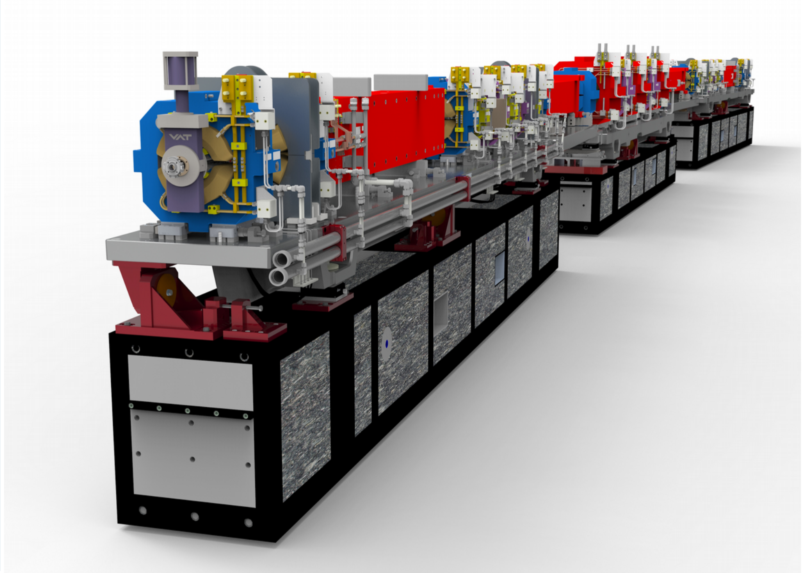
APS Upgrade Beam Diagnostics and R&D Results



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Diagnostics Experts of European Light Sources
Workshop June 3-5, 2019

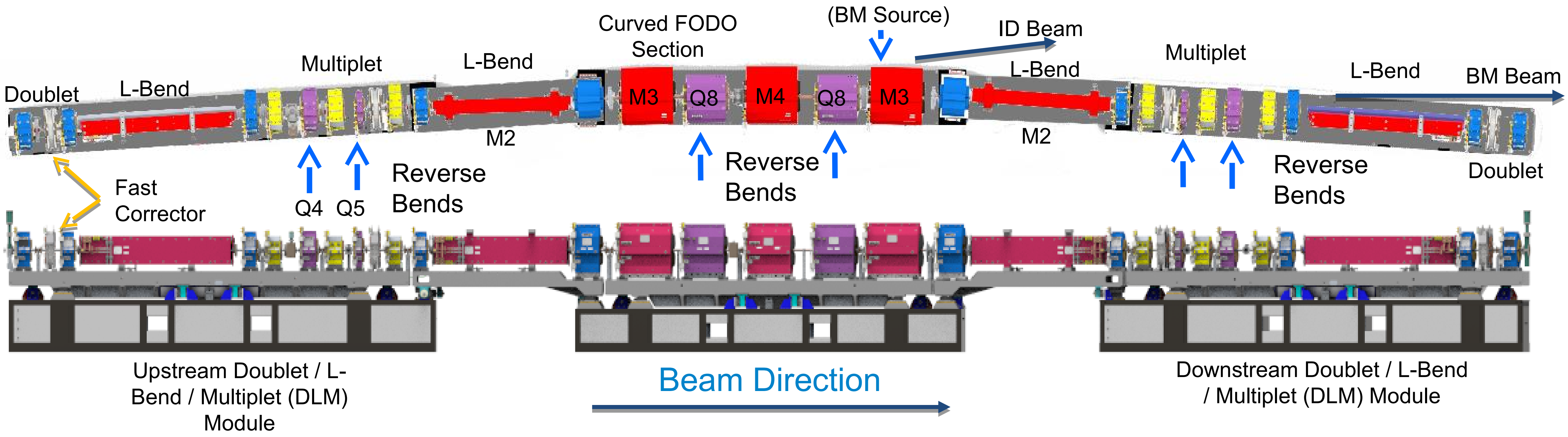
June 3, 2019

Outline

- APS Upgrade Overview
- Diagnostics for the APS Upgrade
- Beam Stability Requirements
- RF and X-ray BPM Design
- Beam Size Measurement Design
- Orbit Feedback System Design and R&D
- Summary

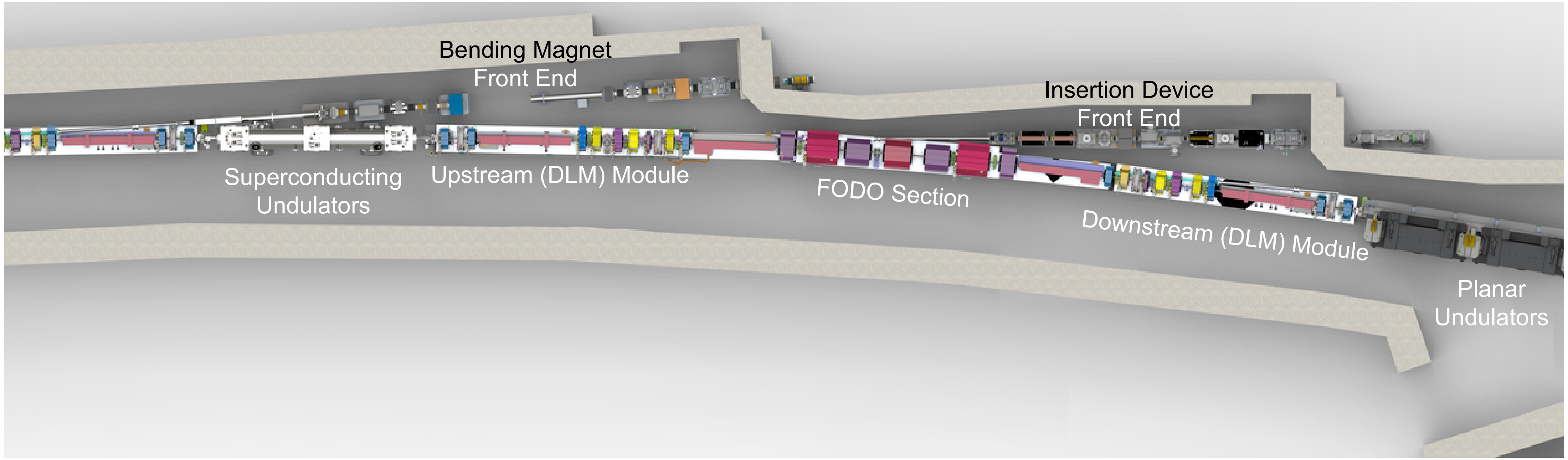
APS Upgrade Overview

- Storage ring consists of 40 Sectors. Each with 33 arc magnets; 27.6 meters / sector.
- Sector arcs consist of five modules, mounted upon three large plinth assemblies.
- Two X-ray sources: BM originating from the M3 Dipole and ID

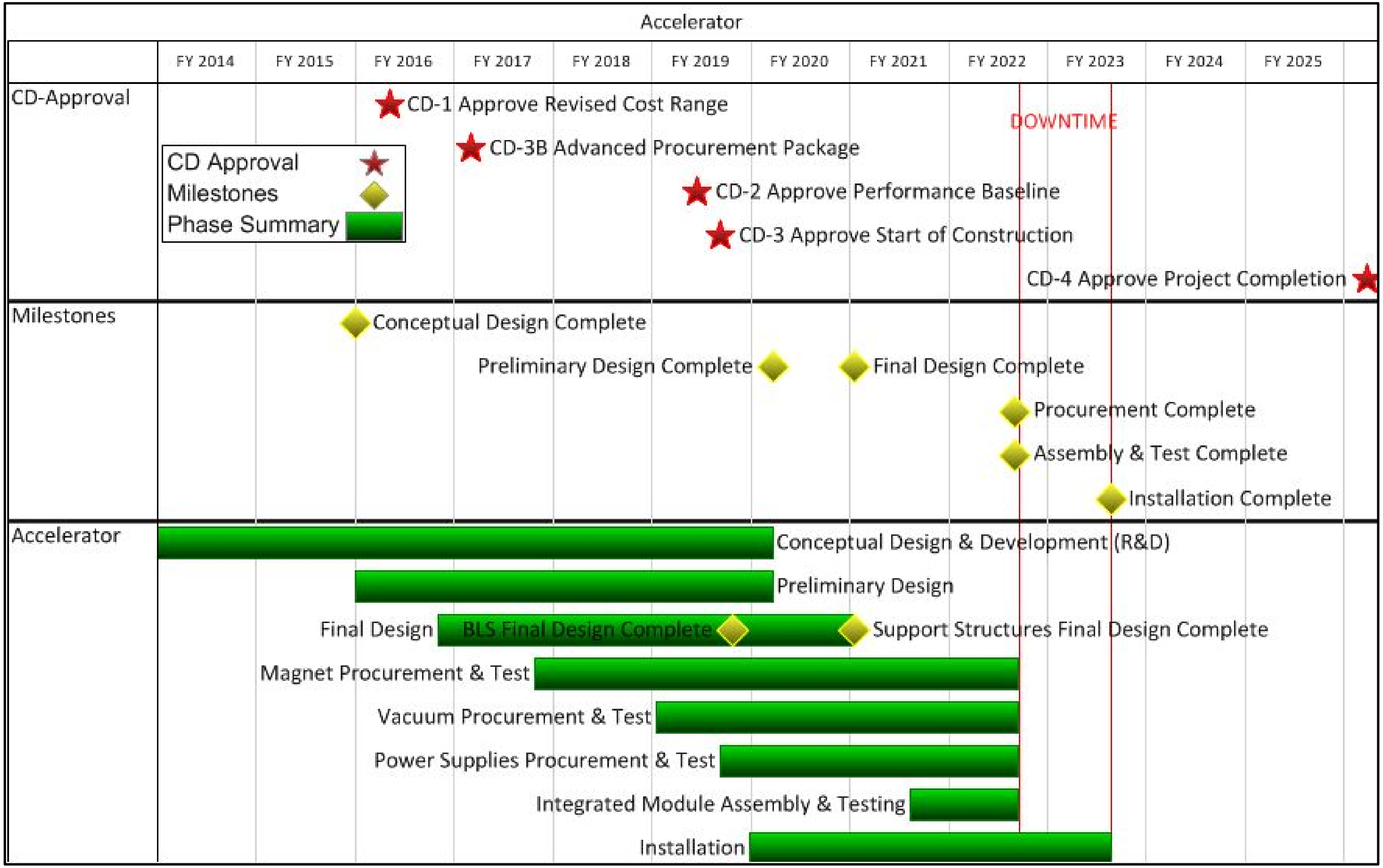


APS Upgrade Overview

- Keep the insertion device (ID) beamline alignment
- Bending magnet beamlines must move 42 mm inboard at the front-end exit



APS Upgrade Overview High-level Schedule



APS Upgrade Overview: Key Performance Parameters

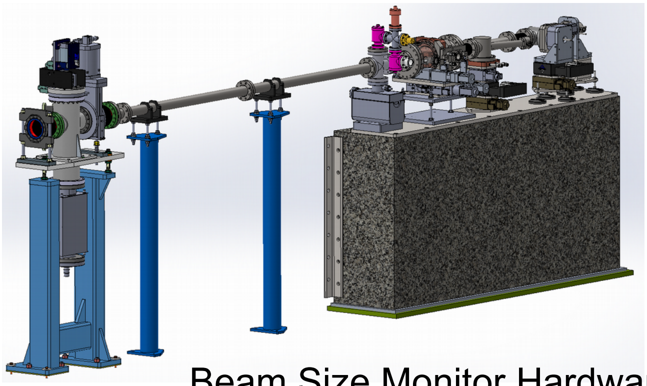
Key Performance Parameter	Thresholds (Performance Deliverable)	Objectives
Storage Ring Energy	> 5.7 GeV, with systems installed for 6 GeV operation	6 GeV
Beam Current	$\geq$ 25 mA in top-up injection mode with systems installed for 200 mA operation	200 mA in top-up injection mode
Horizontal Emittance	< 130 pm-rad at 25mA	$\leq$ 42 pm-rad at 200mA
Brightness @ 20 keV[1]	$> 1 \times 10^{20}$	$> 1 \times 10^{22}$
Brightness @ 60 keV[1]	$> 1 \times 10^{19}$	$> 1 \times 10^{21}$
New APS-U Beamlines Transitioned to Operations	7	$\geq$ 9

- Must have beam size monitor diagnostics in place to demonstrate emittance requirement by the time the three month commissioning period is over

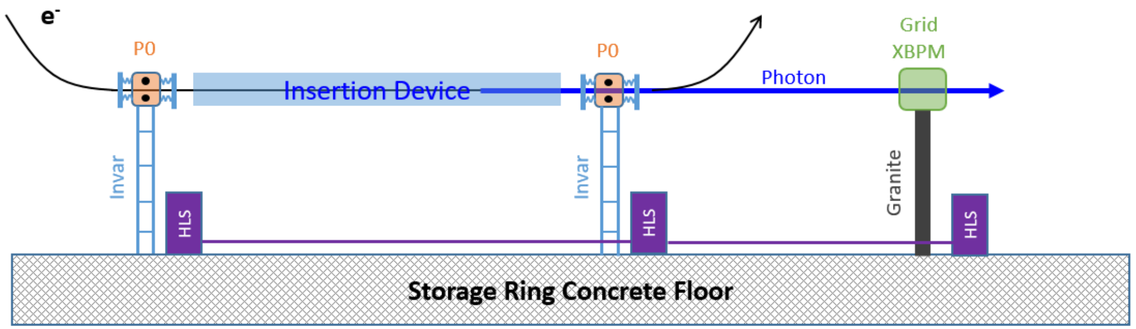
Diagnostic Systems Scope

Diagnostic	Quantity/ Sector	Total
U2.03.03.07.01 RF BPM Systems Arc RF BPMs	12	480
ID RF BPMs (A:P0, B:P0)	2	80
U2.03.03.07.02 Orbit Feedback System	N/A	1
U2.03.03.07.03 Mechanical Motion Monitoring Systems	1	35
U2.03.03.07.04 Current Monitors	N/A	2
U2.03.03.07.04 Bunch Current Monitor	N/A	1
U2.03.03.07.05 Beam Size Monitors	N/A	3
U2.03.03.07.06 Transverse Multi-bunch Feedback System	N/A	2
U2.05.02.01.06 X-Ray BPM Electronics GRID	1	35

Beam Position Monitor Electronic: Libera Brilliance + Used for R&D

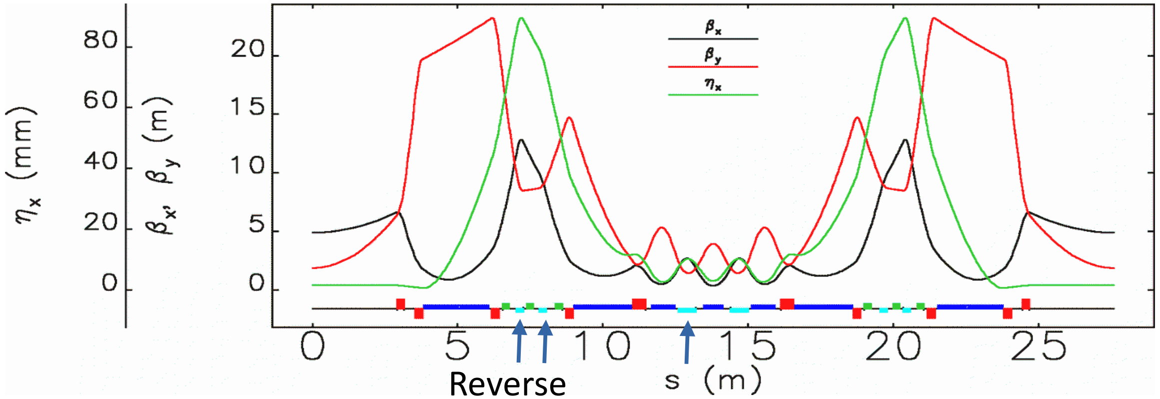


Beam Size Monitor Hardware



Mechanical Motion Monitoring / Hydrostatic Level Sensor System

Beam Stability Requirements



Quantity	APS Now	APS MBA Timing Mode	APS MBA Brightness Mode	Units
Beam Energy	7	6		GeV
Beam Current	100	200		mA
Number of bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Horizontal Emittance	3100	32	42	pm·rad
Emittance Ratio	0.013	1	0.1	
Horizontal Beam Size (rms)	275	12.6	14.5	μm
Vertical Beam Size (rms)	11	7.7	2.8	μm
Betatron Tune	35.2, 19.27	95.1, 36.1		
Natural Chromaticity	-90,-43	-130, -122		

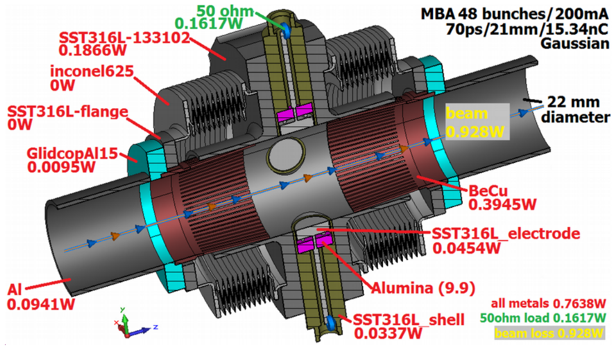
Diagnostics requirements driven by the small beam size of the MBA ring.

