APS UPGRADE INTEGRATED BEAM STABILITY EXPERIMENTS
USING A DOUBLE SECTOR IN THE APS STORAGE RING

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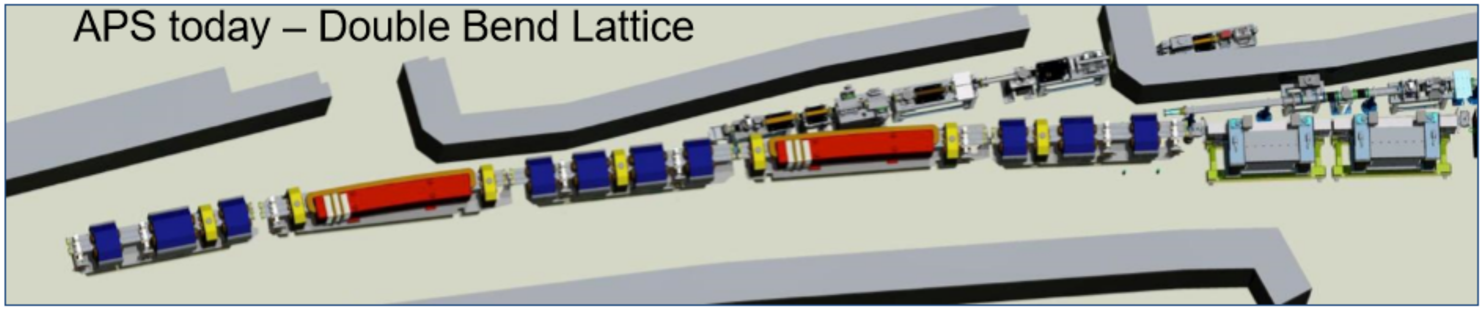
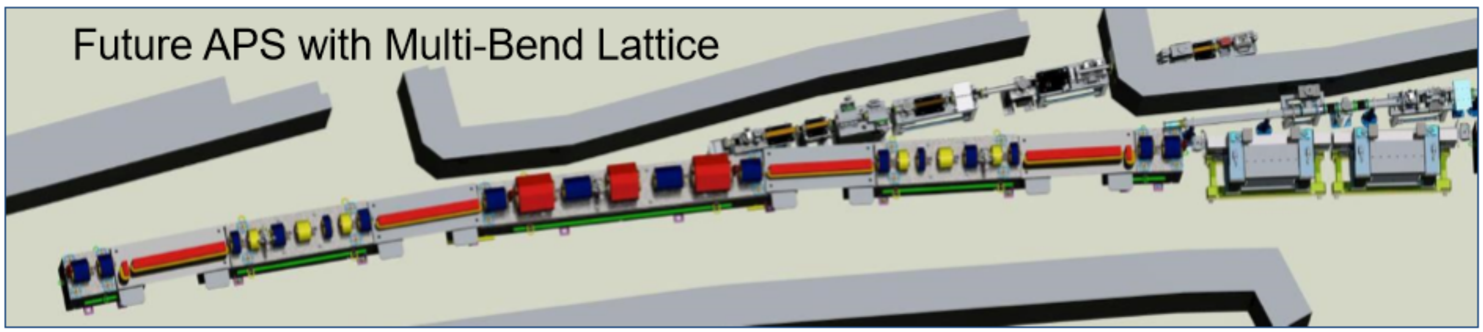
OUTLINE

- Orbit stability requirements
- Unified fast + slow orbit feedback
- Targets for APS-U orbit feedback R&D
- Prototype implementation
- Performance
- Wrap-up

APS UPGRADE MULTI-BEND LATTICE

~70-fold reduction in horizontal emittance





$$\varepsilon_x = C_L \frac{E^2}{N_D^3}$$

E = Beam energy (E = 6 GeV for APS MBA)
N_d = Number of dipoles per sector (N_d = 7 for APS MBA)

Orbit Stability Requirements

Minimum Expected Beam Size at the IDs (42-pm Lattice)

σ_x	$\sigma_{x'}$	σ_y	$\sigma_{y'}$
12.6 μm (275 μm)	2.5 μrad (11 μrad)	2.8 μm (10 μm)	1.7 μrad (3.5 μrad)

Beam Stability Goals for the APS Upgrade

Plane	AC rms Motion (0.01-1000 Hz)	AC rms Motion (0.01-1000 Hz)	Long Term Drift (>100 s)	Long Term Drift (>100 s)
Horizontal	1.25 μm rms (>6 μm)	0.25 μrad rms (>1.7 urad)	1 μm rms (~10 μm*)	0.6 μrad rms (~2.8 urad*)
Vertical	0.4 μm rms (>3 μm)	0.17 μrad rms (>0.85 urad)	1 μm rms (~10 μm*)	0.5 μrad rms (~2.8 urad*)

(Present Storage Ring Performance)
* Peak-to-Peak

PARAMETERS – PRESENT APS ORBIT FEEDBACK SYSTEM (1995)

Parameter		‘Datapool’	RTFB
Algorithm implementation		Separate DC and AC systems for slow and fast correctors	
BPM sampling & processing rate		10 Hz	1.6 kHz
Corrector ps setpoint rate		10 Hz	1.6 kHz
Signal processors (20 nodes)		EPICS IOC	DSP (40 MFLOPS)
Num. rf bpms / plane		360	160 (4 per sector)
Fast correctors / plane		-	38 (1 per sector)
Slow correctors / plane		282	-
Fast corrector ps bandwidth		-	1 kHz
Fast corrector latency		-	~250 usec
Closed-loop bandwidth		DC - 1 Hz	1 Hz - 80 Hz

