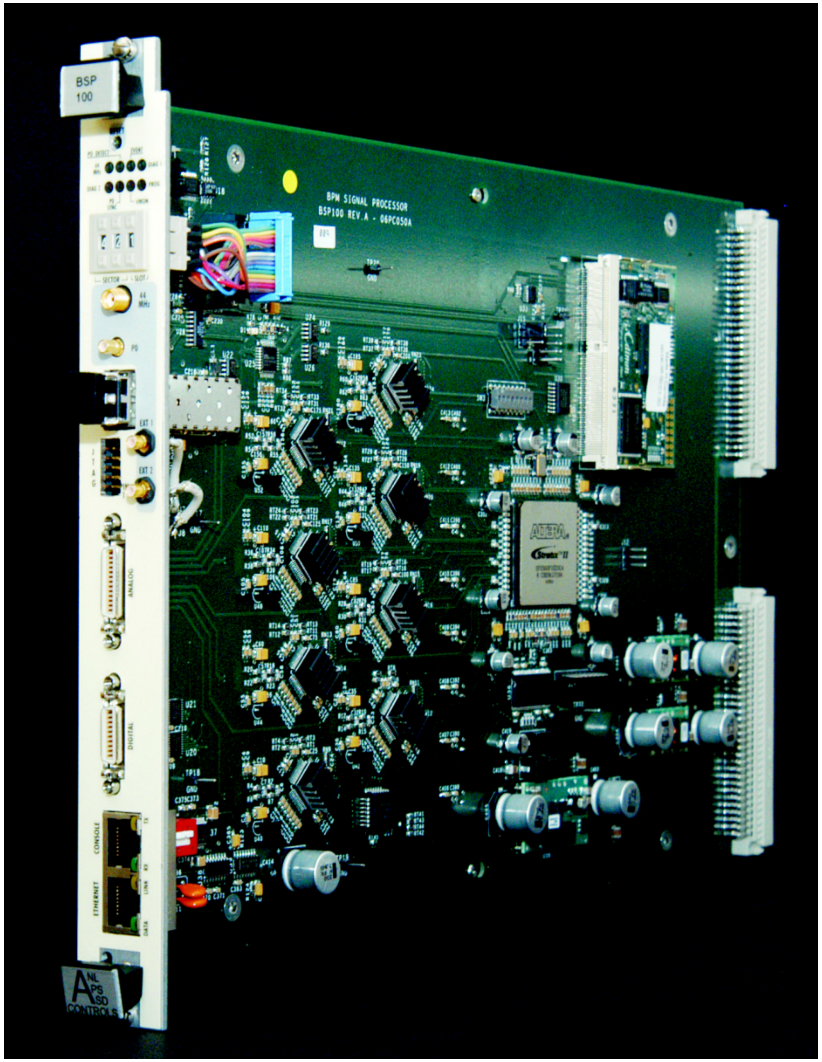
Noise floor approaching 2 nm / √Hz.

Insensitive to fill pattern

Long term drift 200 nm p-p / 24 hours*.

* Guenther Rehm, Diamond Light Source, EPAC 2008

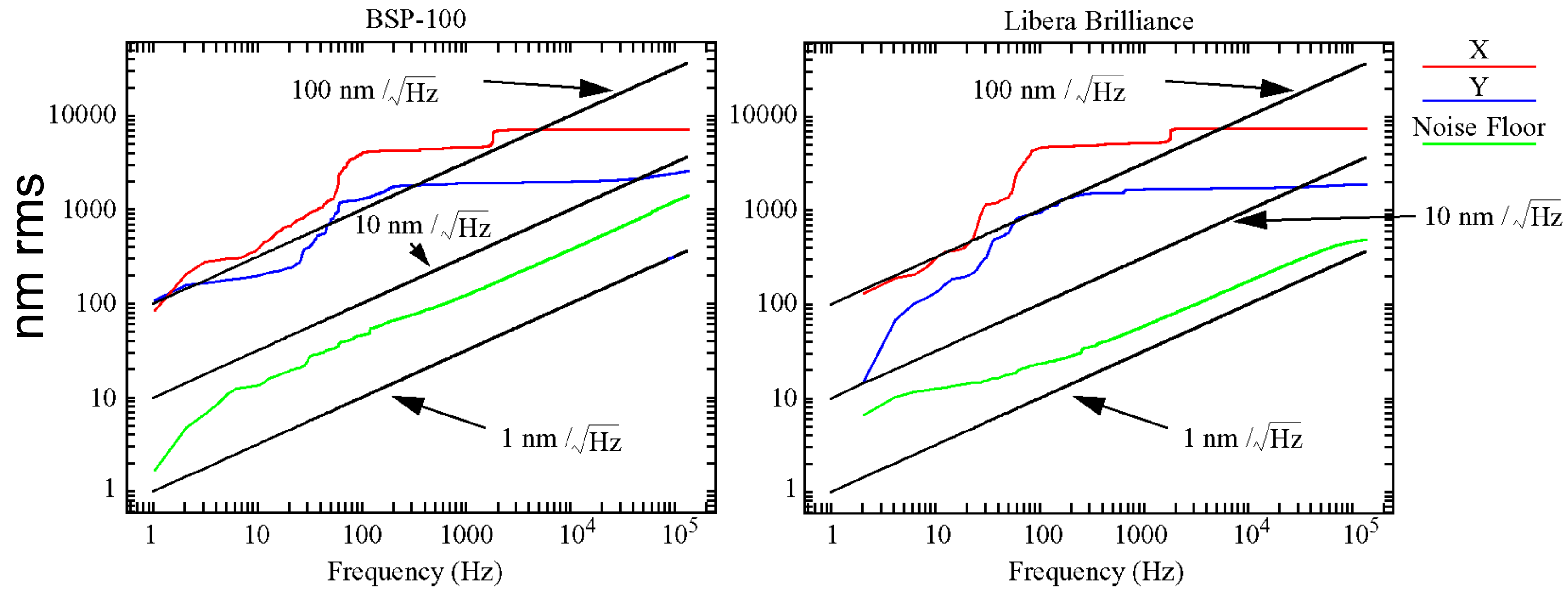
APS Broadband RF BPM data acquisition (BSP-100)