Plane	AC rms Motion (0.01-1000 Hz)		Long Term Drift (7 Days)	
Horizontal	1.3 μm	0.25 μrad	1.0 μm	0.6 μrad
Vertical	0.4 μm	0.17 μrad	1.0 μm	0.5 μrad

Diagnostics must have sufficient performance at low signal levels to allow commissioning

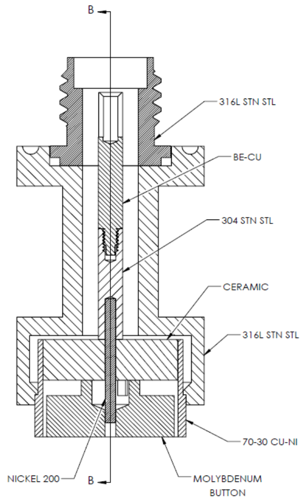
RF BPM System*

- Tested Libera Brilliance+ BPM electronics from Instrumentation Technologies in APS SR and with prototype orbit feedback controller
- 40 Shielded EMI cabinets for BPM and orbit feedback system electronics
- BPM pickup electrode assembly with integrated shielded bellows re-design due to problems with brazing and assembly
  - Molybdenum button (previously 316 SST)
  - Two piece center conductor rod (previously one piece 304 SST)
  - Two piece external shell (previously one piece)
  - Cu-Ni shell bonded to Alumina disk, brazed to external shell (previously Alumina disk alone brazed internally to shell

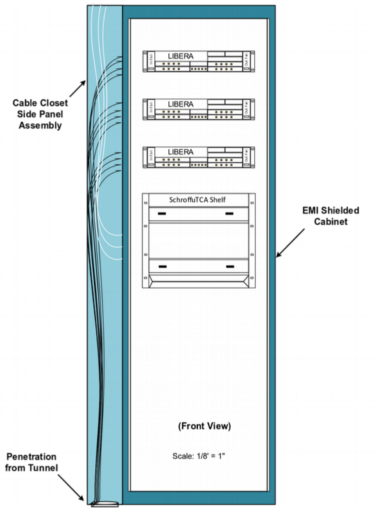


BPM Button Assembly

Libera Brilliance+



BPM Button Electrode

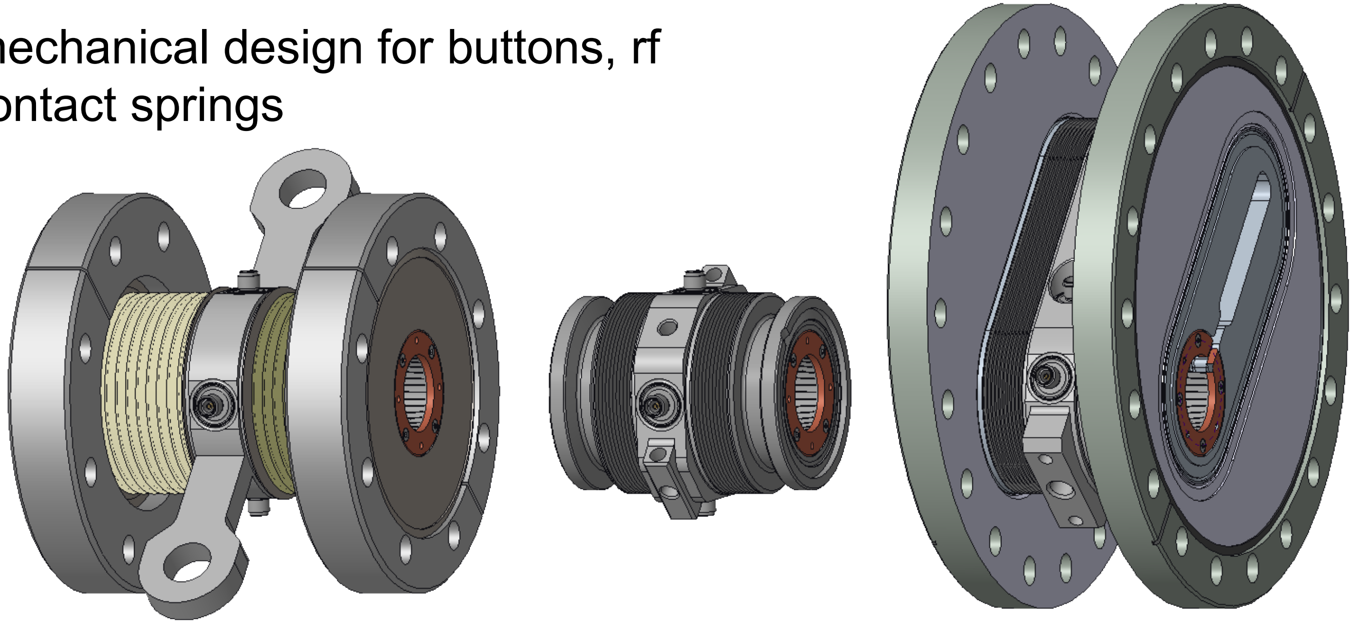


EMI Cabinet

* R. Lill etal. IBIC 2016, Barcelona, Spain 2016
X. Sun etal. IBIC 2017, Grand Rapids, MI, 2017
J. Carter: BPM button and assembly mechanical design

RF BPM System cont.

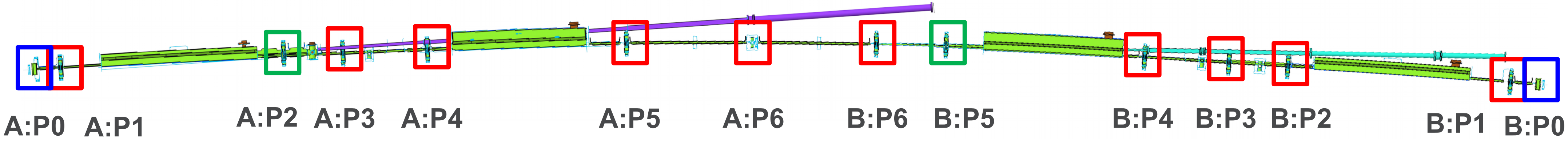
- 14 rf BPMs per sector
- Used same mechanical design for buttons, rf fingers and contact springs



P0 BPM, 2x per sector
4.5” DN63 CF rotatable flanges
104 mm flange to flange

Standard BPM, 10x per sector
DN40 QCF flanges
70 mm flange to flange

Keyhole BPM, 2x per sector
6” & 6.75” CF fixed flanges
70 mm flange to flange



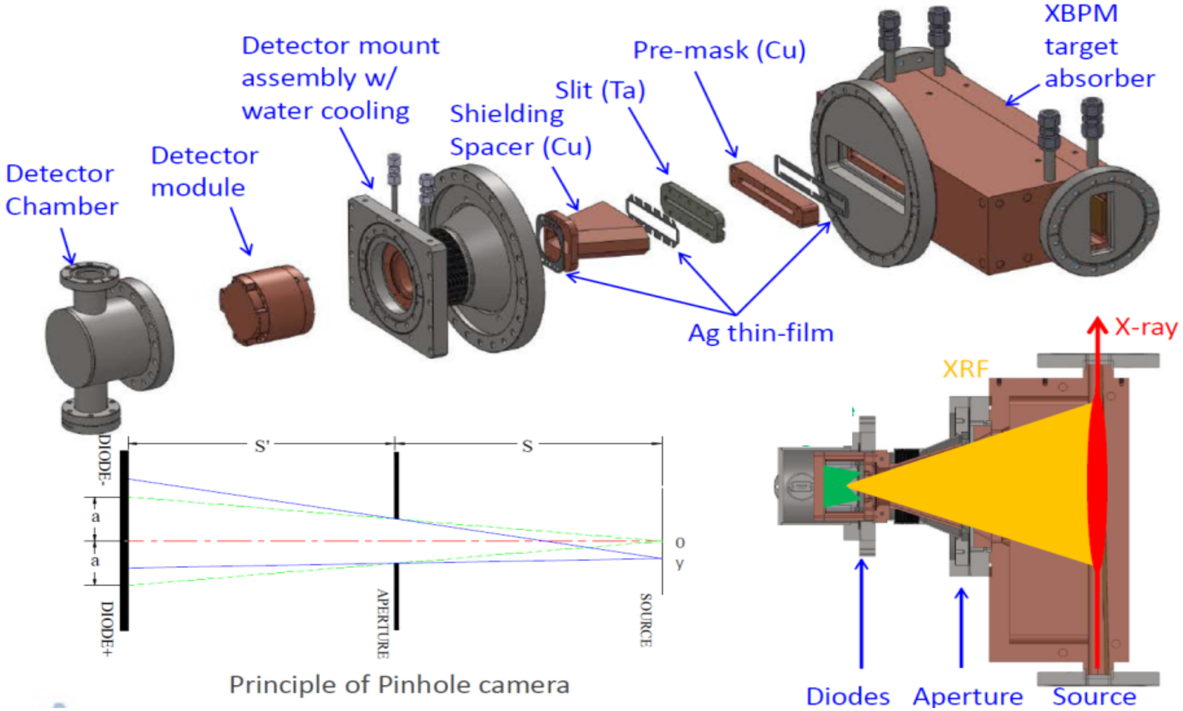
RF BPM System cont.

MBA Fill Pattern	Mode	Current Max (mA)	Single bunch current (mA)	Bunch charge (nC)	Signal Level	Measured Resolution (TBT) (μm)	Measured RMS (μm) (0.01-1000 Hz)
48*	User	200 (mA)	4.2 (mA)	15.34	-4.4 dBm	< 1.3	< 0.112
324*	User	200 (mA)	0.6 (mA)	2.27	-21.0 dBm	< 1.3	< 0.112
Single Bunch Stored**	Studies/ Commissioning	1 (mA)	1 (mA)	3.68	-16.8 dBm	< 16.5	< 1.42
Single Bunch Single Pass**	Studies/ Commissioning	-	-	1	2.7 V Peak	***< 58	-

*CW even fill pattern
**Low duty factor fill pattern
***Measured using 1000 shots

- AC resolution and RMS measurements listed in the table used Libera Brilliance+ bpm electronics in the APS ring connected an APS ID bpm (P0 bpm) using a combiner/splitter
- Planning a test this fall using the final design BPM button assembly prototype in sector 25 of APS ring.
- Long term drift specification on the electronics set to 10 % of the 1 mm rms specification
  - Measured 13 nm rms drift over 5 days with switching enabled for the Libera Brilliance+
  - Measured 325 nm/^{o}C drift over 7 days without switching enabled for the Libera Brilliance+

GRID X-Ray BPM Design and R&D

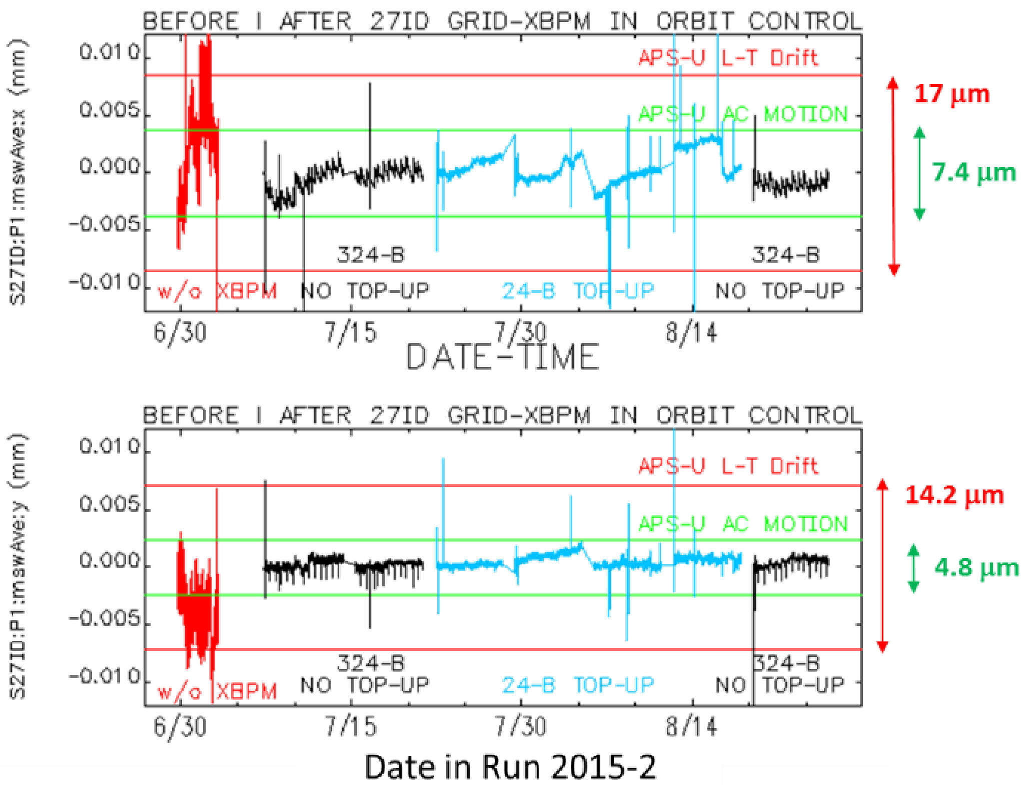


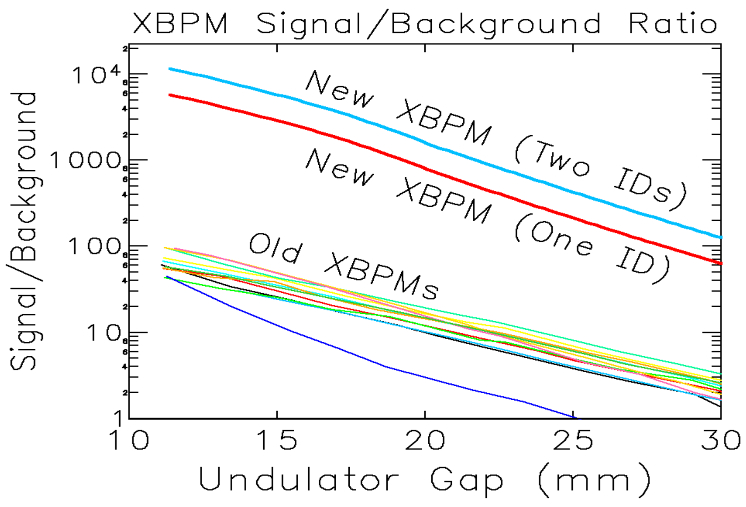
- Based on interception of hard X-rays and subsequent fluorescence by Cu (GlidCop)
- Vertical position obtained by pinhole imaging, horizontal from difference over sum using upstream and downstream detector modules
- Final engineering of system underway due to higher energy/flux of bending/quad magnet backgrounds in the 42 pm MBA ring (16 pin diode detector channels used to subtract background radiation)
- BM X-ray BPMs use the M3 source, contamination by the Q8 and M4 sources mean only one half the fan is useable (by users and the BM XBPM)