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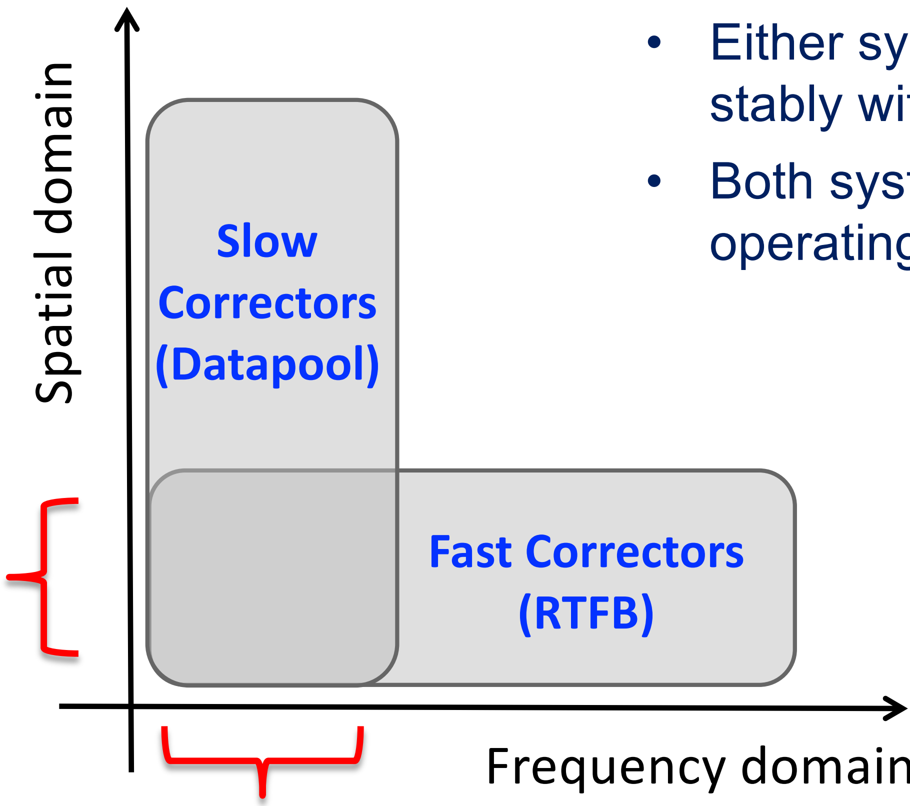
OVERLAP IN COVERAGE OF SLOW AND FAST ORBIT FEEDBACK SYSTEMS

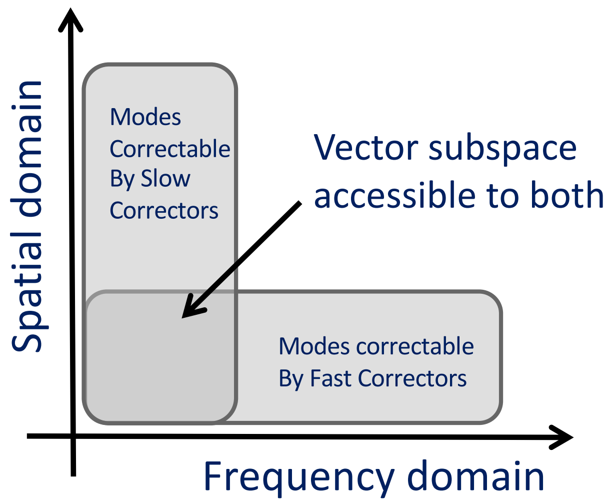


Both systems have access to this vector space

Both systems can respond over this frequency range

- Either system can operate stably without the other, **but**
- Both systems go unstable if operating simultaneously

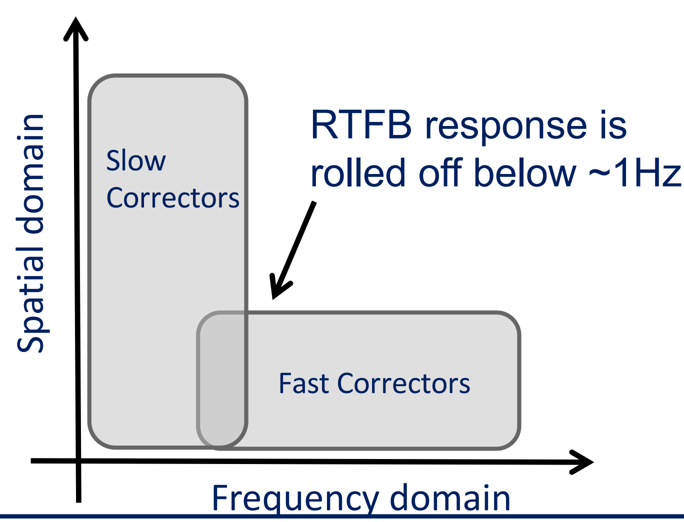
UNIFIED FEEDBACK ALGORITHM CONCEPT:
SPATIAL- VS FREQUENCY-DOMAIN ORTHOGONALIZATION



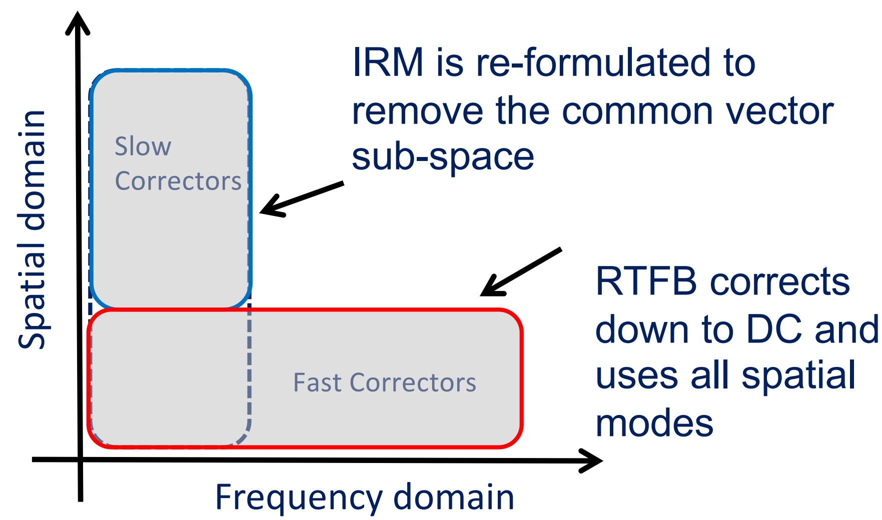
Issue: combination of slow + fast systems is unstable

- Present scheme: separate into high- and low-frequency systems (‘woofer/tweeter’ concept)
- Unified scheme: orthogonalize vector spaces