- Eight channels/board, 88 MS/sec sampling. Altera FPGA processing.
- Used with AM/PM rf front end
- One second (262144 samples) turn-by-turn beam history for machine studies / fault diagnosis.
- Demonstrated noise floor

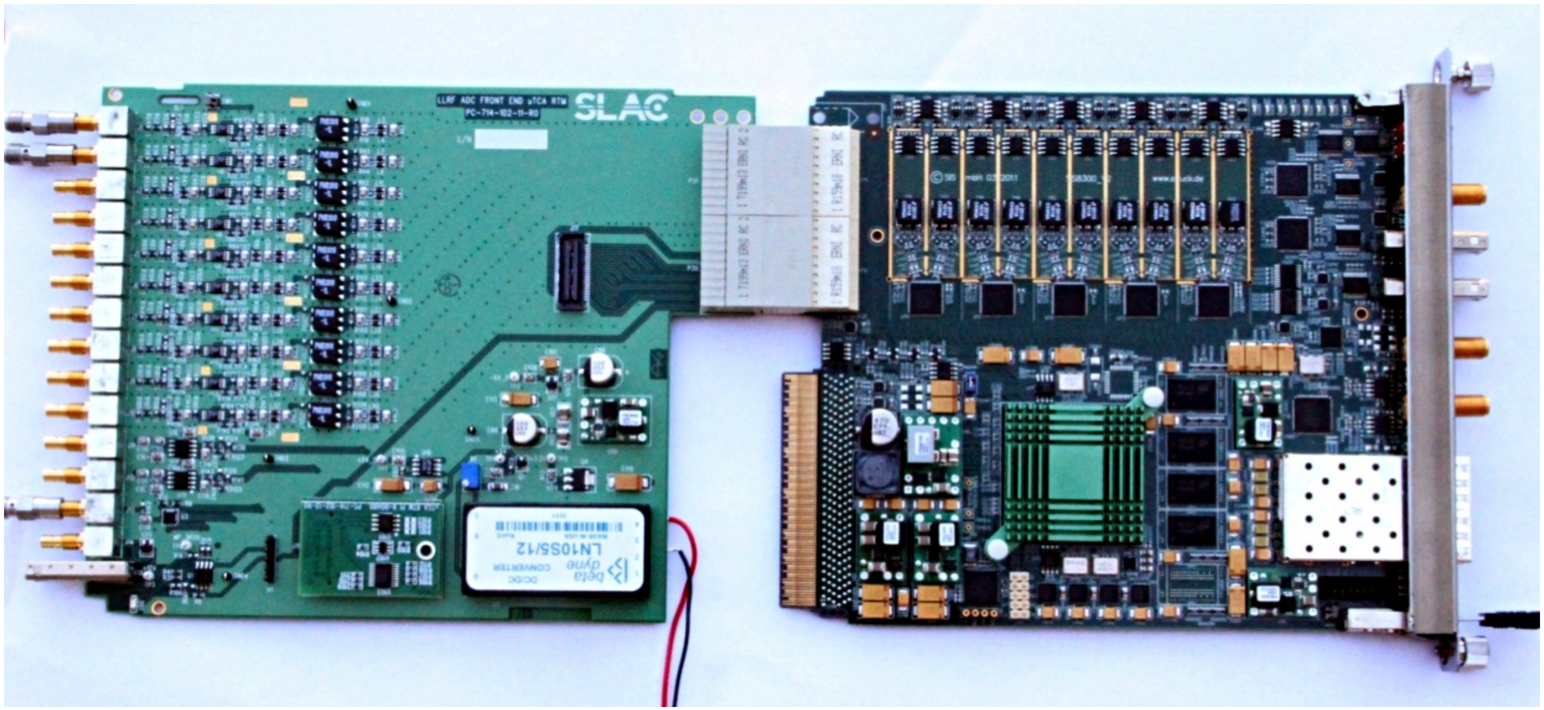
  < 6 nm / √Hz

Storage Ring BPM Electronics Performance



Plots show the square root of the forward-integrated power spectral density.

LCLS Cavity BPM Electronics*



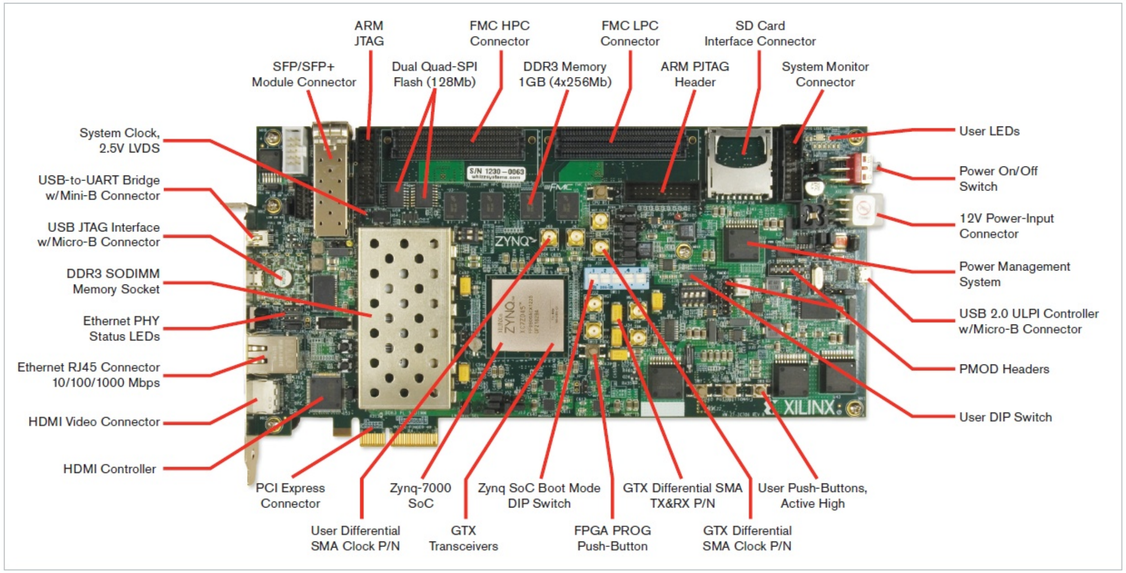
μTCA
Rear Transition Module
(RTM)