GRID X-Ray BPM Design and R&D cont.*

Horizontal beam positions in 60-days of User Operations

Vertical beam positions in 60-days of User Operations





- GRID prototype installed in the sector 27 (summer 2015) front-end of the APS storage ring (Long-term drift)
- GRID has a factor of 30 better signal to bending magnet background compared to existing (Old) photoemission (PE) XBPMs
- PE bpms made useable by Decker distortion that directs background radiation away from the XBPM
- GRID and ID rf BPM Mechanical Motion R&D program completed including analysis of SR tunnel air and water temperature stability

* B. X. Yang etal. IPAC 2015, Richmond, VA, 2015
B. X. Yang etal. IBIC 2016, Barcelona, Spain, 2016
G. Decker, PAC 2007, Albuquerque, NM, 2007

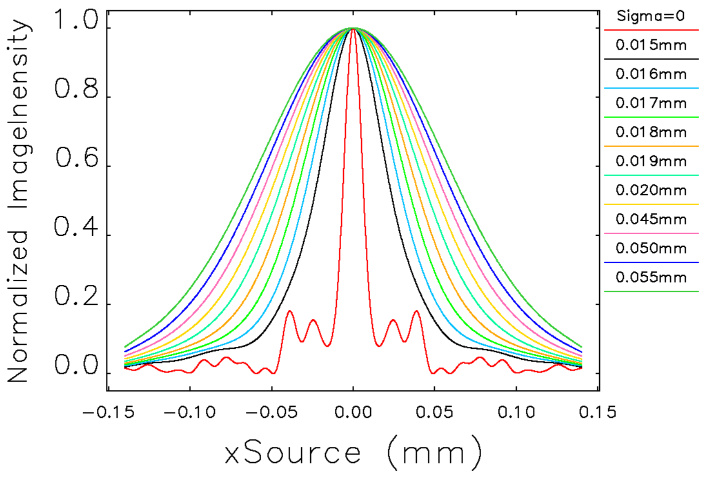
Beam Size and Emittance Measurement Design Considerations*

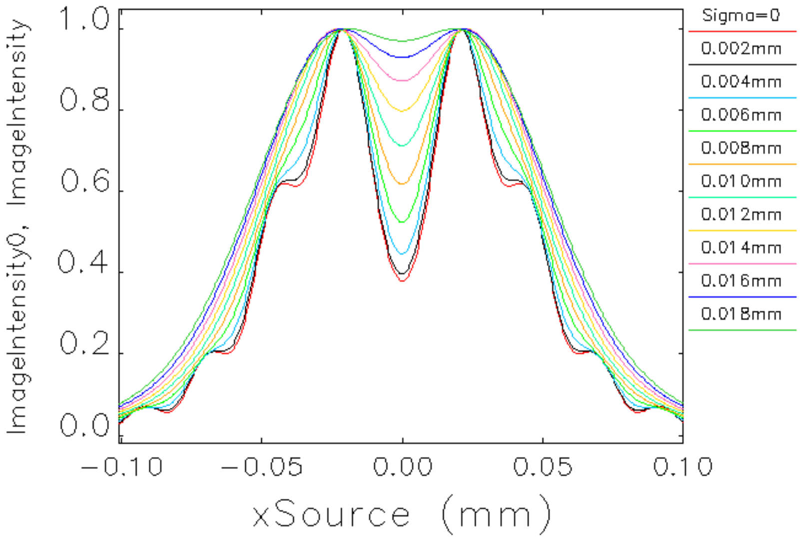
- APS-U MBA ring A:M1 source to be used to emittance measurement diagnostics (B:Q8 to be used for energy spread measurements and redundant vertical beam size)
  - Low dispersion allows for clean emittance measurements
  - Larger beam sizes relax resolution requirements compared to other possible lattice sources
- Three measurement techniques are considered to cover all expected beam conditions and the smallest expected emittance of 4 pm-rad
- For absolute beam size measurements we will use:
  - Pinhole camera for beam sizes from 8-100 microns
  - Wide aperture Fresnel diffractometer for beam sizes 4-16 microns
  - Another Fresnel diffractometer for beam sizes 1-5 microns
- For relative beam size changes when adjusting coupling, a 1-D double-slit collimator will be used to monitor normalized peak intensities
- **Coherence preservation for measurement of small beam size is the greatest concern**

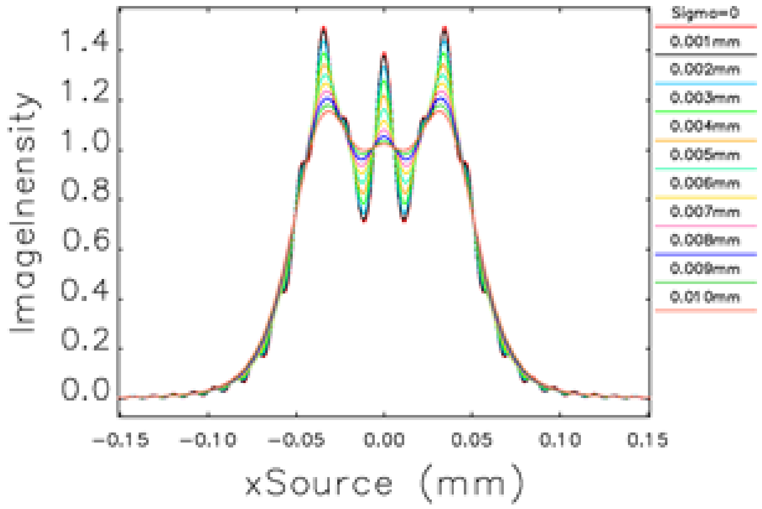
* B. X. Yang, Emittance 2018 Workshop, Barcelona Spain, January 2018

Beam Size and Emittance Measurement Design Considerations cont.*

- Extended beamline length for 3:1 magnification
- Three X-ray diffraction imaging branch lines:
  - 12 keV X-ray pinhole camera (right) for beam sizes 8-100 microns
  - 12-keV Fresnel diffractometer (lower-left) for beam sizes 4-16 microns
  - Another 12-keV Fresnel diffractometer (lower-right) for beam sizes 1-5 microns (0.5-1.2 pm-rad vertical)



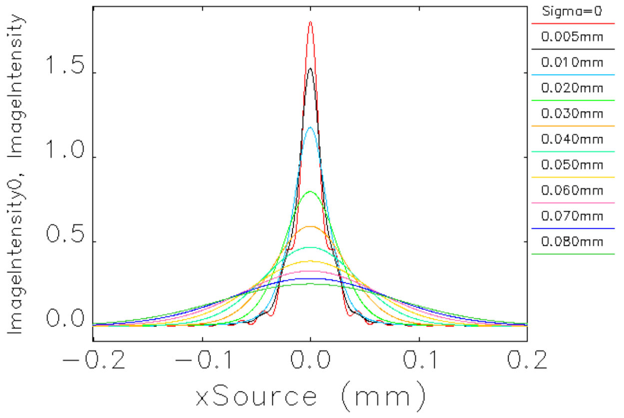


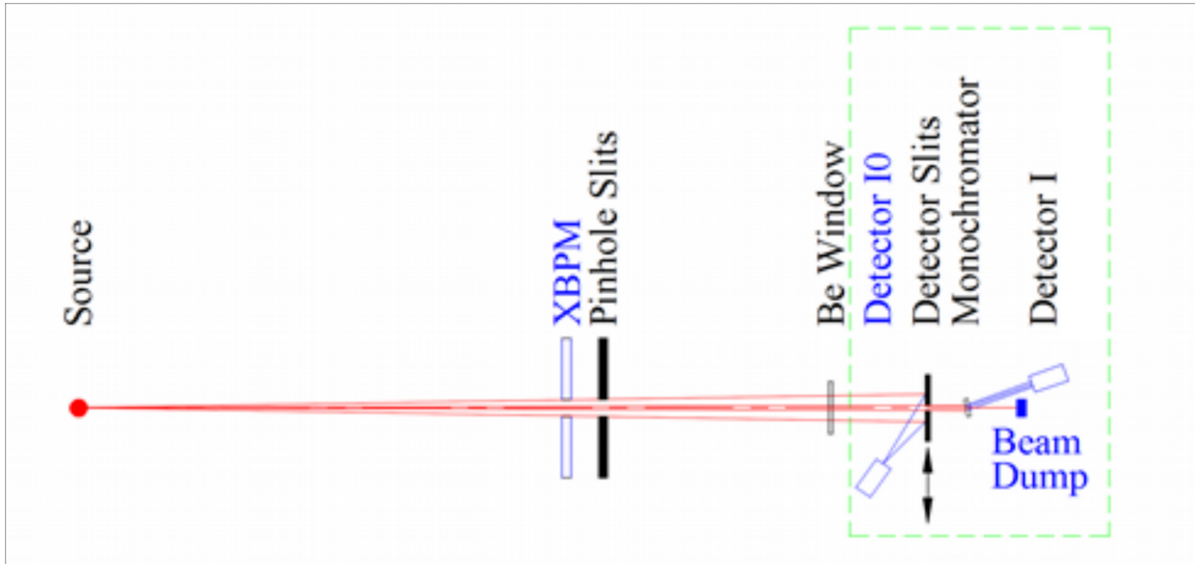


Beam Size and Emittance Measurement Design Considerations cont.*

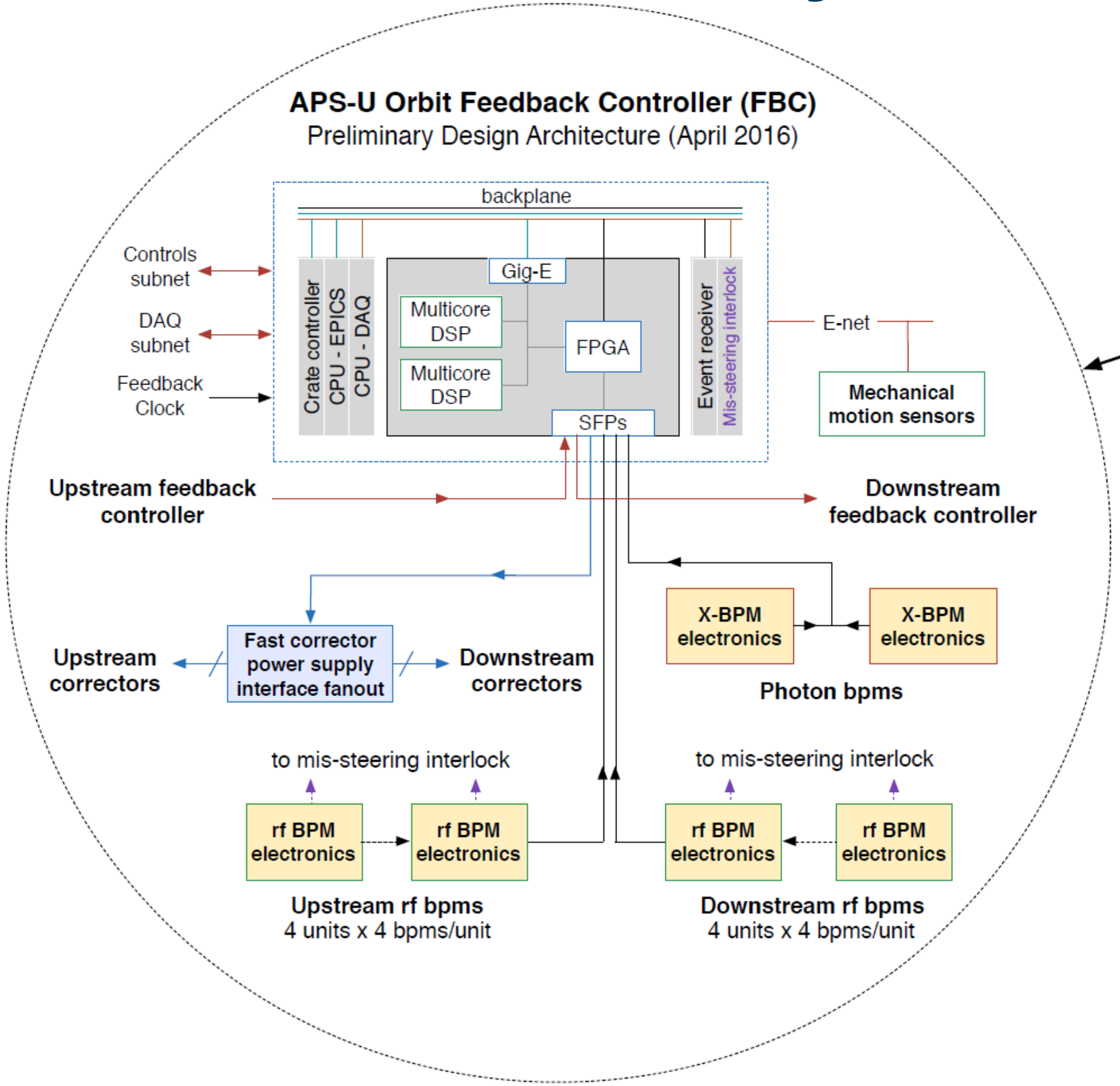
- One-Dimensional 12-keV X-ray pinhole Camera for Relative Beam Size Monitor
- Pinhole slit width chosen to maximize peak intensity at the detector
- The slit length increases the X-ray flux five fold relative to a single pinhole
- Detector slit width chosen to balance good resolution and good signal level

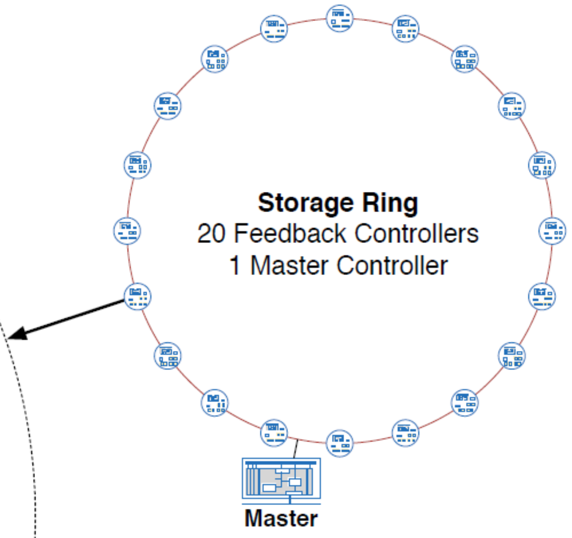
Source distance	Pinhole slits	Detector distance	Detector slits	M	Source sizes
6.6 m	34 μm × 150 μm	13.4 m	10 μm × 400 μm	2.6	4 – 100 μm