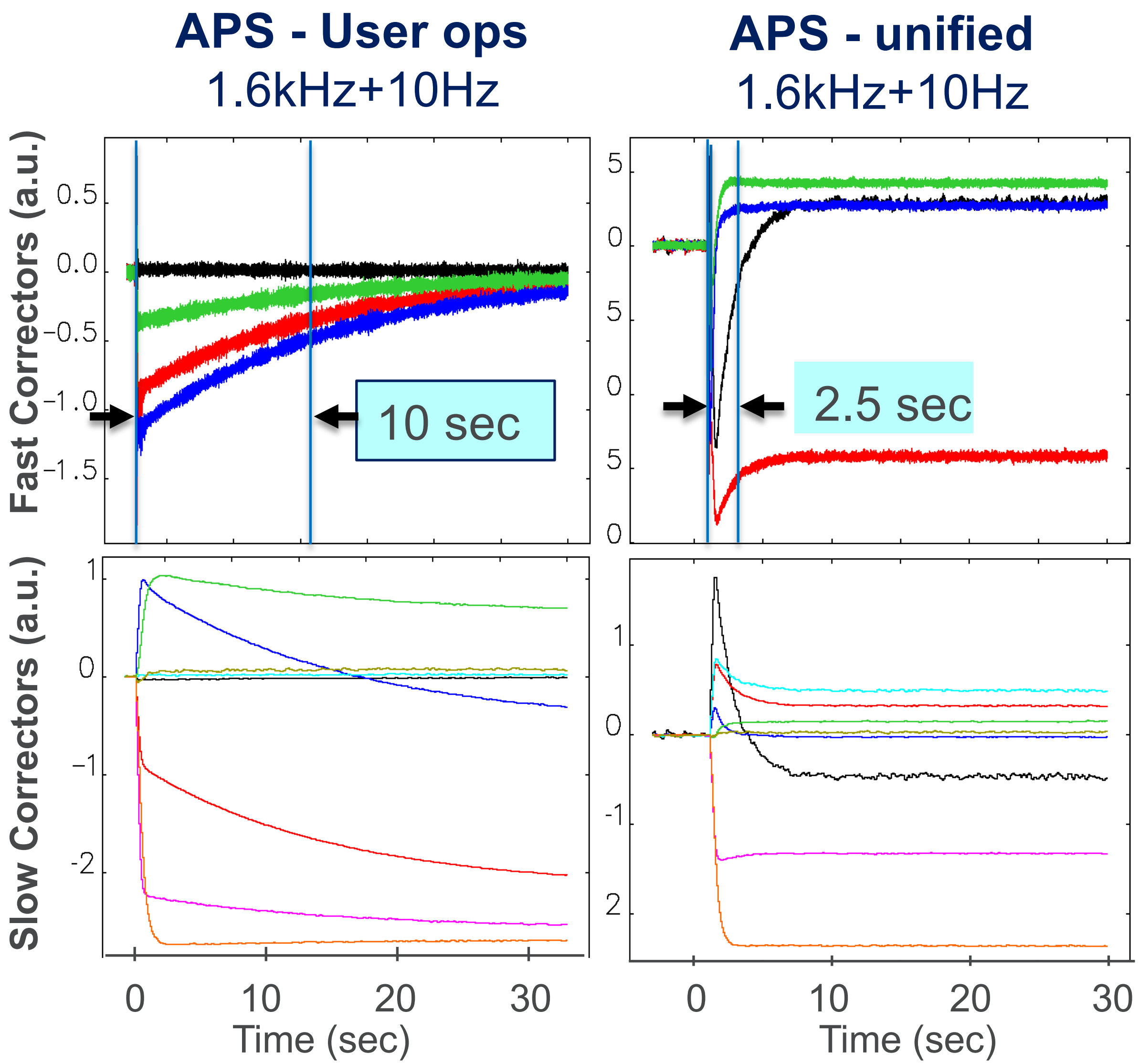
Present scheme



Unified algorithm



IMPROVEMENTS IN ORBIT FEEDBACK SETTLING TIMES WITH UNIFIED FEEDBACK ALGORITHM USING EXISTING 20-YR OLD HARDWARE



- Slow: Datapool at 10 Hz
- Fast: RTFB at 1600 Hz

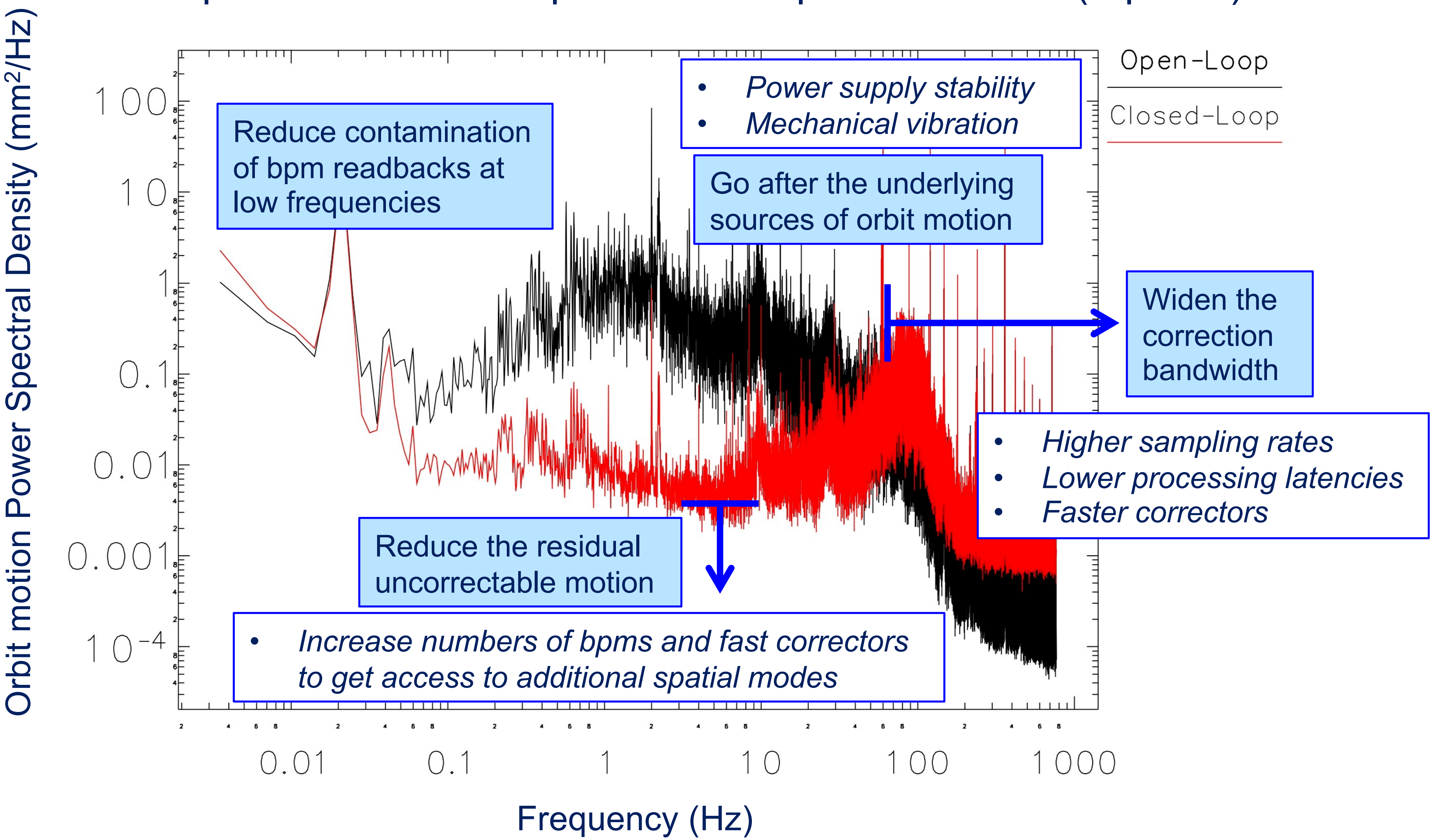
- Plots show time-domain responses to a step change in the orbit