16-bit 119 MS/sec digitizer
w/ FPGA processor (SIS)

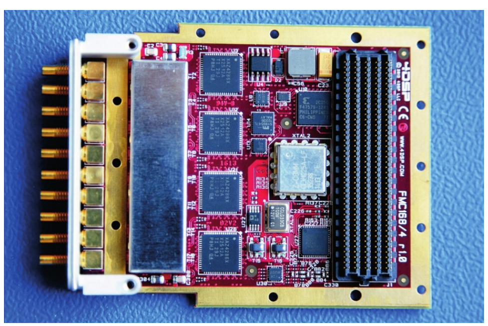
*Courtesy A. Young, SLAC

Field-Programmable Gate Arrays

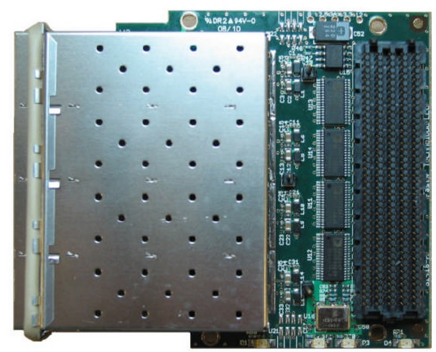
ZC706 EVALUATION BOARD



Xilinx ZC706 evaluation board.