Orbit Feedback System Design and R&D*



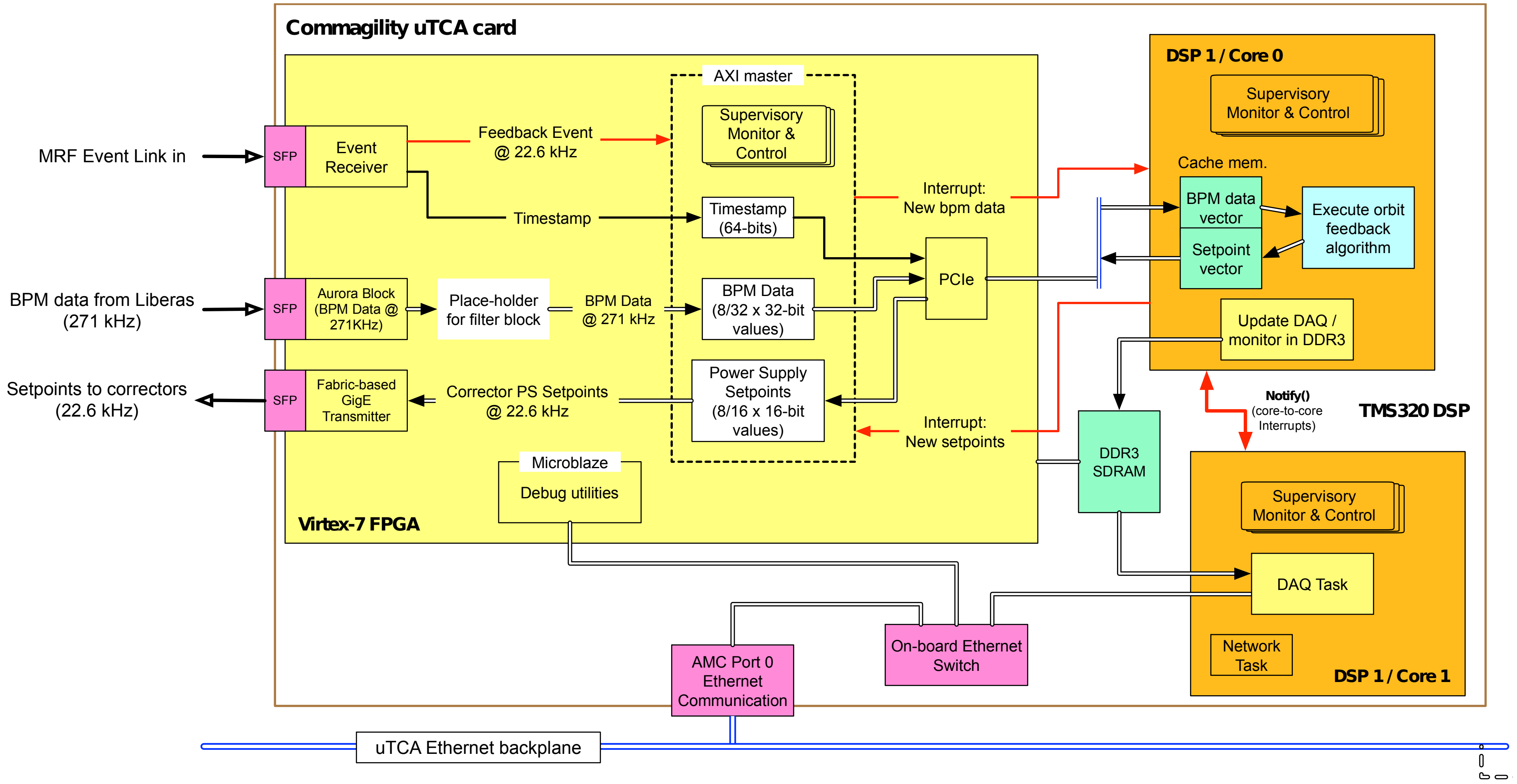


Use "double sector" architecture with one Feedback Controller (FBC) every two sectors

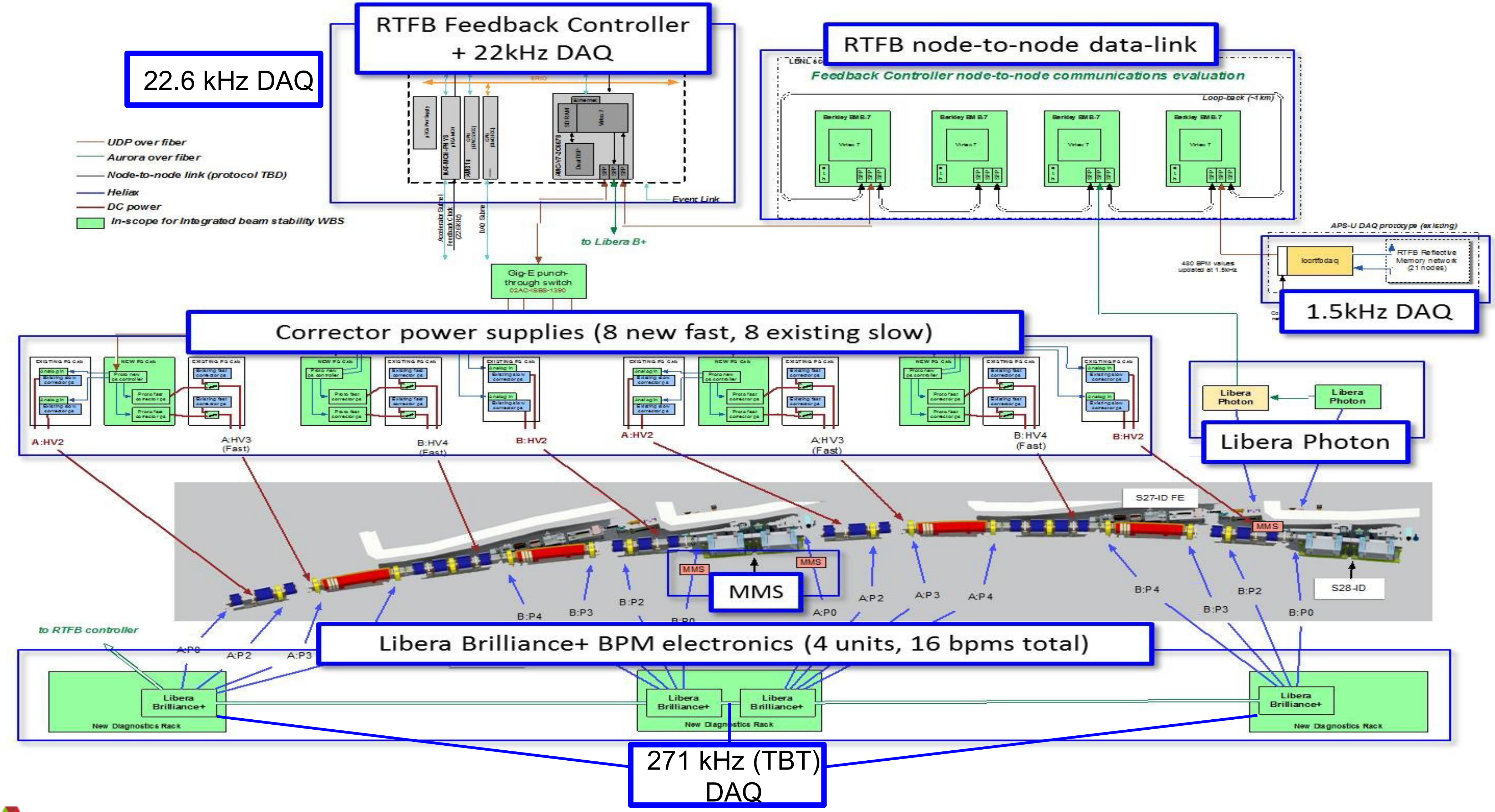
J. Carwardine (14 April 2016)

*P. Kallakuri etal., IBIC 2017, Grand Rapids Mi, 2017
N. Sereno etal., IPAC 2018, Vancouver, BC
N. Sereno etal., 6th International DLSR Workshop, Berkeley CA. 2018

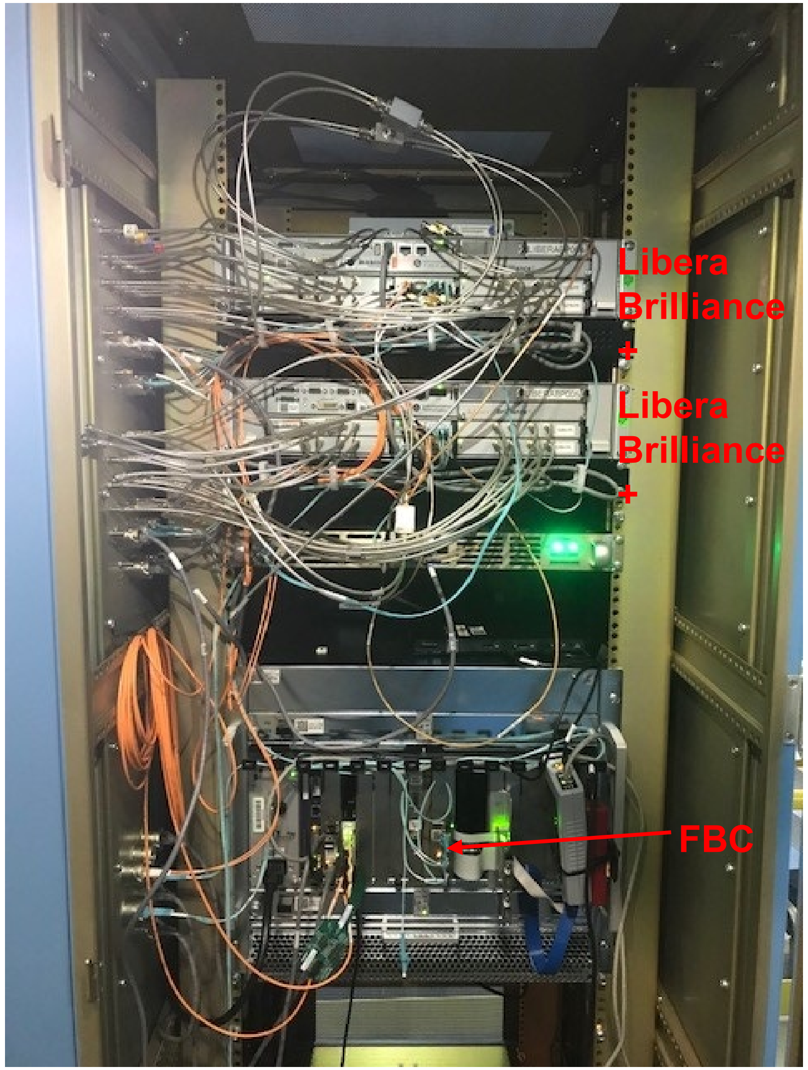
Orbit Feedback System Design and R&D: Prototype Orbit Feedback Controller



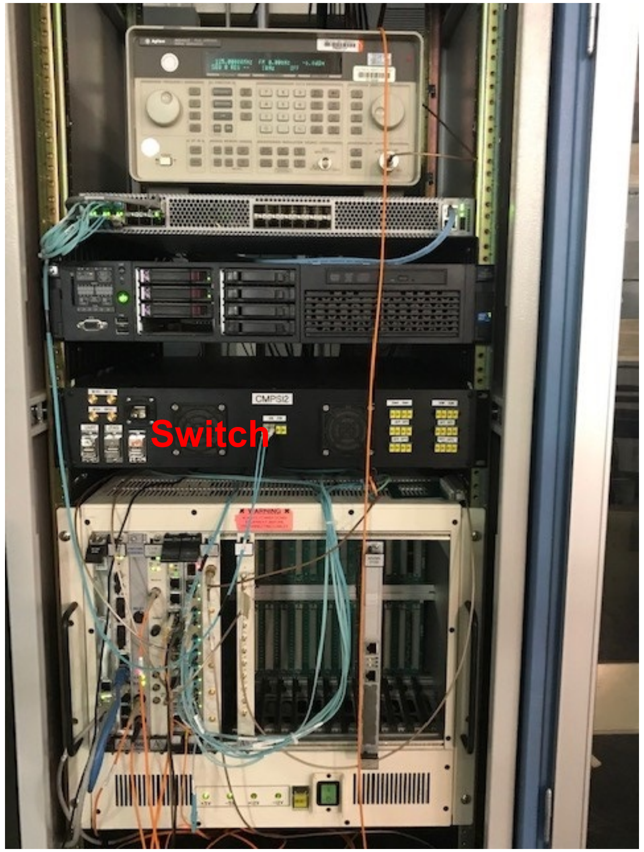
Orbit Feedback System Design and R&D: Sector 27 Test Using a Prototype FBC



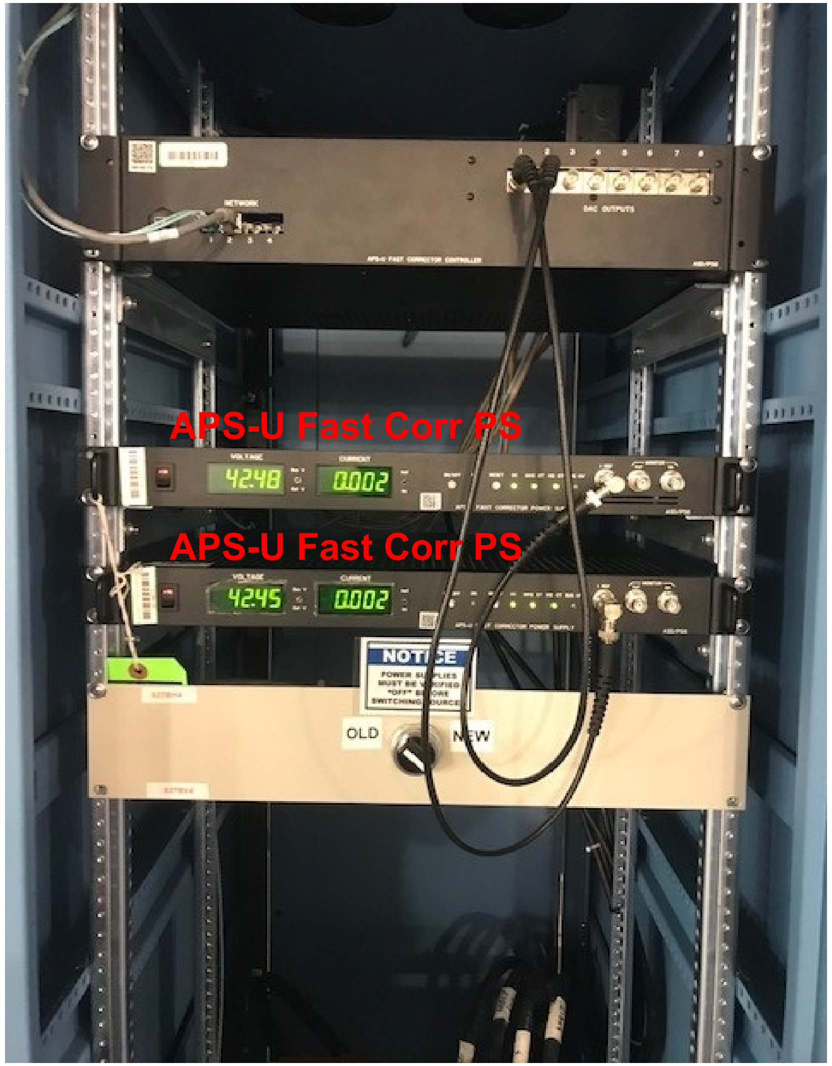
Orbit Feedback System Design and R&D: Hardware



Libera Brilliance+ and FBC uTCA Cabinet



Corrector setpoint switch ~22.6 kHz Cabinet



APS-U Prototype Fast Corrector PS Cabinet

Orbit Feedback System Design and R&D: Hardware Demonstrated

Present system (circ. 1995)

Parameter	APS-U design	'Datapool'	RTFB
Algorithm implementation	'Unified feedback' algorithm ✔	Separate DC and AC systems for slow and fast correctors	
BPM sampling & processing rate	271 kHz (TBT) ✔	10 Hz	1.6 kHz
Corrector ps setpoint rate	22.6 kHz ✔	10 Hz	1.6 kHz
Signal processors (20 nodes)	DSP (320 GFLOPS) + FPGA (Virtex-7) ✔	EPICS IOC	DSP (40 MFLOPS)
Num. rf bpms / plane	560 (14 per sector) ✔	360	160 (4 per sector)
Fast correctors / plane	160 (4 per sector) ✔	-	38 (1 per sector)
Slow correctors / plane	320 (8 per sector) ✔	282	-
Fast corrector ps bandwidth	10 kHz ✔	-	1 kHz
Fast corrector latency	<10 us ✔	-	~250 usec
Closed-loop bandwidth	DC to 1 kHz ✔	DC - 1 Hz	1 Hz - 80 Hz