- **Left**: present scheme with RTFB rolled-off towards DC using conventional formulation of inverse response matrices

- **Right**: with both systems operating down to DC using unified formulation for inverse response matrices

TARGETS FOR APS-U ORBIT FEEDBACK R&D IN TERMS OF ORBIT MOTION SPECTRA

Open- vs closed-loop PSDs with present RTFB (x-plane)



PARAMETERS – COMPARISON OF PRESENT AND NEW

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	570 (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
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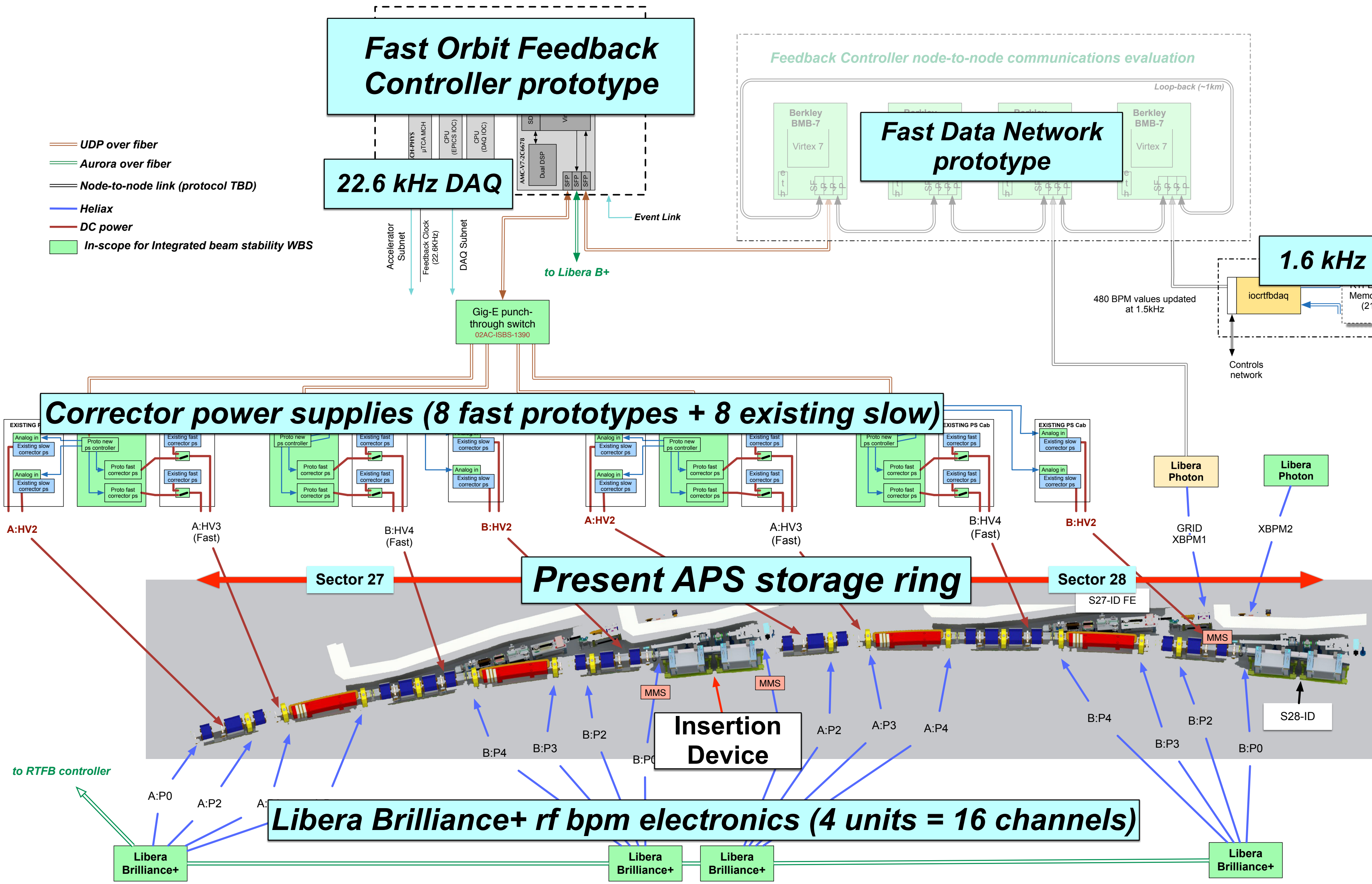
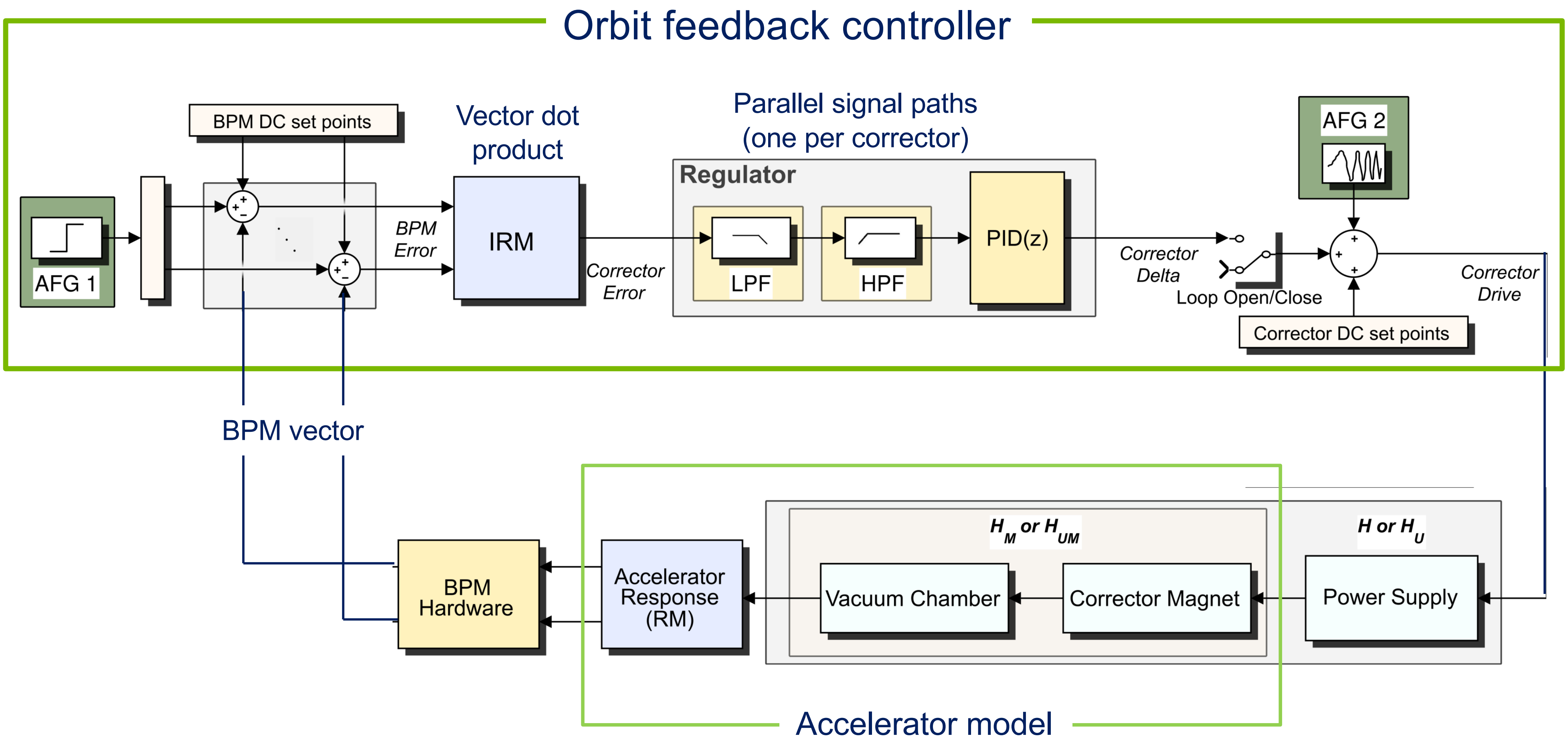
* Goal of R&D was to demonstrate key parameters in beam studies at APS