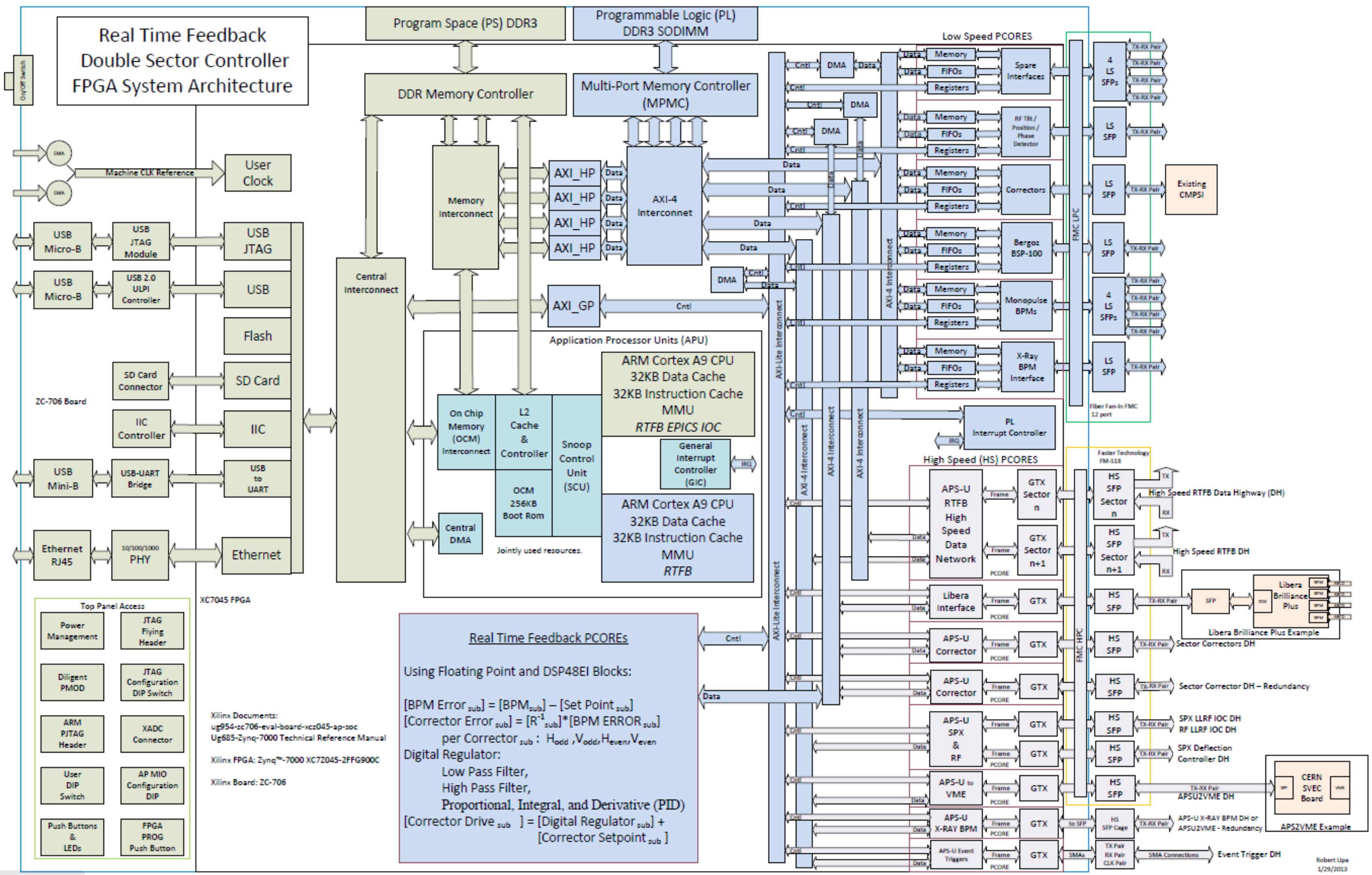


4dsp 8-channel 16 bit 250 MS/sec FMC ADC



Faster Technology FM-S18
8*SFP FMC MGT

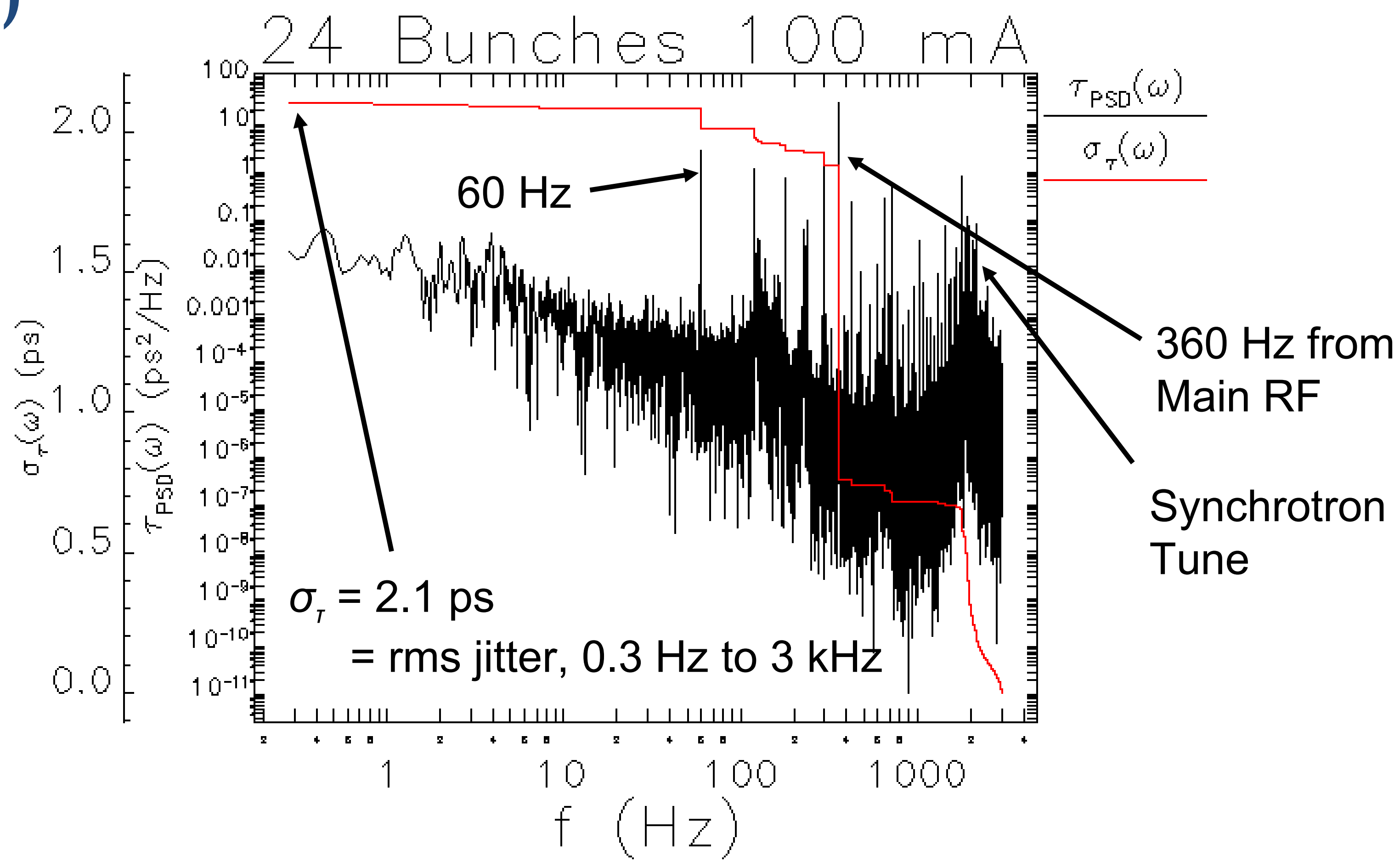
APS Fast Orbit Feedback FPGA System Architecture



Glenn Decker APS, IBIC 2013

Courtesy R. Lipa, ANL

Beam Arrival Time Jitter Power Spectral Density (APS)



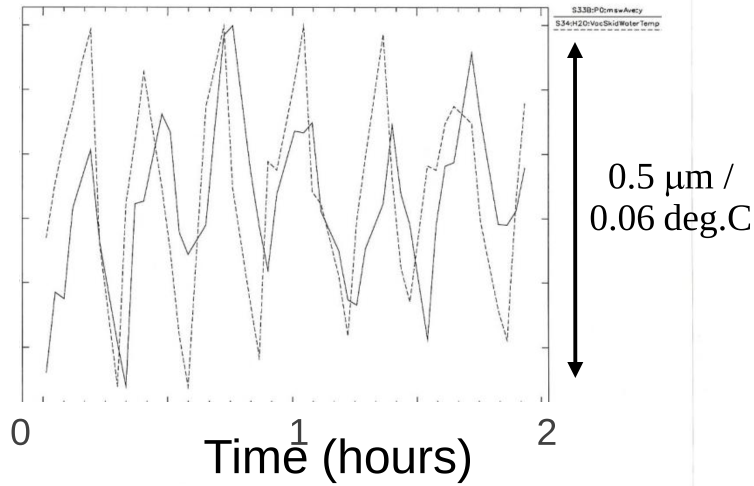
$\sigma_\tau(\omega)$ = Square Root of reverse-integrated power spectral density