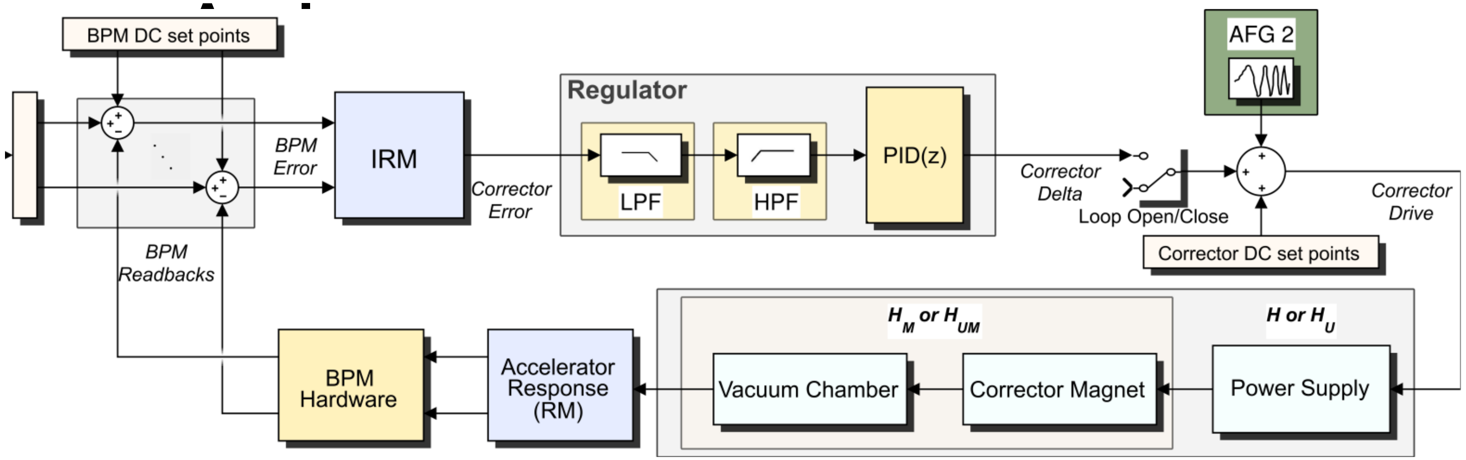
✔ (purple) Demonstrated
✔ (green) Demonstrated in a double-sector

Orbit Feedback System Design and R&D: Feedback System Measurements

- Need to evaluate the effects of latency on regulator tuning
- Obtaining orbit attenuation by dividing open and closed loop BPM position PSDs is noisy
- Dynamic-system analyzer approach: measure response to a known excitation using AFGs

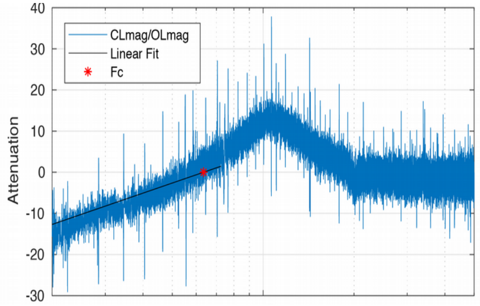
Built In Dynamic Signal

Applied perturbation



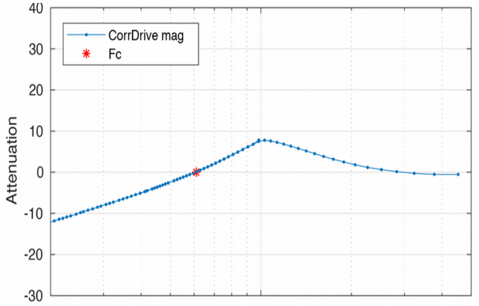
Residual perturbation

Compute ratio of PSDs (Noisy, imprecise)



Frequency (Hz)

Measure response to applied perturbation

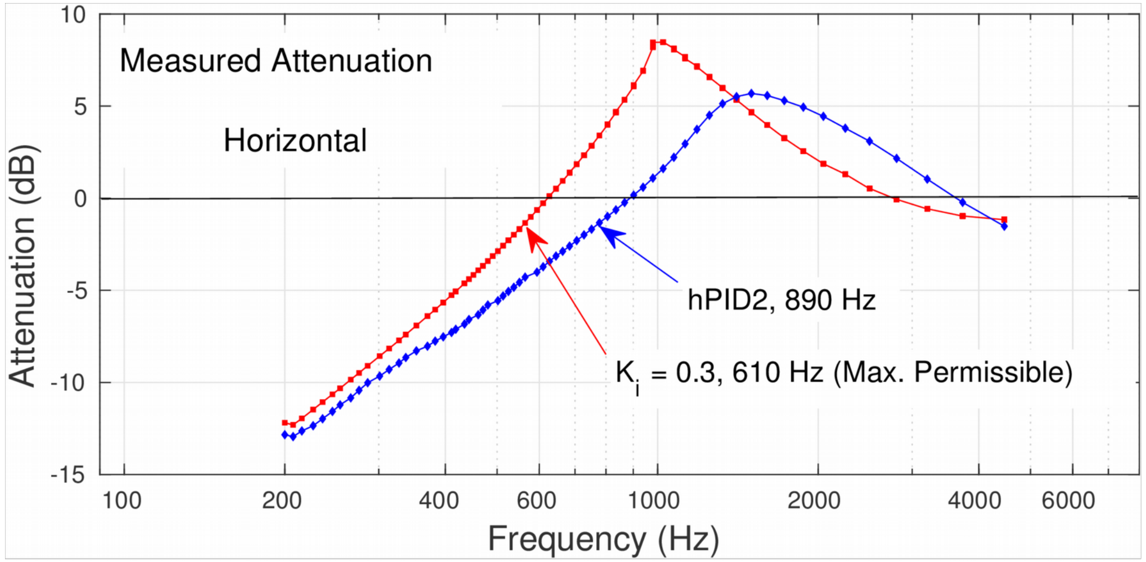


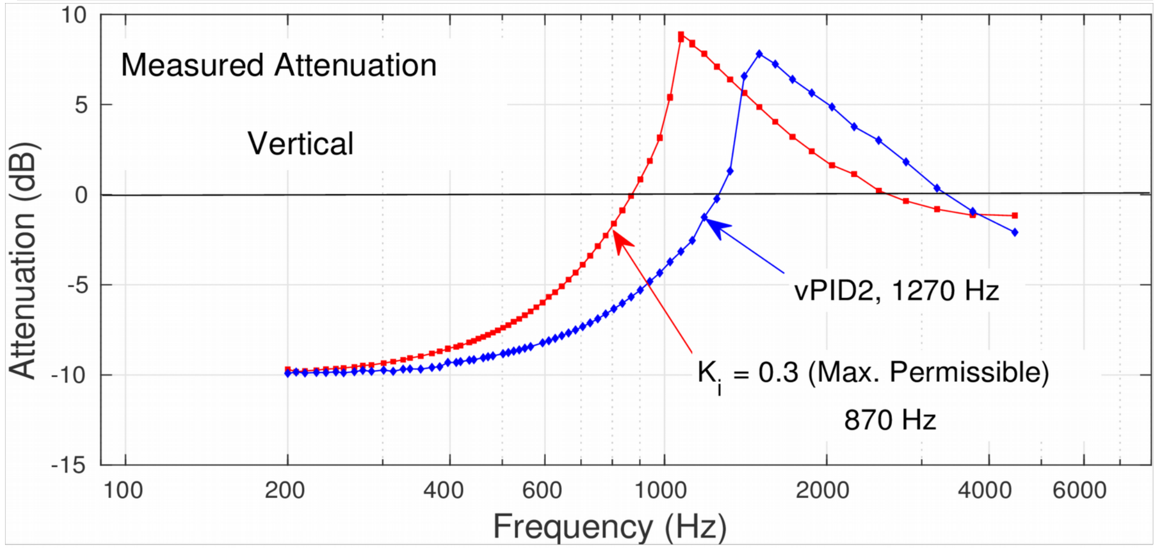
Frequency (Hz)

- Multiple simultaneous bpm/corrector measurement channels
- Beam-based measurement of frequency- and time-domain responses
- Resolve differences in transfer-function to <10Hz
- Closed-loop Response Matrix measurements

Orbit Feedback System Design and R&D: Measuring Orbit Feedback Effectiveness

- Red curve is orbit attenuation for integral gain only
- Blue curve is using all three PID gains calculated using a system model to improve closed loop bandwidth and overshoot
- Amplification at high frequencies corresponds to overshoot in the step response
- Obtained 1 kHz closed-loop bandwidth using PID gains calculated using a system model

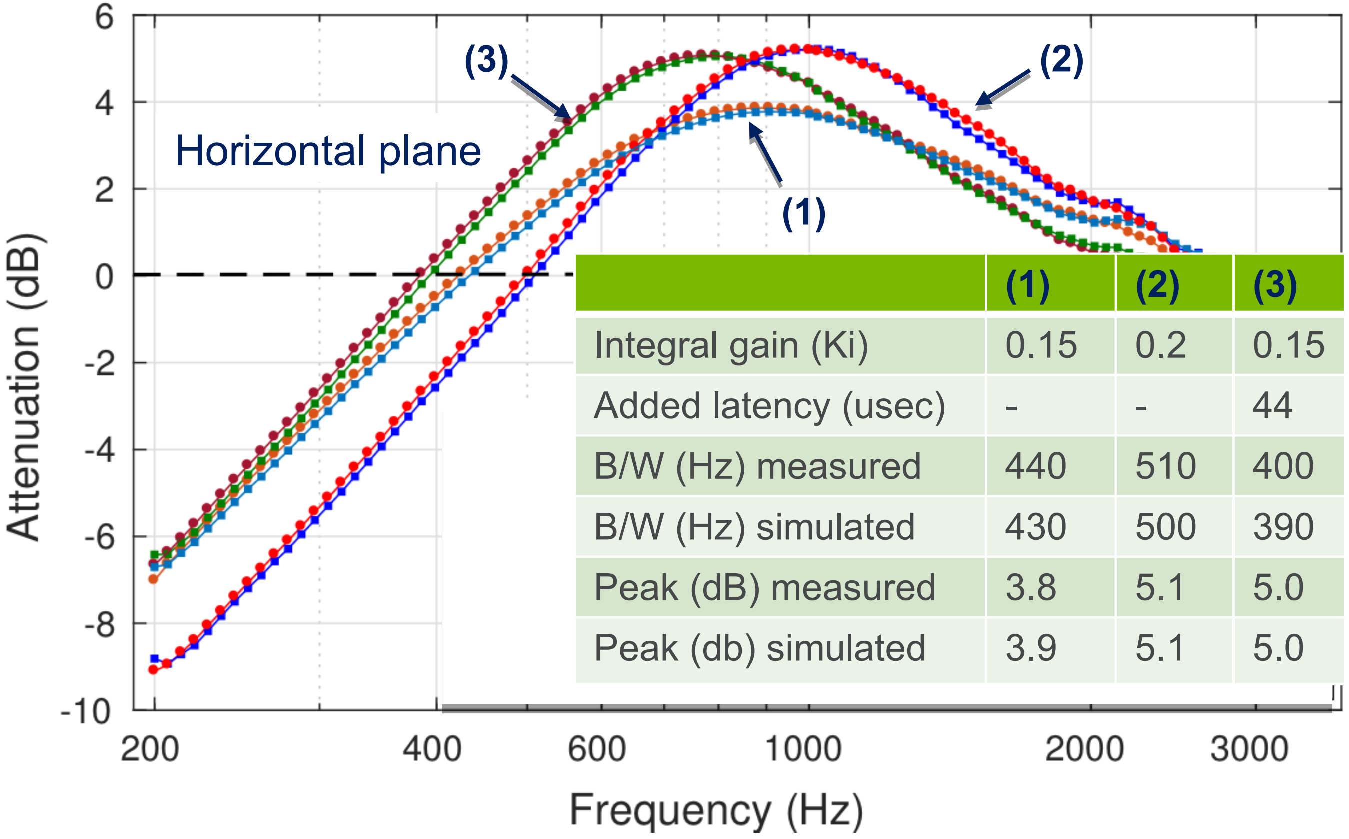




Orbit Feedback System Design and R&D: Comparison of Model with Measurement

- Used only integral gain for this comparison showing excellent agreement between model and experiment
- Adding 44 ms latency decreases the closed-loop bandwidth for the same gain
- Case 2 is in fact unstable when adding 44 ms latency

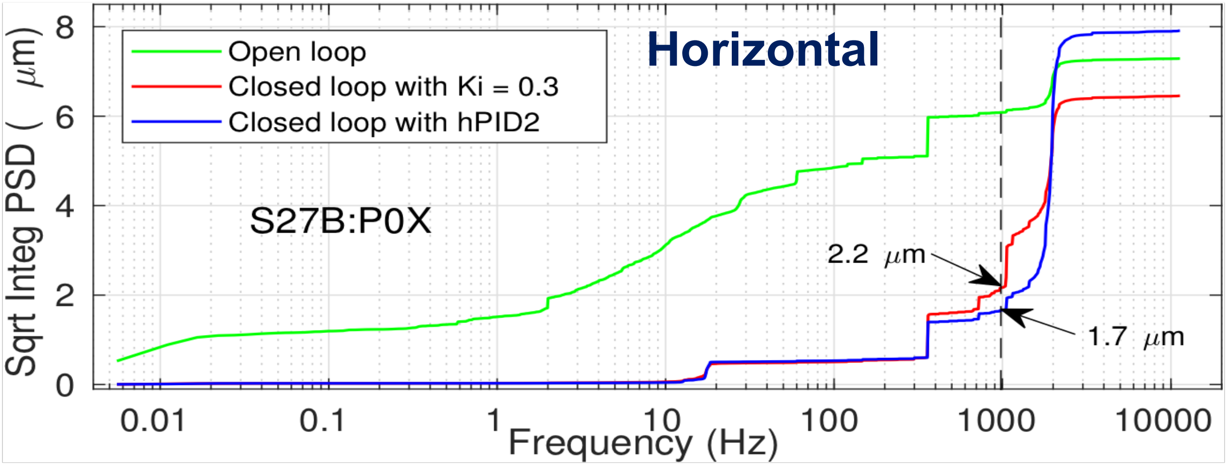
Attenuation responses with/without added latency

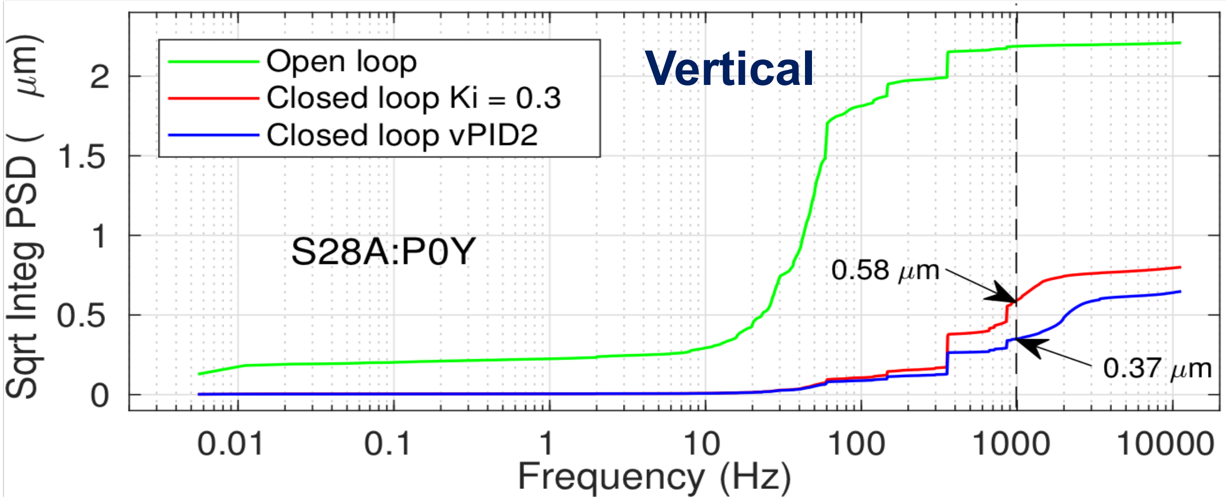


	(1)	(2)	(3)
Integral gain (Ki)	0.15	0.2	0.15
Added latency (usec)	-	-	44
B/W (Hz) measured	440	510	400
B/W (Hz) simulated	430	500	390
Peak (dB) measured	3.8	5.1	5.0
Peak (db) simulated	3.9	5.1	5.0

Orbit Feedback System Design and R&D: Cumulative RMS Motion

- Demonstrated APS-U AC beam stability goals in a double-sector of the APS ring
- Large horizontal motion at frequencies corresponding to 360 Hz rf system power supply ripple