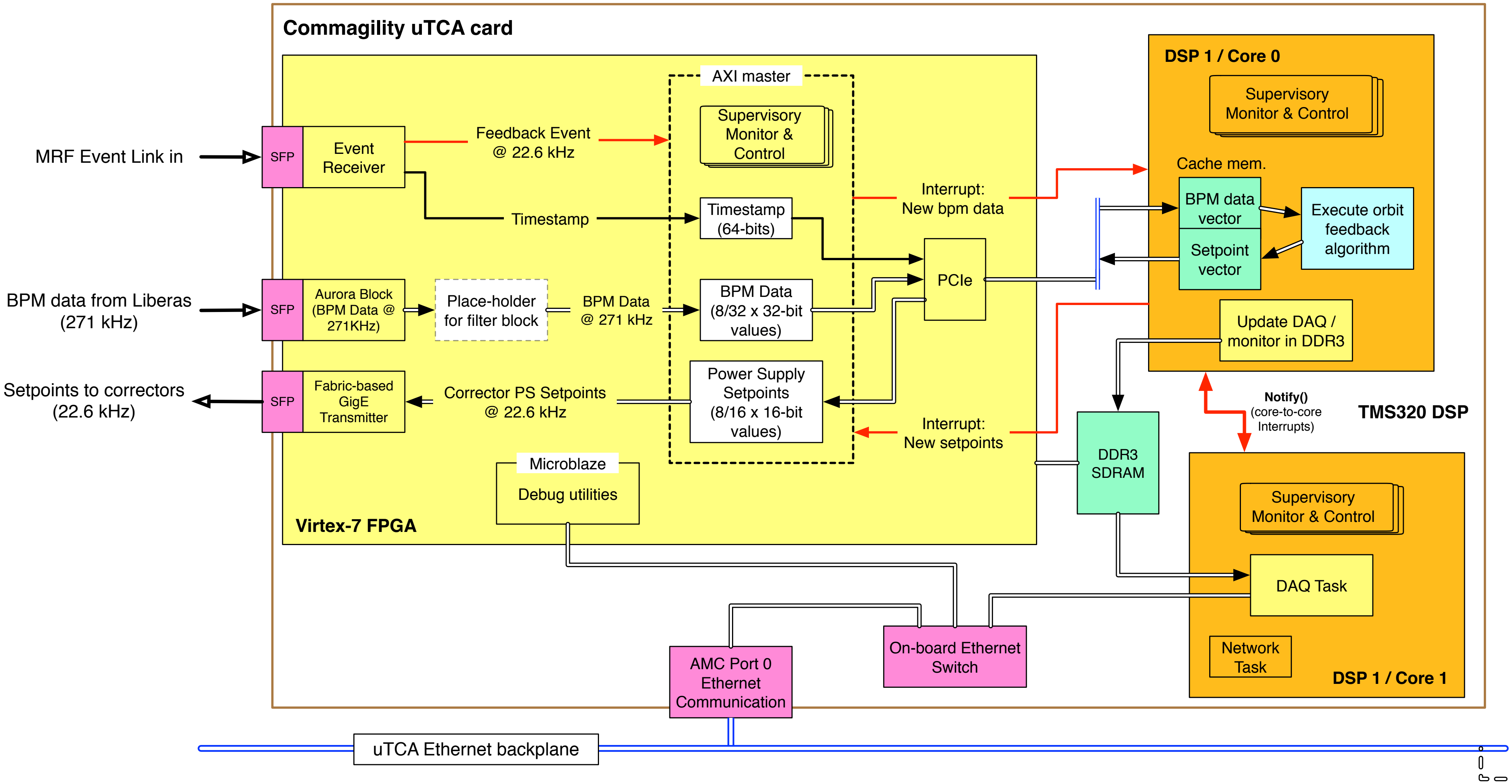
APS-U ORBIT FEEDBACK PROTOTYPE



ORBIT FEEDBACK SYSTEM MODEL



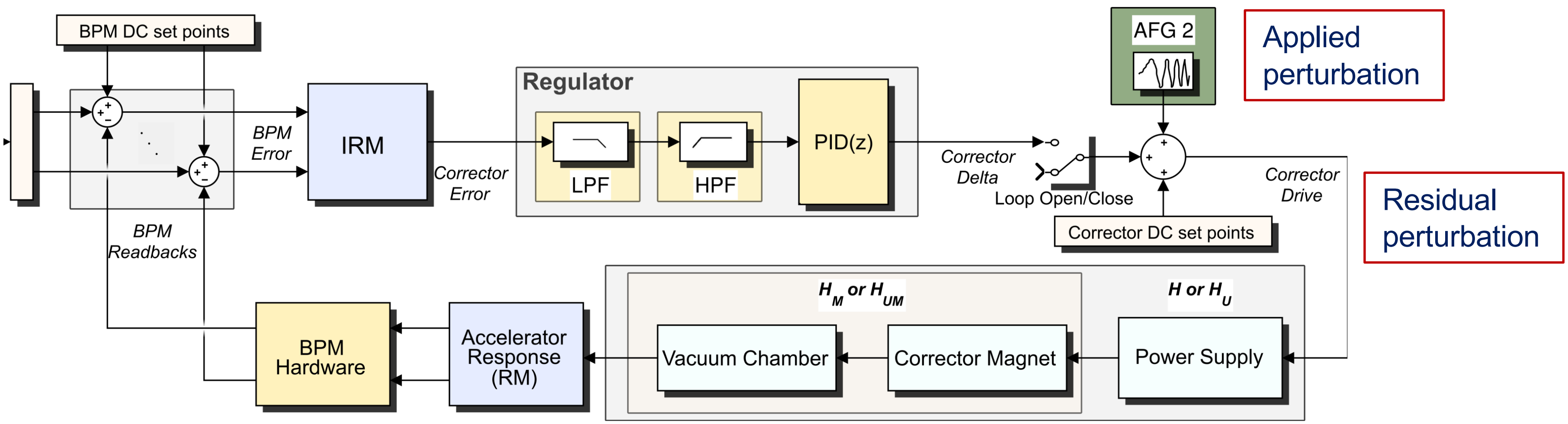
PROTOTYPE FAST ORBIT FEEDBACK PROCESSOR DATAFLOW



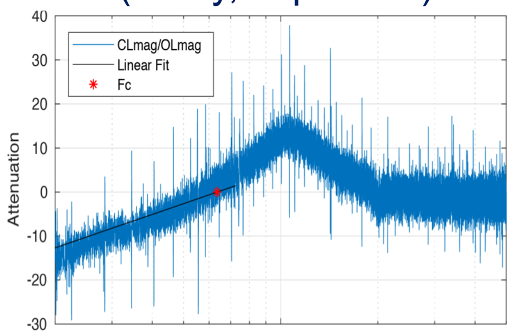
- FPGA manages bpm and corrector data-streams
- DSPs perform orbit feedback computations

BUILT-IN DYNAMIC-SYSTEM ANALYZER

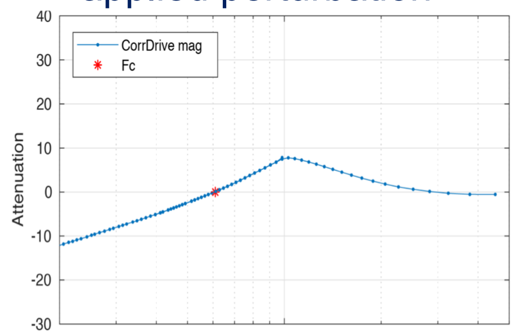
- Need a means of evaluating effects of latency and regulator tuning
  - Method of dividing open-loop and closed-loop PSDs is noisy and imprecise
  - Dynamic-system analyzer approach: measure response to known excitation



Compute ratio of PSDs
(Noisy, imprecise)