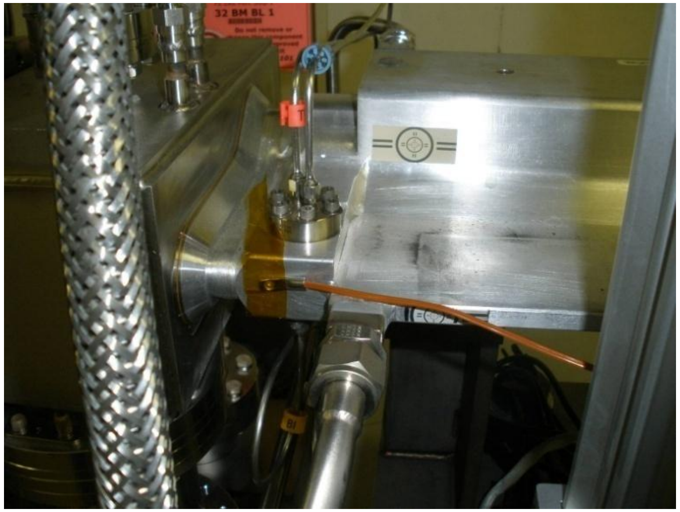
Note: the rms bunch length for 24-singlets fill pattern is 34 ps.

Mechanical Motion Correlated with Temperature

- Vacuum chamber water temperature correlates with BPM position readback.
- BPM Instrumented with a Keyence Laser tracker to measure BPM movement relative to APS Air / WaterTemp.
- Temperature regulation is at the level of 0.3 – 0.5 deg. C p-p for air, and 0.06 deg. C p-p for water. (24 hours)
- Mechanical motion monitoring system proposed for APS Upgrade

Correlation of measured beam position and water temperature

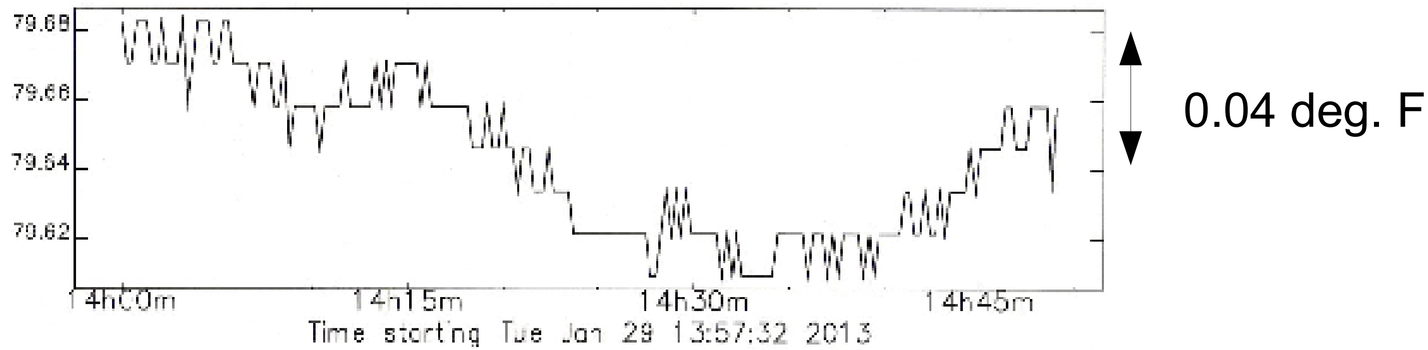




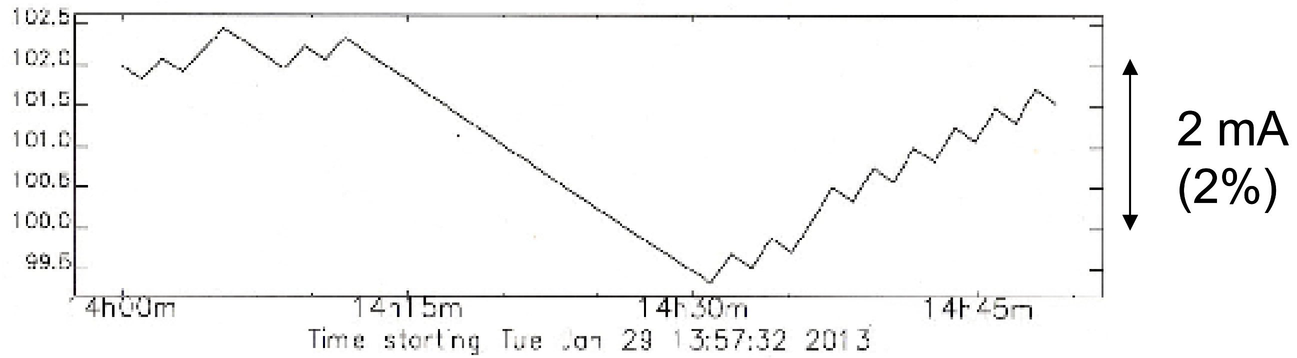
ID Chamber BPM Pickup Electrode
Courtesy Bob Lill ANL

Impact of missed top-up shots

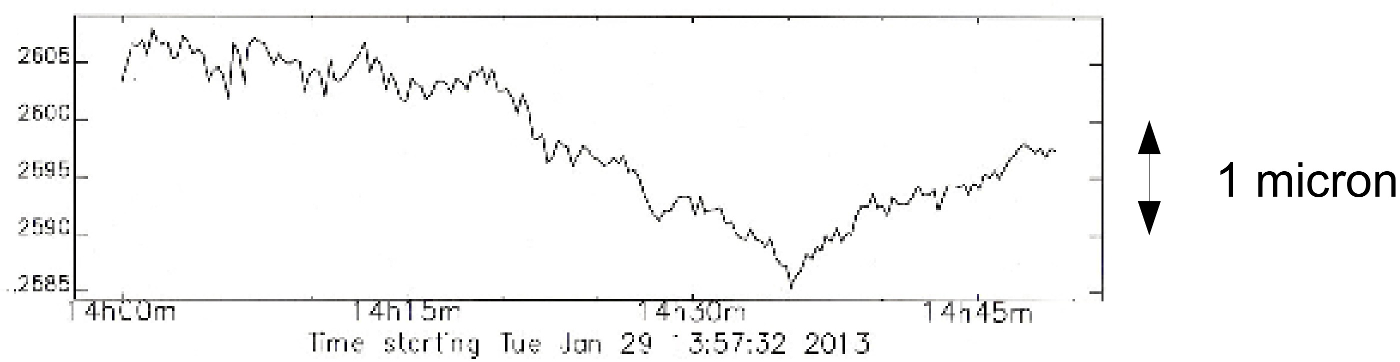
Air Temp. (deg. F)