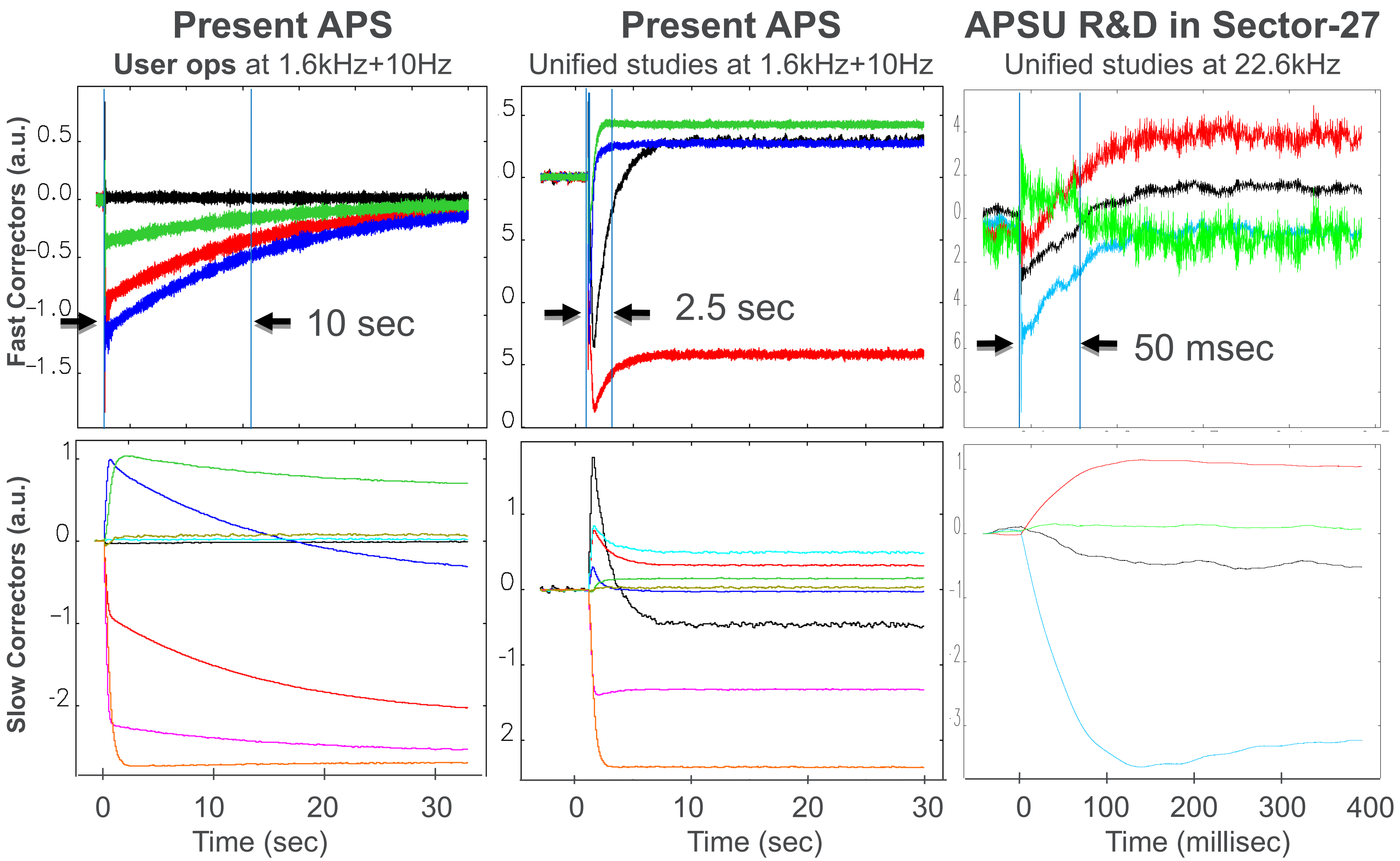
Plots show cumulative RMS motion up to 11 kHz:

- Open-loop
- Ki regulator
- Ki+Kp+Kd regulator

Large sources of orbit motion at 360 Hz and 1.8kHz is due to synchrotron motion

Orbit Feedback System Design and R&D: Unifying Fast and Slow Orbit Correction

- Algorithm uses a modification of the slow corrector response matrix using the full machine (fast+ slow correctors) response matrix



Summary

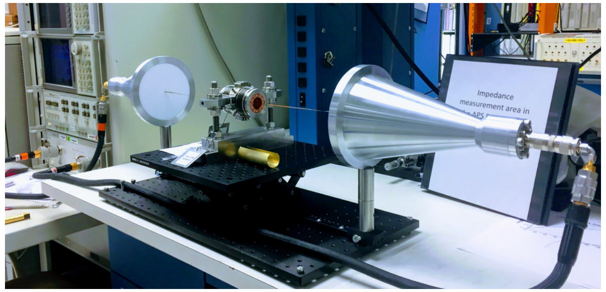
- APS-U diagnostics requirements driven by small beam sizes
- Diagnostics also required to have sufficiently good performance for initial commissioning at low signal levels
- Must be able to measure KPPs after initial commissioning
- Orbit feedback R&D program demonstrated ability to meet demanding AC stability requirements.
- Demonstrated ability to meet long-term drift requirements in R&D using mechanical motion monitoring of ID rf and GRID X-ray bpms
- Other interesting R&D topics not discussed are MMS R&D, Open/Closed loop response matrix measurements, unified feedback but would be happy to discuss these
- Looking forward to hearing from DEELs participants about their diagnostics experiences at the European light sources

Acknowledgements

- ASD – Diagnostics:
  - R. Blake, A. Brill, H. Bui, W. Cheng, P. Dombrowski, L. Erwin, R. Keane, R. Lill, X. Sun, B. X. Yang, R. Zabel
- AES – Controls:
  - N. Arnold, T. Fors, P. Kallakuri, D. Paskvan, A. Pietryla, G. Shen, S. Shoaf, S. Xu
- ASD – Power Supplies:
  - B. Deriy, J. Wang
- APS Upgrade Vacuum:
  - J. Carter, H. Cease, B. Stillwell
- ASD – Accelerator Operations and Physics
  - M. Borland, L. Emery, V. Sajaev, H. Shang, A. Xiao
- APS Upgrade Project:
  - J. Carwardine, G. Decker, U. Wienands
- Facilities:
  - M. Kirshenbaum, G. Kailus

Backup Slides

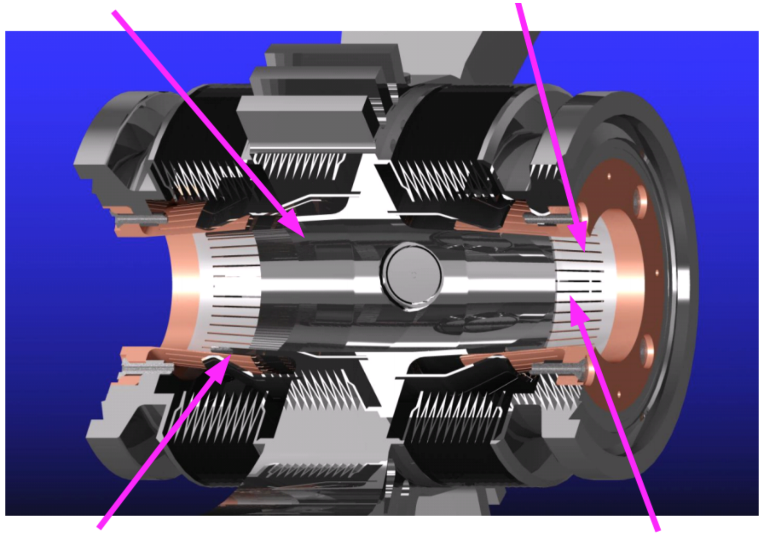
RF BPM System cont.



- Characterized coupling impedance of prototype BPM assembly using a Goubau line test fixture
- BPM assembly indicates a broadband low-loss response
- Need to repeat the test with the final BPM assembly

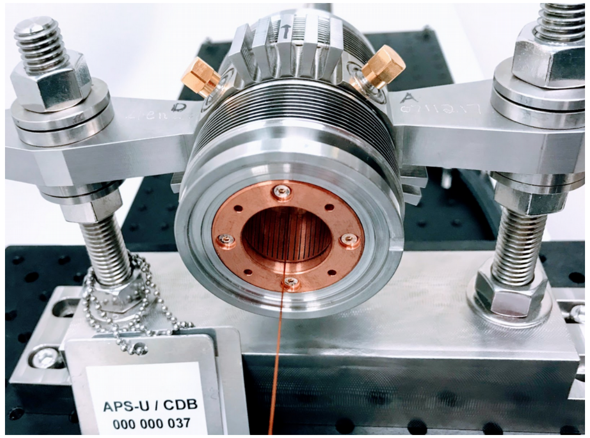
Minimize the size of cavity to reduce effect of trapped modes

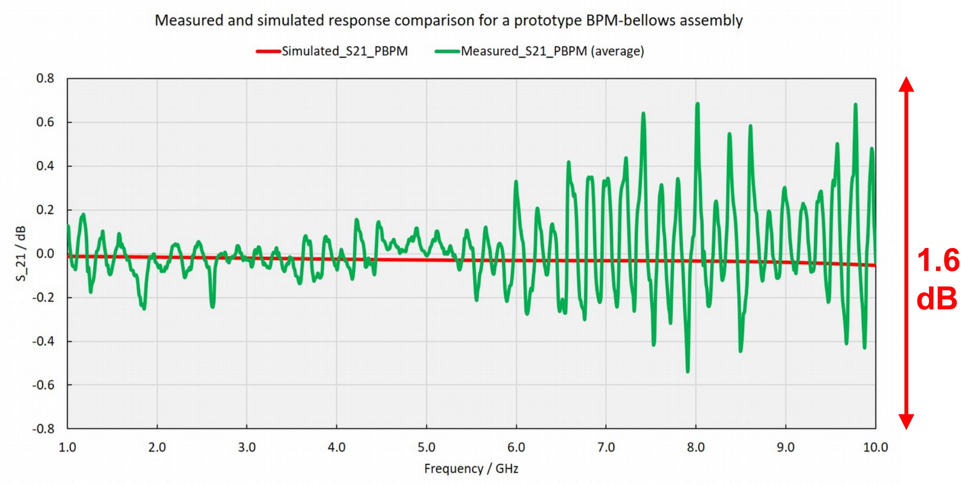
Use small slots to shield low-frequency EM fields



Gradual tapering to different dimensions

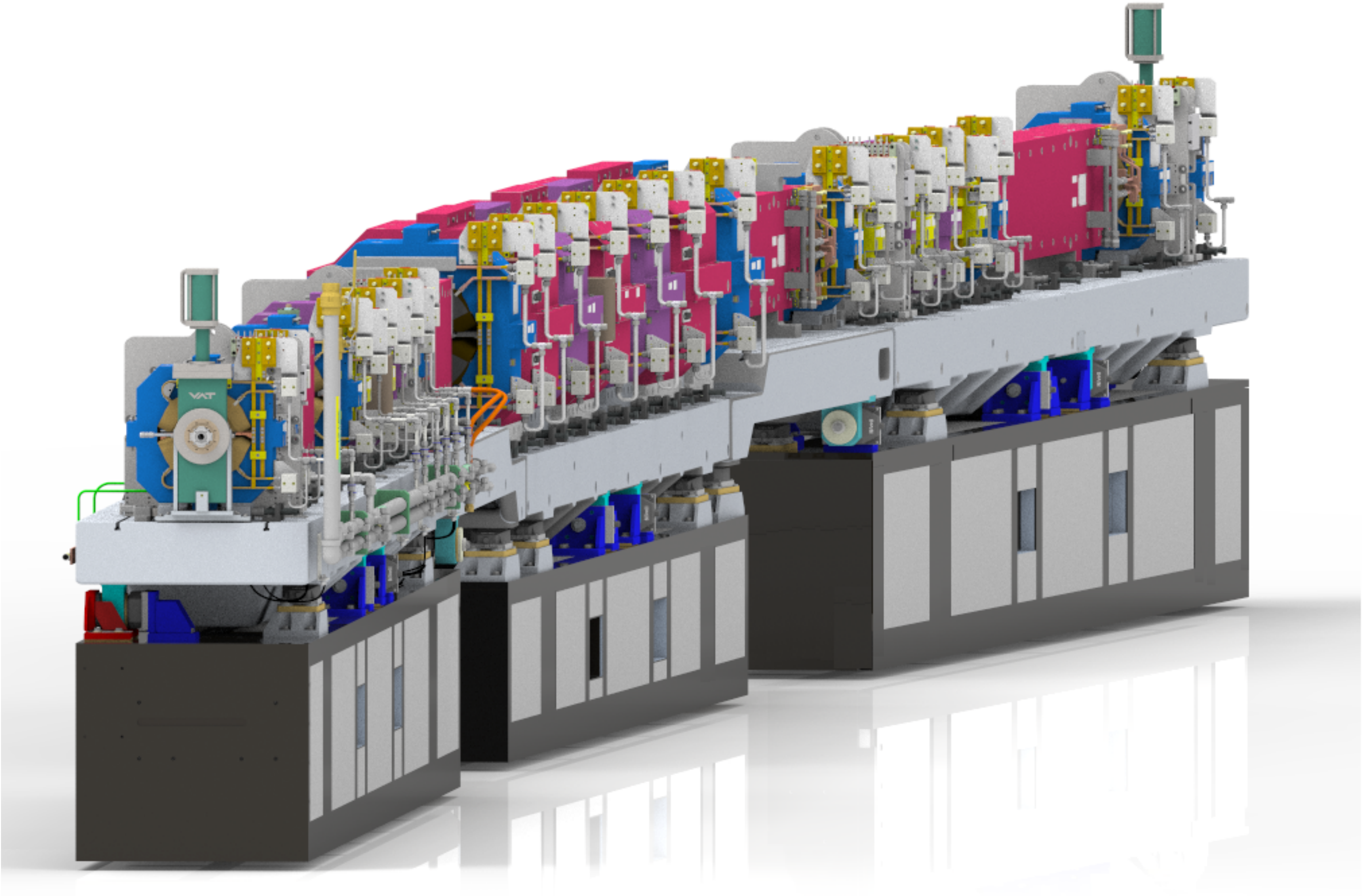
Plate poor conductors with good conductors (if possible)





Mechanical Support Structures

- Large assemblies (DLM, FODO) have been demonstrated.



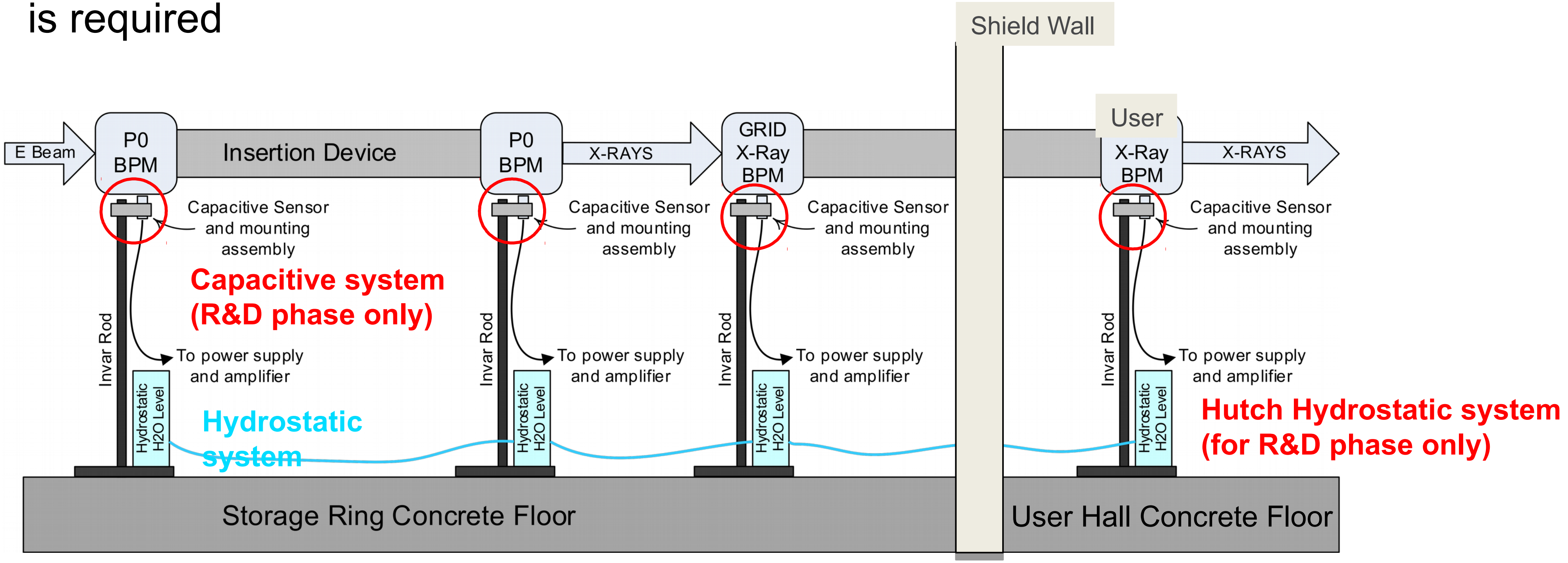
One of Forty Sectors of APS-U Arc Components

Large integrated assemblies reduce installation time.