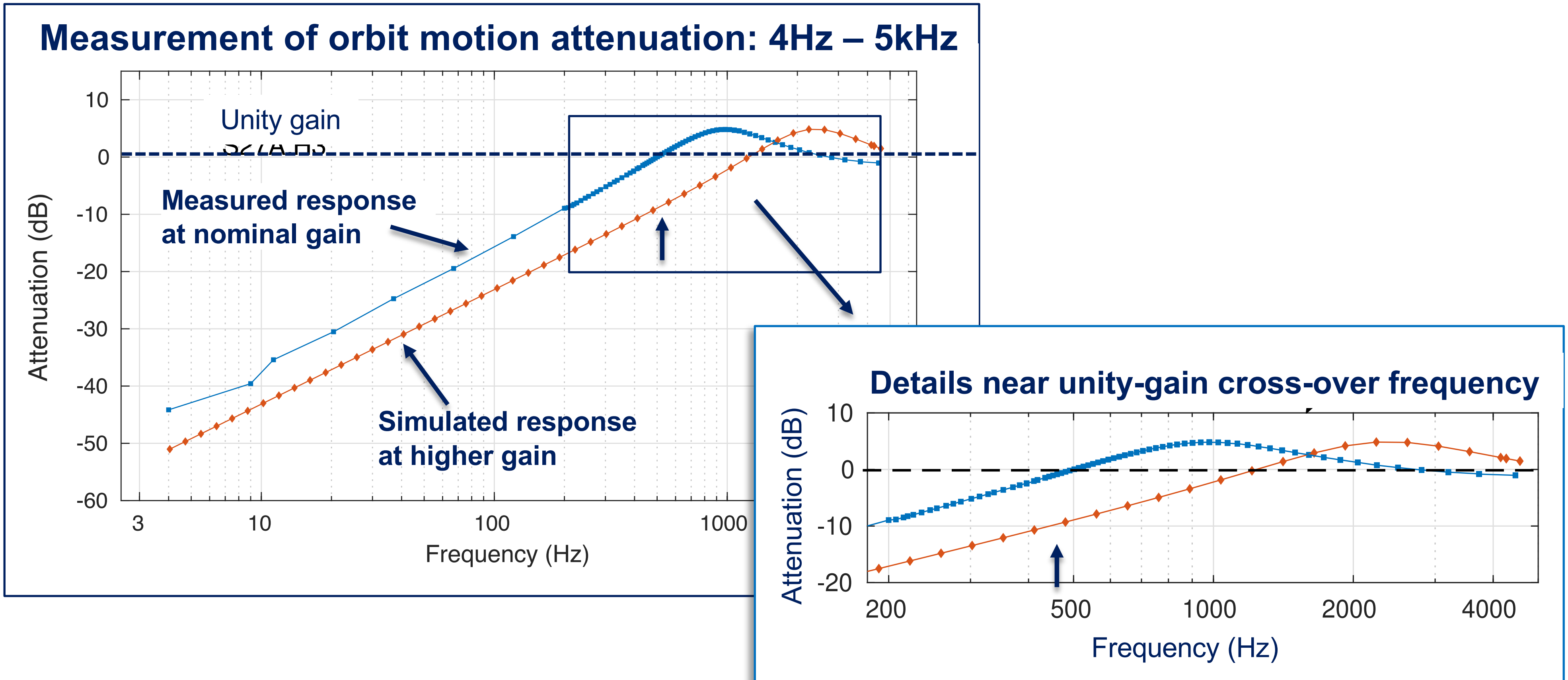
Measure response to applied perturbation



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

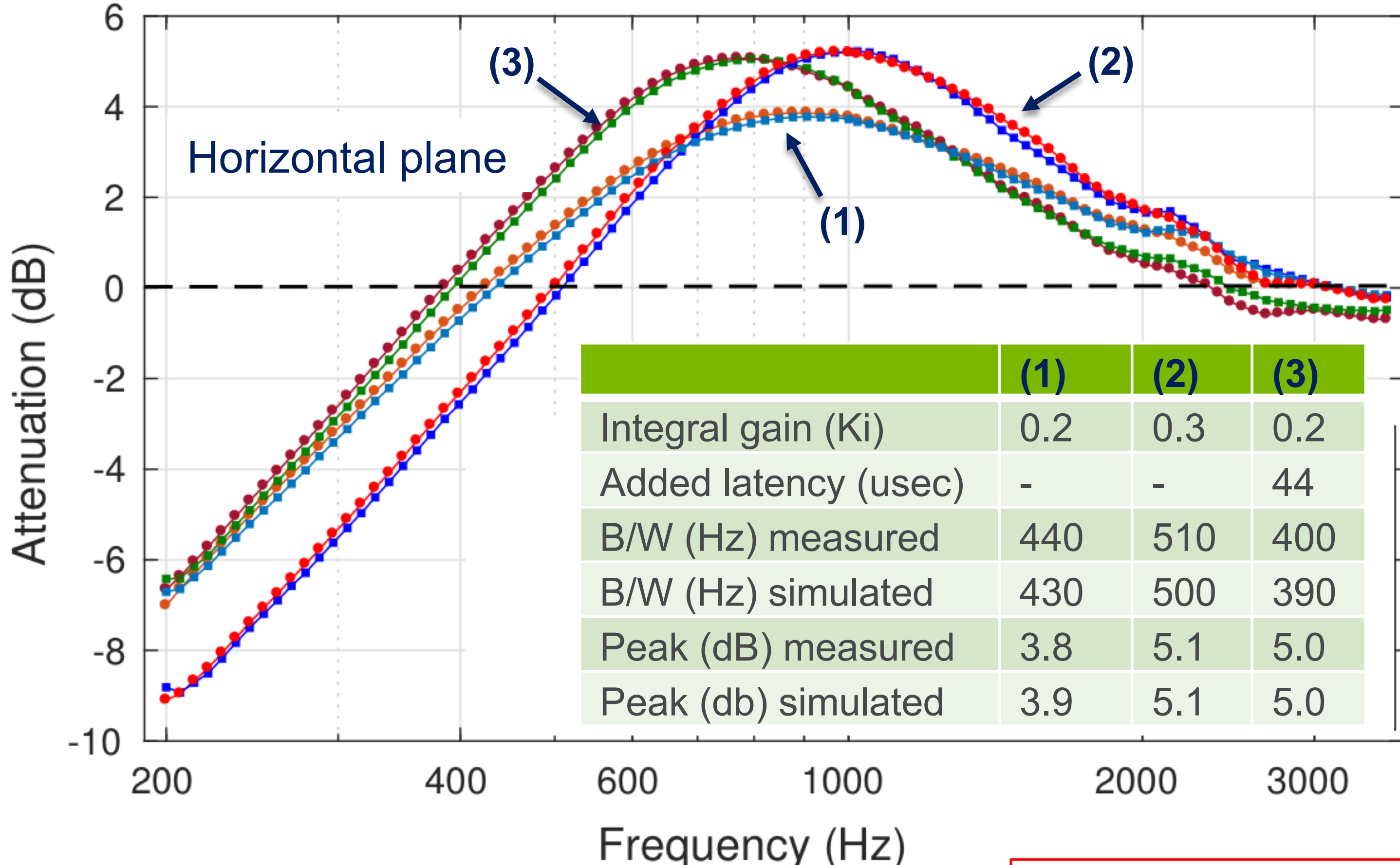
MEASURING ORBIT FEEDBACK EFFECTIVENESS

Plots show the attenuation response (fraction of motion remaining with feedback enabled)
- At low frequencies, there is more than 40dB attenuation.
- Amplification at higher frequencies corresponds to overshoot in the step response.