Beam Current (mA)

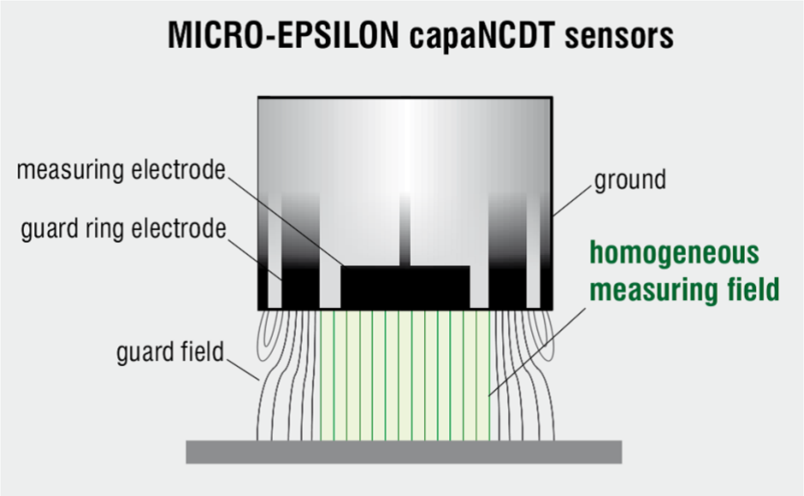


Position Sensor Readback



Capacitive Proximity Sensors

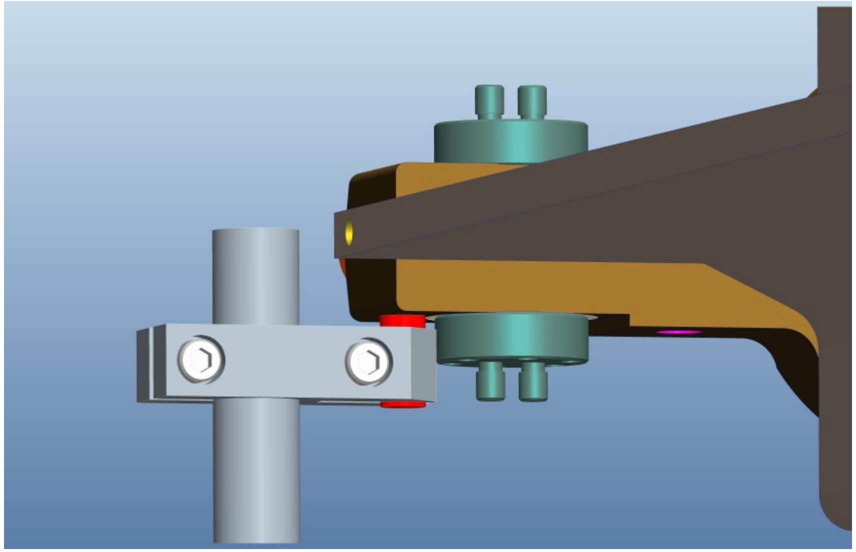
- Capacitive sensors provide a simple non-contact measurement
- Reactance of the capacitor, changes in direct proportion to the gap distance.
- NCDT 6300 single channel system 0.01 % FSO resolution in 8KHz BW