Design optimized to minimize static deflection and sensitivity to ground vibration.

Mechanical Motion Measurement System (MMS) Configuration for R&D

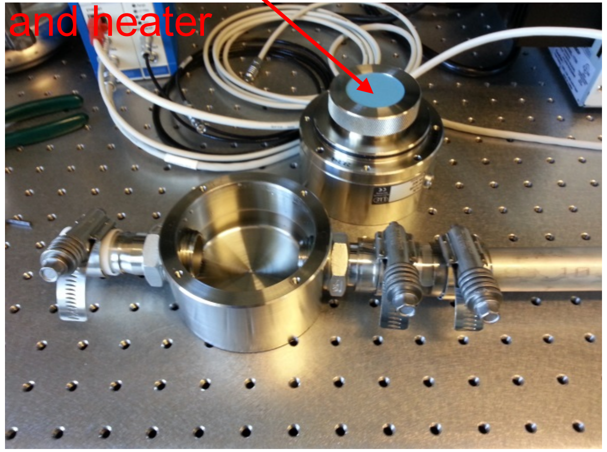
- Instrument BPMs with capacitive and hydrostatic detectors for R&D in sector 27 of the APS ring (Capacitive sensors descoped for APS-Upgrade)
- Use data from the system to show in R&D how to correct bpm position for mechanical motion of the bpms
- Instrumented ID rf bpms and GRID X-ray BPM in sector 27
- APS-U final design retains only the hydrostatic system: capacitive system informed the design by indicating rigid supports for ID rf and GRID XBPMs is required

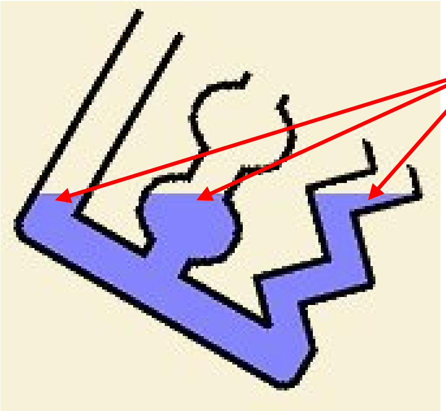


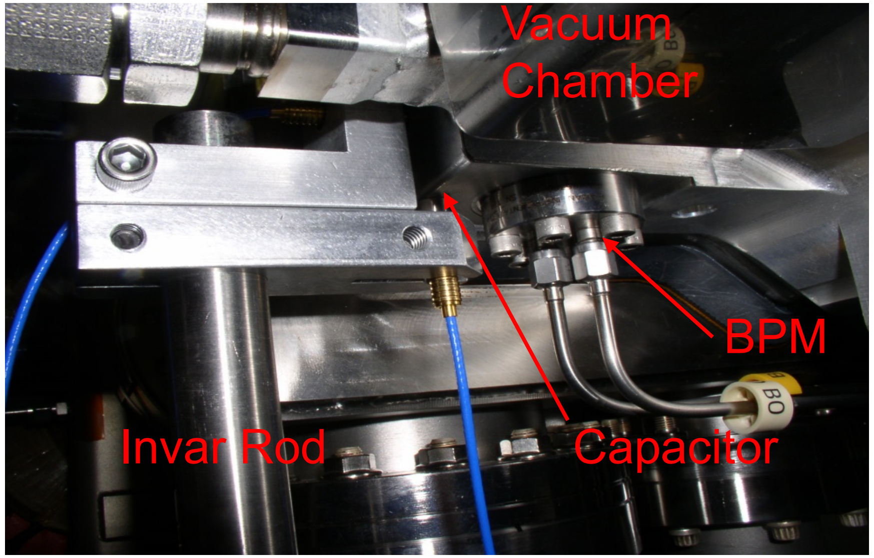
*R. Lill etal. IPAC 2015, Richmond, Va. 2015
R. Lill etal. IBIC 2016, Barcelona, Spain, 2016

MMS R&D Design

Capacitive electrode and heater

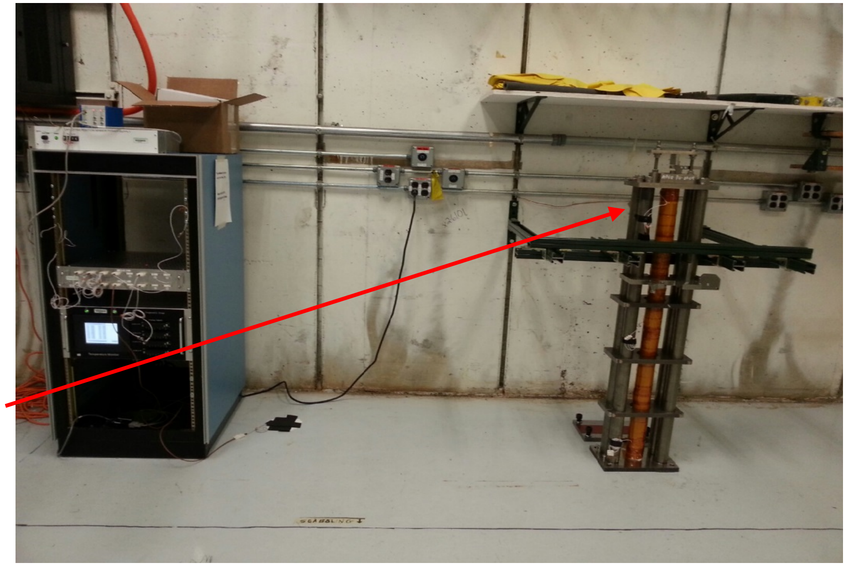






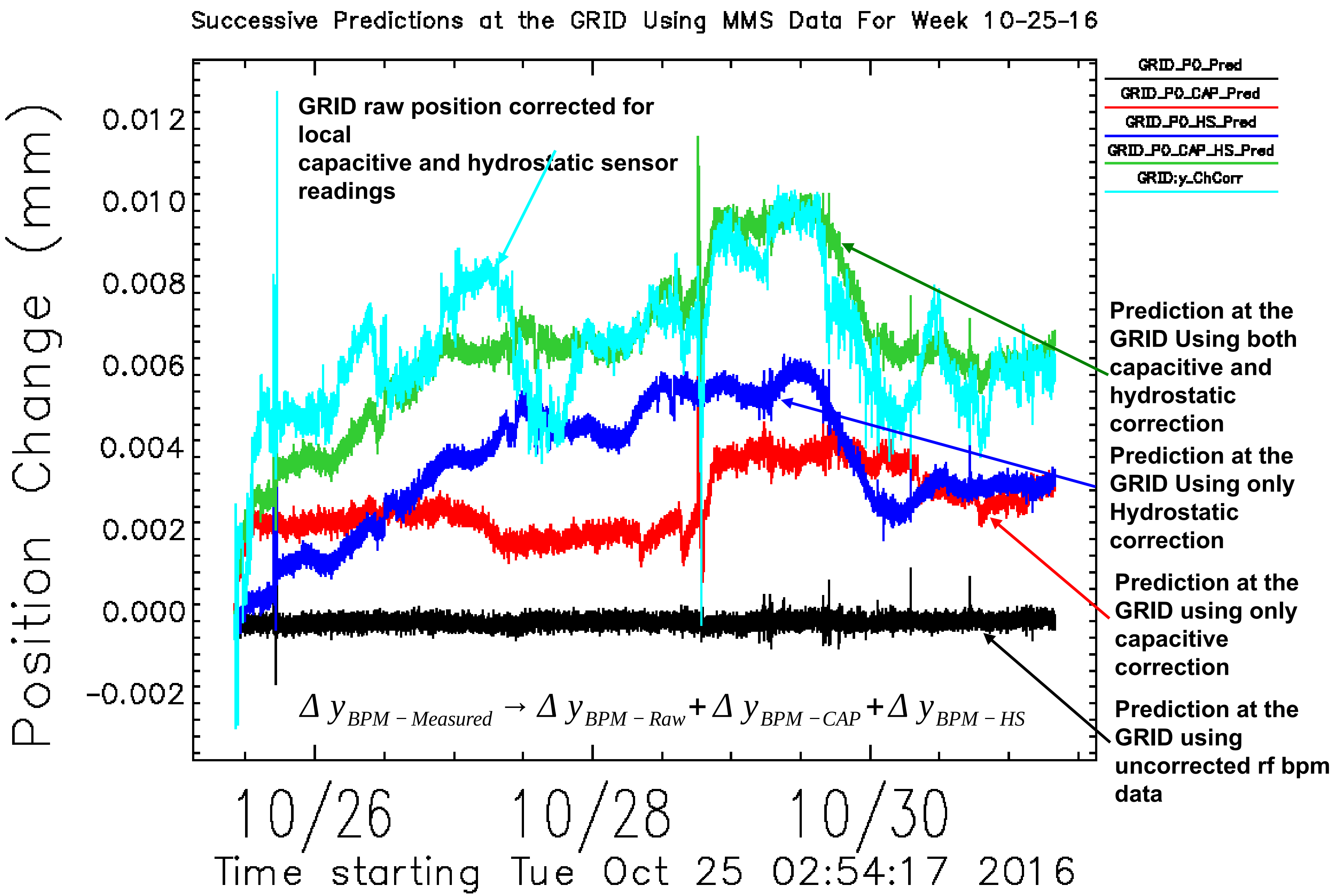
Communicating Vessels: H_20 level is the same relative to ground no no matter the orientation or shape of the vessels

Provides an absolute vertical Reference



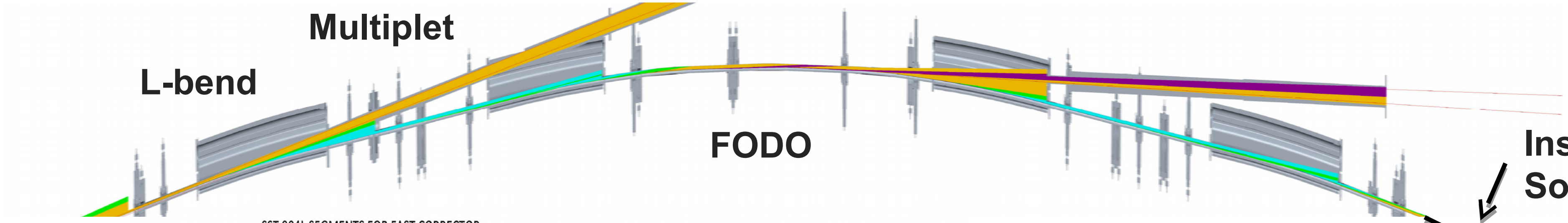
- ID rf bpms for MBA are now planned to have their own Invar support system similar to that for NSLS-II

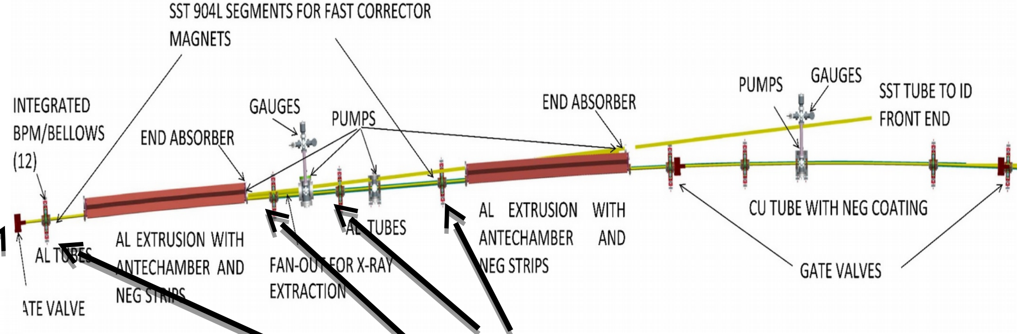
MMS Correction of Raw BPM Position Using Orbit Feedback*

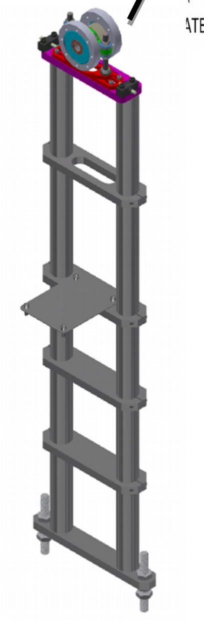


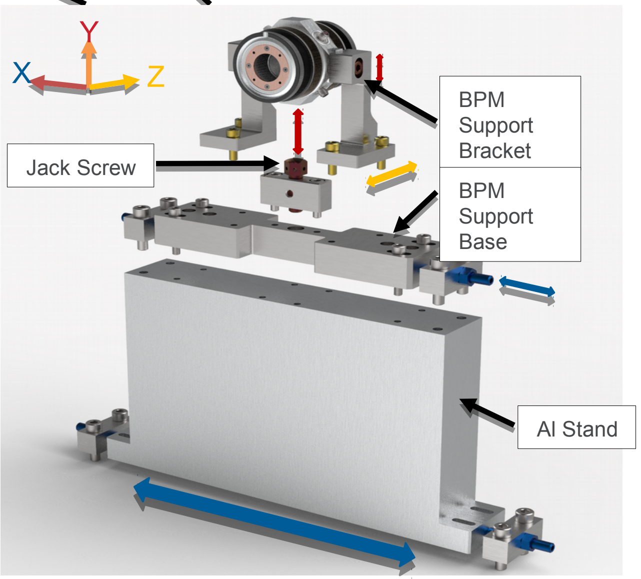
*N. Sereno etal., GM2017 Workshop, Beijing, China 2017