BEAM-BASED MEASUREMENT OF CLOSED-LOOP PERFORMANCE VS PROCESSING LATENCY

Attenuation responses with/without added latency

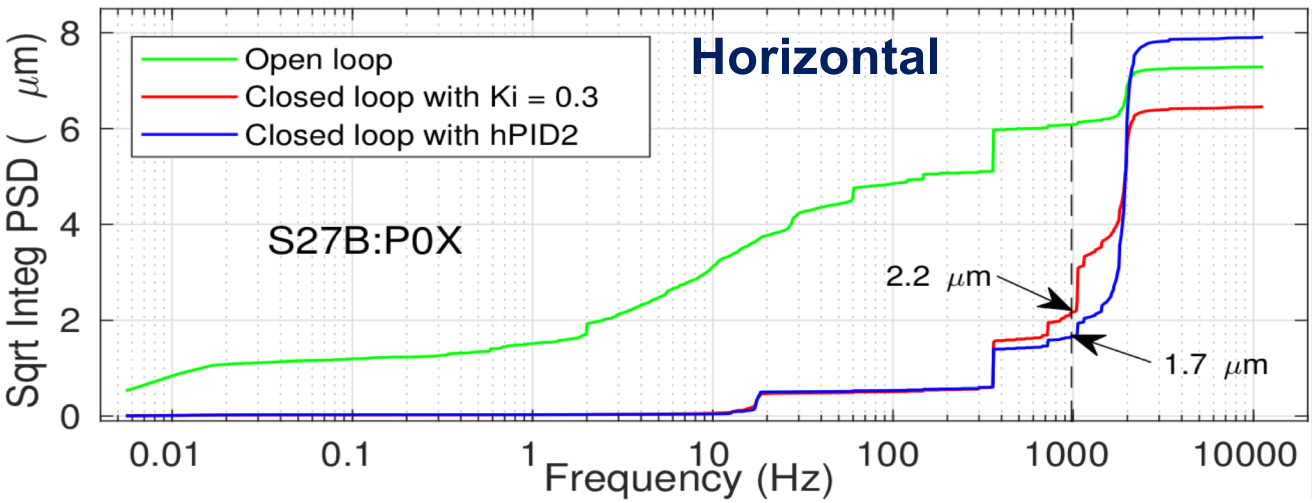


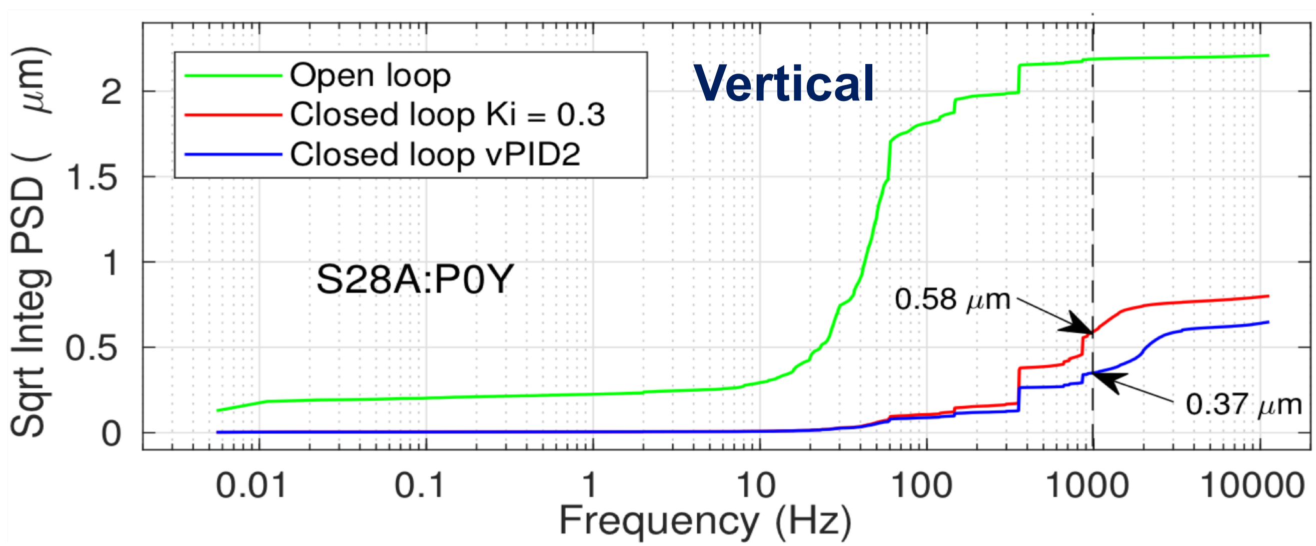
	(1)	(2)	(3)
Integral gain (Ki)	0.2	0.3	0.2
Added latency (usec)	-	-	44
B/W (Hz) measured	440	510	400
B/W (Hz) simulated	430	500	390
Peak (dB) measured	3.8	5.1	5.0
Peak (db) simulated	3.9	5.1	5.0

44 usec (1 tick) of added processing latency costs ~100Hz in bandwidth

MEASURED PERFORMANCE:
REDUCTION IN CUMULATIVE RMS MOTION

RMS beam stability goals for APS-U have been demonstrated on APS





Plots show cumulative RMS motion up to 11 kHz:

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

Large source of orbit motion at 1.8kHz is due to synchrotron motion

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✔ Demonstrated
✔ Demonstrated in a double-sector

SUMMARY

Small APS-U beam sizes lead to very challenging orbit stability goals

- APS-U fast orbit feedback system uses the same architecture and functionality as the 20-yr old APS RTFB, but is implemented using ‘modern’ components
  - 4000-fold increase in performance vs 1995-era processors
  - Hybrid DSP-FPGA processor chosen over FPGA-only implementation

- APS-U fast orbit feedback controller has been prototyped on the present APS
  - Unified feedback algorithm combines fast and slow correctors without compromising spatial or dynamical performance (replaces present ‘woofer/tweeter’ scheme).
  - 22.6 kHz orbit correction rate with 16 bpms and 8 fast correctors per sector per plane.
  - Unique diagnostic and measurement capabilities are built into the controller
  - Parametric dynamical model for testing ‘optimal’ control techniques.
  - All key parameters for APS-U fast orbit feedback system design have been demonstrated during beam studies, including 1kHz closed-loop bandwidth

THANK YOU FOR YOU ATTENTION

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