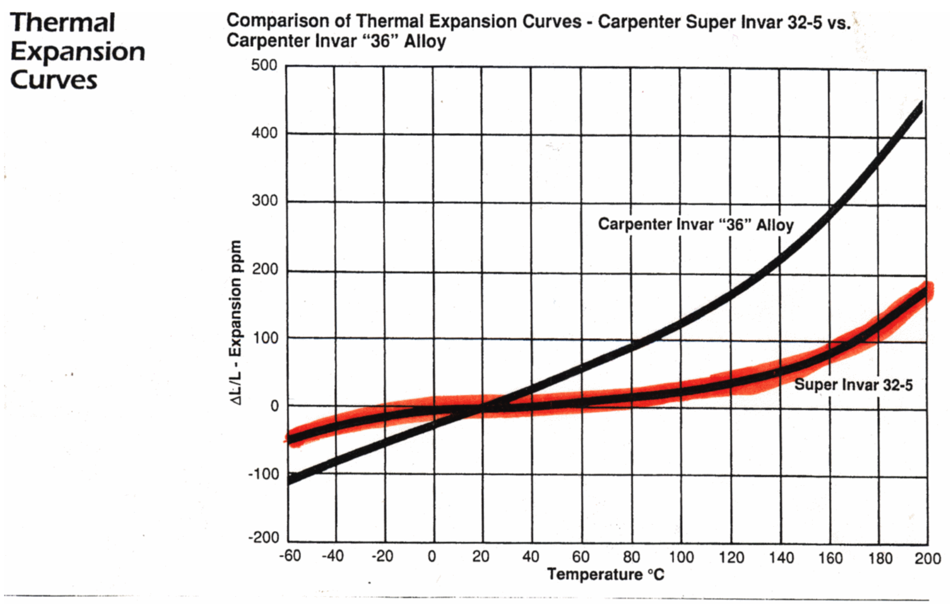


Courtesy Bob Lill ANL

Super Invar

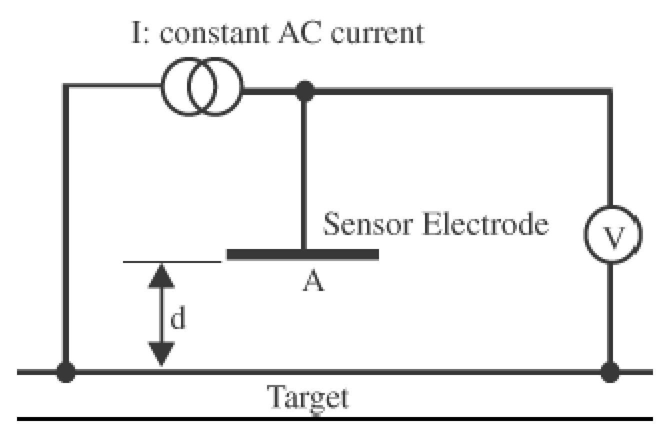
- Simple Invar stand was designed to evaluate capacitive detection of BPM
- Super Invar was used because of its very low thermal expansion (270 nm/C) for full length of support
- Standard Invar can provide a significant cost saving if requirements relaxed.





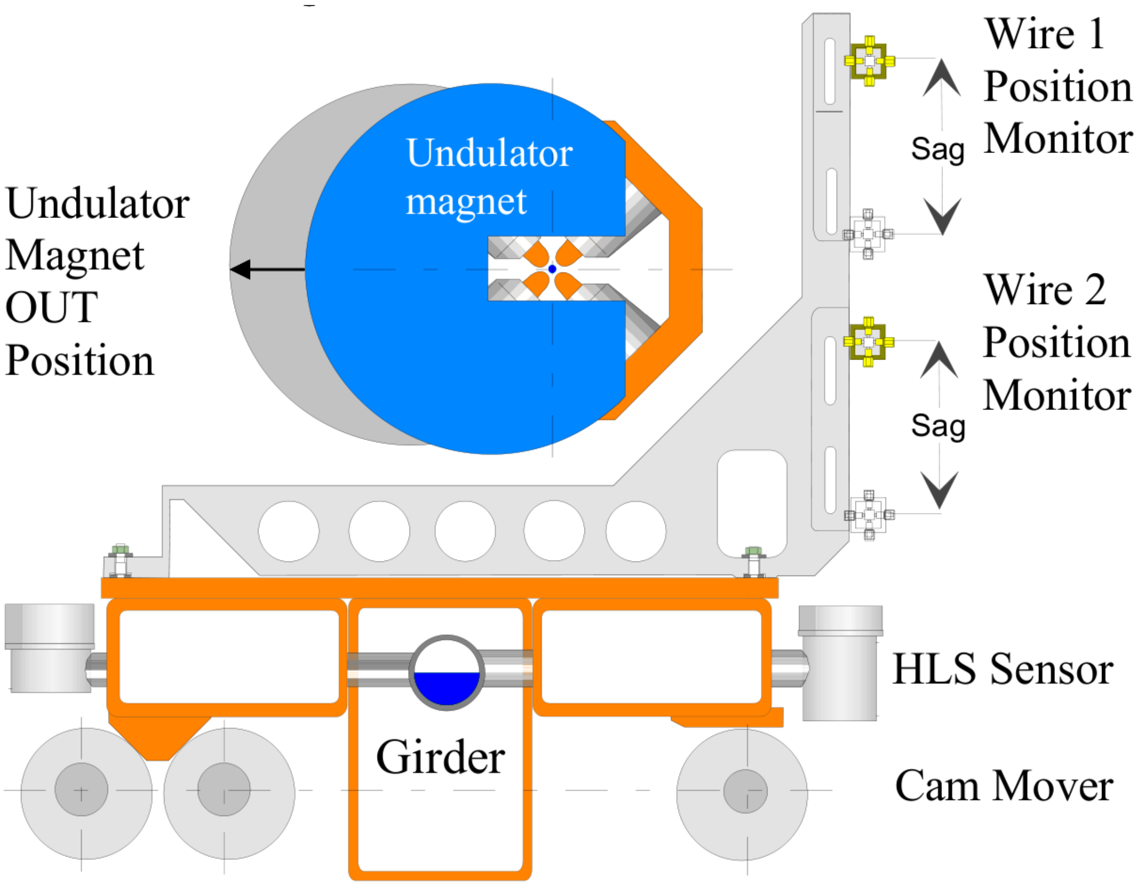
Hydrostatic Leveling System (HLS) Hardware

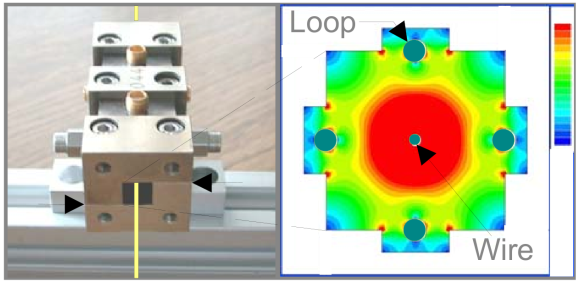
- Sensors have two main parts: reservoir and the electronics
- The face of the upper part is the capacitive pick up
- Reactance of the capacitor changes in direct proportion to the water level
- HLS is based on the communicating vessels principle