Vacuum System





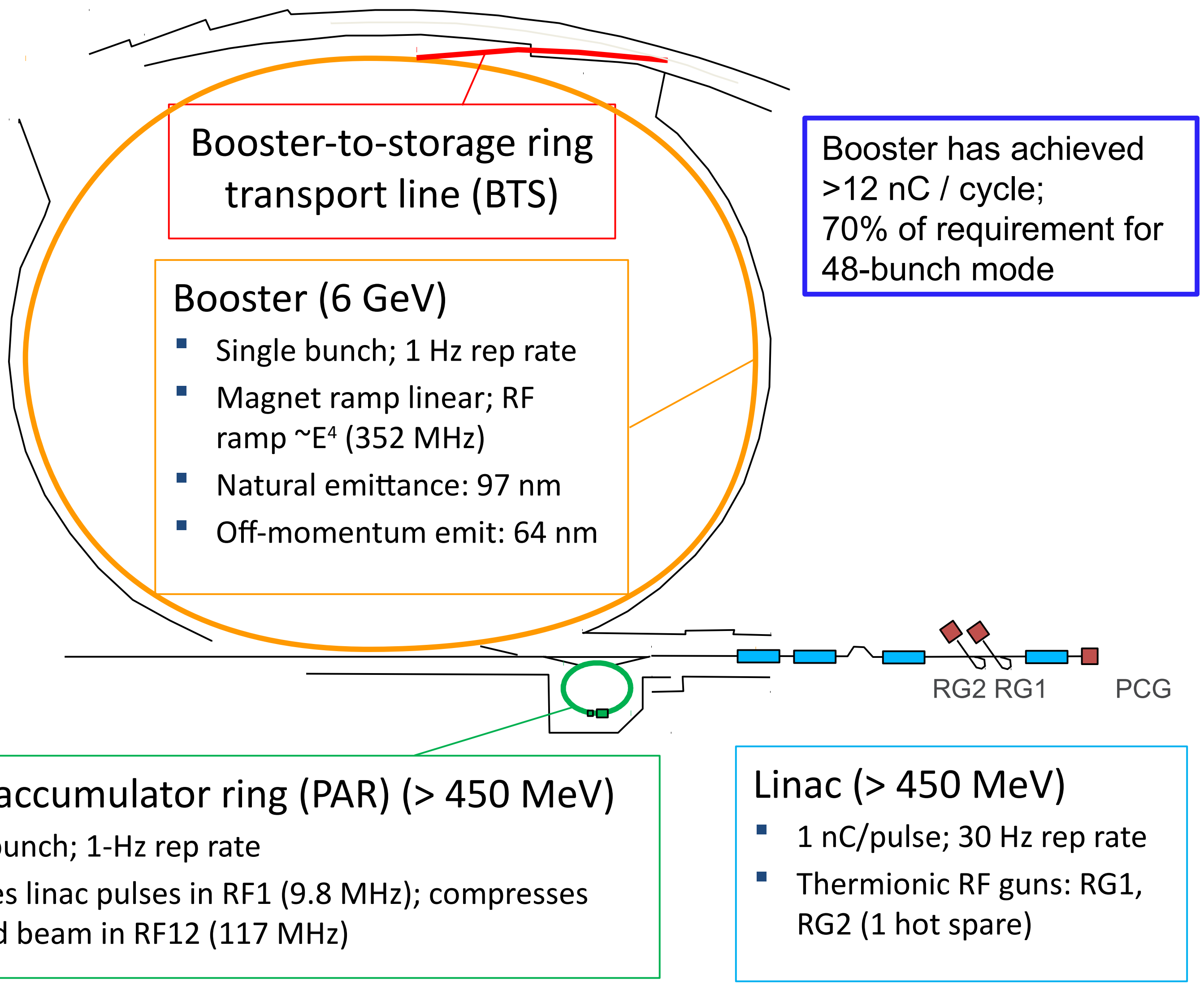




Round Chambers

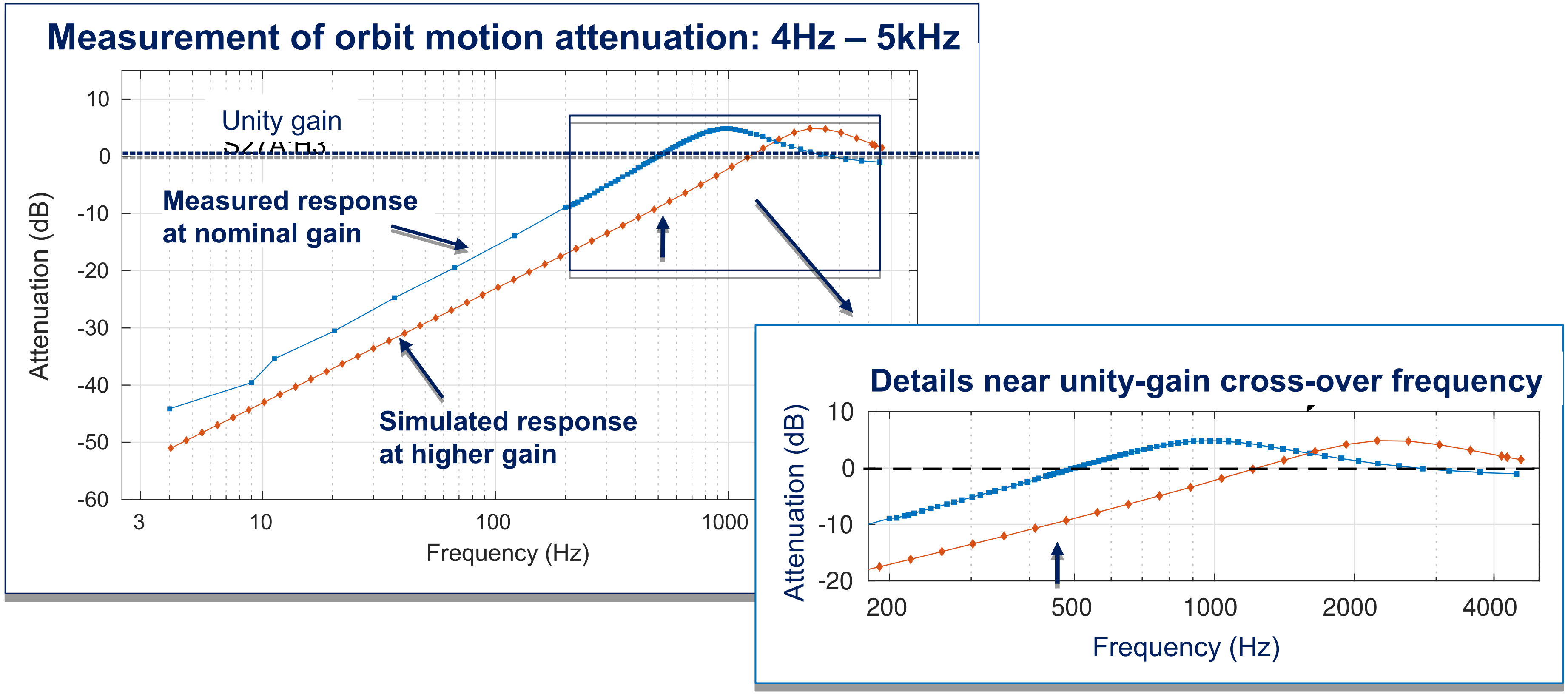
Injector Upgrades

- Injector upgrades –
  - Increase PAR extraction / booster injection energy
    - 375 to > 450 MeV
  - Decouple booster / storage ring rf frequencies to accommodate new storage ring circumference.
    - New timing system
    - New low-level rf controls
  - Reconfigure Booster-to-Storage Ring (BTS) transport line



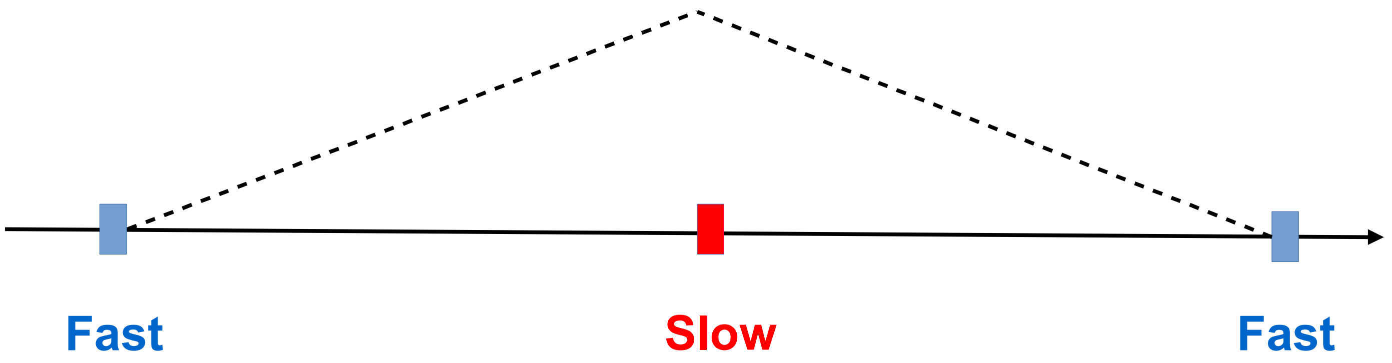
Orbit Feedback System Design and R&D: Modeling Orbit Feedback Effectiveness

- Measured more than 40 dB of orbit attenuation at low frequencies (blue curve)
- Simulated attenuation curve used a model of the APS-U power supply, magnet and vacuum chamber using integral control (orange curve)
- We predict we can obtain >1 kHz closed-loop bandwidth in APS-U assuming latencies transporting b pm data around the ring are minimized



Orbit Feedback System Design and R&D: Unified Feedback Idea

- Problem is to use both fast and slow correctors down to DC to correct the beam without the system becoming unstable
- How would one modify the response matrix to achieve this? First took an experimental approach:
- Run the fast correctors using their standard response matrix down to DC
- Measure the response matrix of the slow correctors
- Invert and run the slow correctors using this measured response matrix.



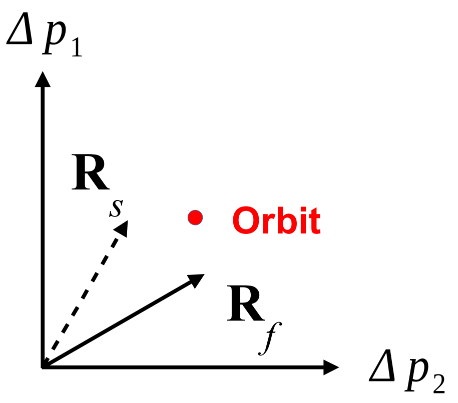
Fast correctors cannot correct to zero DC perturbations inside the 3-bump
Hence, the measured slow corrector response matrix is band diagonal
and slow correction effectively only uses nearby bpms

Orbit Feedback System Design and R&D: Unified Feedback Idea With Reference to Linear Algebra

- The unified “slow” corrector response matrix is exactly calculable from the standard machine response matrix
- Imagine a very simple orbit feedback system consisting of two bpms and two correctors: one fast and the other slow
- The standard response matrix is: $\left[R_f R_s\right]\Delta c=\Delta p$
- The unified response matrix is: $\left[R_f R_{us}\right]\Delta c=\Delta p$
- The unified response matrix has an orthogonal column space (the columns of the response matrix)
- Conclusion: one can tune up slow and fast correctors independently using different (for instance) PID controllers
- Requires there be more bpms than correctors or bpms associated with the fast correctors be less than that for the slow correctors

$$\Delta p=\begin{bmatrix}\Delta p_1\\ \Delta p_2\end{bmatrix}$$

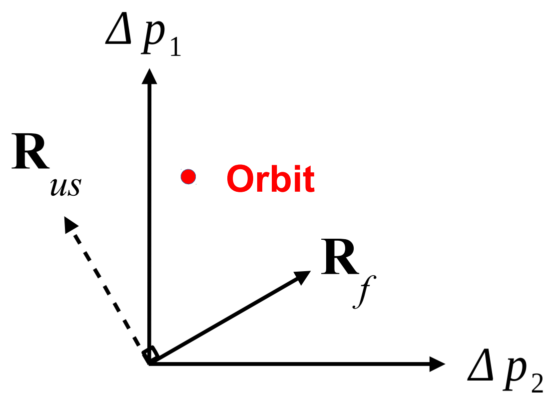
$$\Delta c=\begin{bmatrix}\Delta c_f\\ \Delta c_s\end{bmatrix}$$



Standard orbit feedback

$$R_{us}=\left(I-R_f R_f^{-1}\right)R_s$$

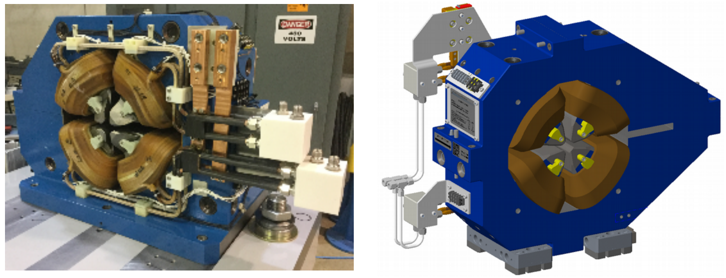
$$P_{R_f}^{perp}=I-R_f R_f^{-1}$$



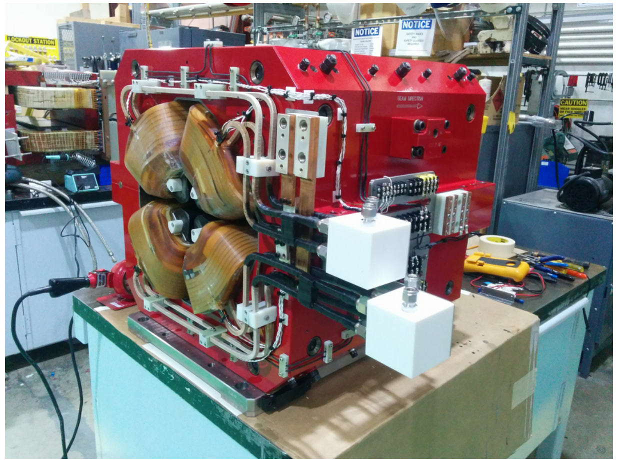
Unified orbit feedback

APS-U Magnets Scope

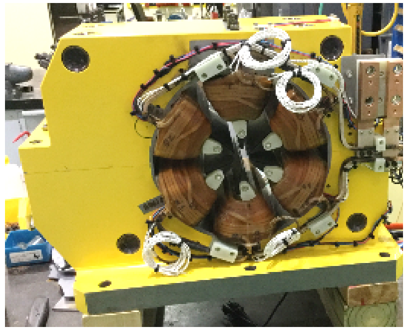
M1 Longitudinal-Gradient Dipole



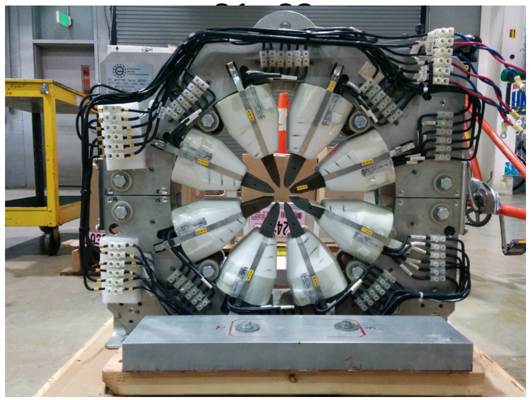
Q1, Q2, Q3, Q6 and Q7 Quadrupole Magnets



Q-Bend Magnets M3,M4



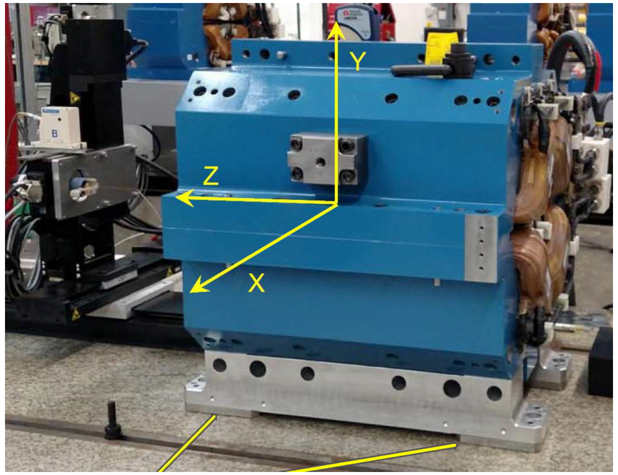
Sextupole Magnets



8-Pole Corrector
(FC1 and FC2)

Item	ID	Types of Magnets	Pole tip material	Total Quantity
1	M1	Longitudinal dipoles	steel	80
2	M2	Longitudinal dipoles	steel	80
3	M3	Transverse-Gradient dipoles	VP	80
4	M4	Transverse-Gradient dipoles	VP	40
5	Q1	Quadrupole	VP	80
6	Q2	Quadrupole	steel	80
7	Q3 and Q6	Quadrupole (**similar to Q2**)	**steel**	160
8	Q4	**Reverse bend Quadrupole**	VP	80
9	Q5	**Reverse bend Quadrupole**	**steel**	80
10	Q7	Quadrupole	VP	80
11	Q8	**Reverse bend Quadrupole**	VP	80
12	S1 and S3	Sextupole	steel	160
13	S2	Sextupole	VP	80
14	FC1 and FC2	Fast Corrector	lamination	161
VP = vanadium permedur			Total Magnets	1321

Every arc magnet type has been prototyped



Reverse bend Quadrupole Magnets
Q4, Q5, and Q8

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