Sensor design from Budker Institute, used at Fermilab

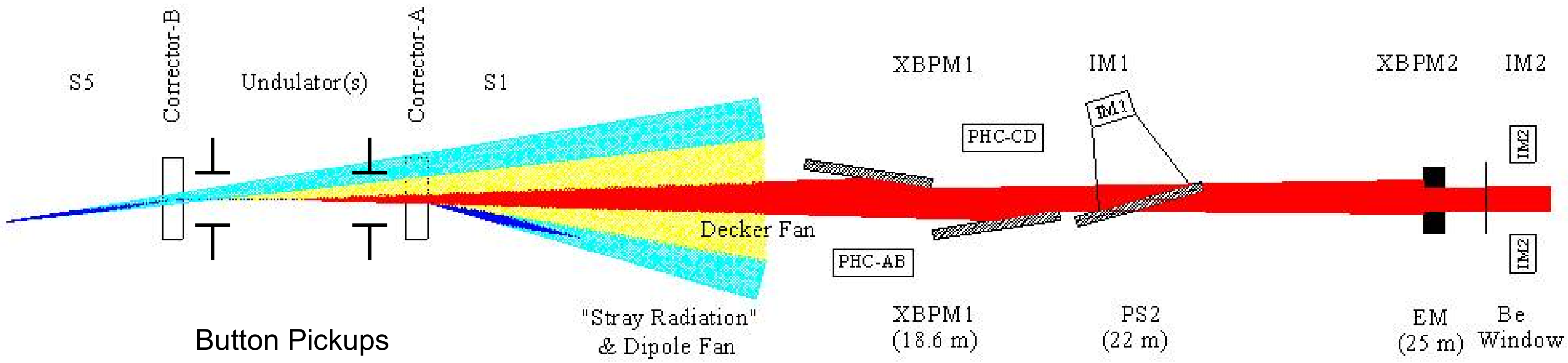
LCLS Wire Position Monitor and HLS





H.D. Nuhn etal.,, FEL'11

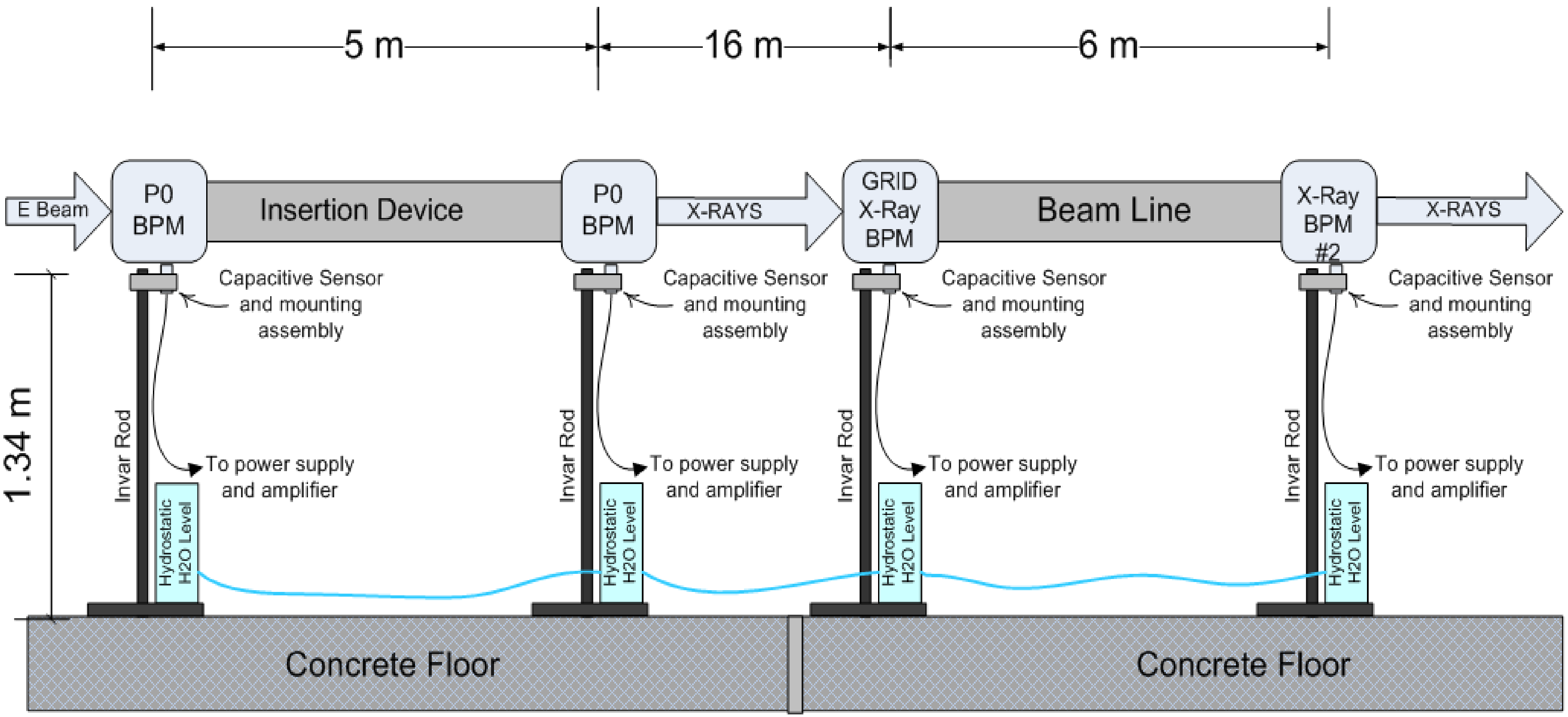
Proposed X-ray Beam Alignment System at APS*



- Direct detection of hard x-ray beam position (XBPMs) provides factor of 5 lever arm advantage.
- Intensity monitors (IM) monitor hard x-ray flux through critical apertures.
- Mechanical motion sensing network links rf BPMs, x-ray BPMs, and critical apertures, e.g the beamline exit mask (EM).

* B.X. Yang, PAC’11

Block Diagram for Proposed APS Mechanical Motion Sensor System



Summary / Conclusions

- BPM System must be tailored to the application
  - Ring-based light sources
  - FELs
  - Colliders
- Electronics are largely not the performance limitation
- FPGAs provide huge untapped potential
- BPM mechanical stability extremely difficult below 1 micron