Architecture of the APS Real-Time Orbit Feedback System

J.A. Carwardine and F.R. Lenkszus

Advanced Photon Source, Argonne National Laboratory

Advanced Photon Source Storage Ring Characteristics

• **Energy:**	**7.0 GeV**
• **Stored Beam Current (design):**	**100 mA**
• **Stored Beam Lifetime (design):**	**>10 hrs**
• **Circumference:**	**1104 m**
• **Number of Super-periods:**	**40**
• **Harmonic Number:**	**1296**
• **RF Frequency:**	**351.93 MHz**
• **Horizontal Tune:**	**35.2**
• **Vertical Tune:**	**14.3**
• **Synchrotron Tune:**	**0.0072**
• **Horiz. Beam Size at ID Source:**	**325 μm rms**
• **Vertical Beam Size at ID Source:**	**86 μm rms**
• **Straight Sections for I.D.'s:**	**35**

Orbit Feedback System Requirements

APS Orbit Stability Specifications

- **Beam must be stable to within 5% of its size.**
- **Horizontal stability specification: 17µm rms.**
- **Vertical stability sepecification: 4.4µm rms.**

Orbit Feedback System Functionality

- **'Global' (long wavelength) feedback to minimize rms orbit errors.**
- **'Local' feedback to steer the orbit through x-ray source points.**

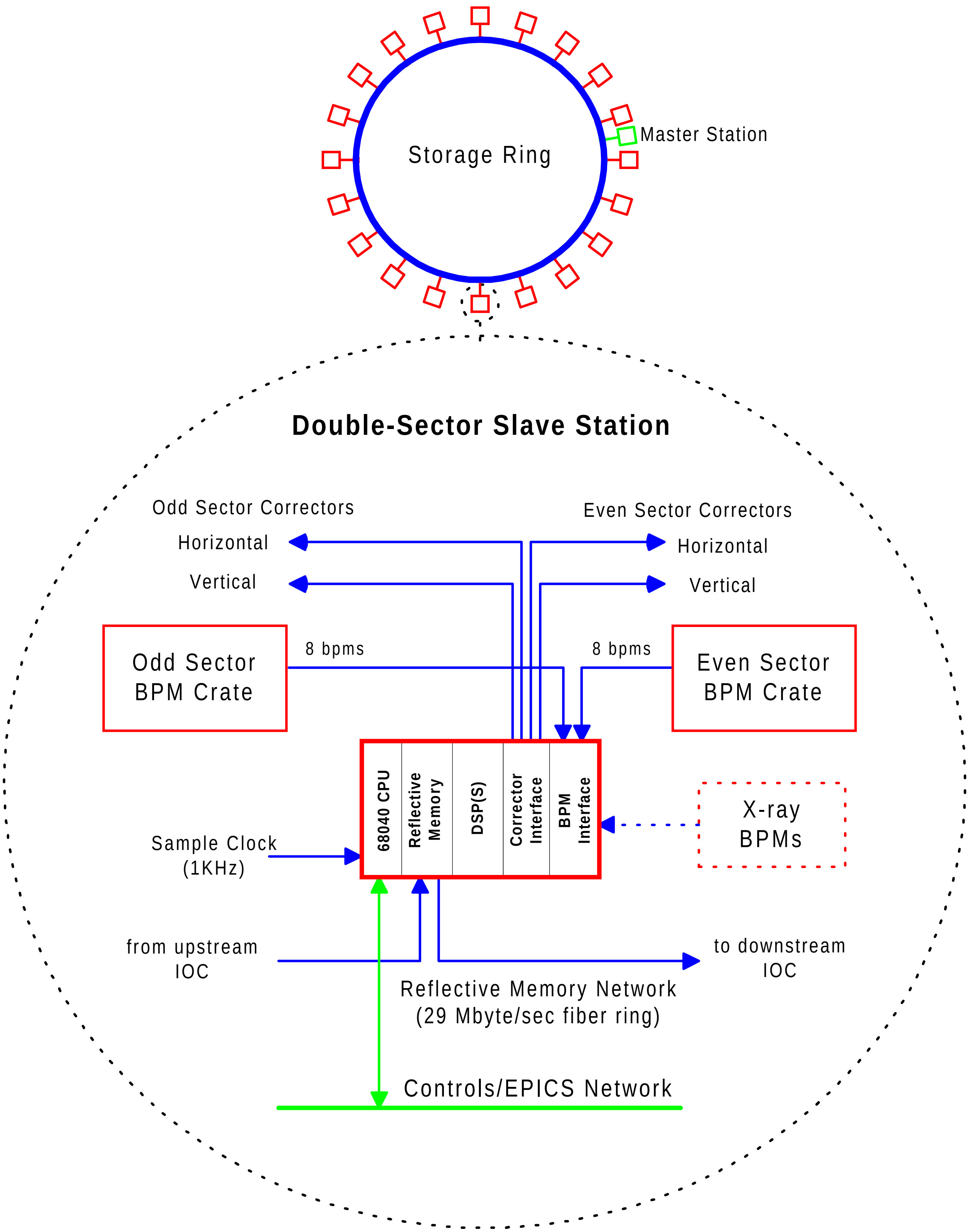
Implementation

- **Beam Position Monitors (BPMs) are used to measure the orbit.**
- **Dipole 'corrector' magnets are used to correct the orbit errors.**
- **Local and global feedback are implemented in the same system.**
- **The system is entirely digital, using DSPs to perform the real-time computations.**

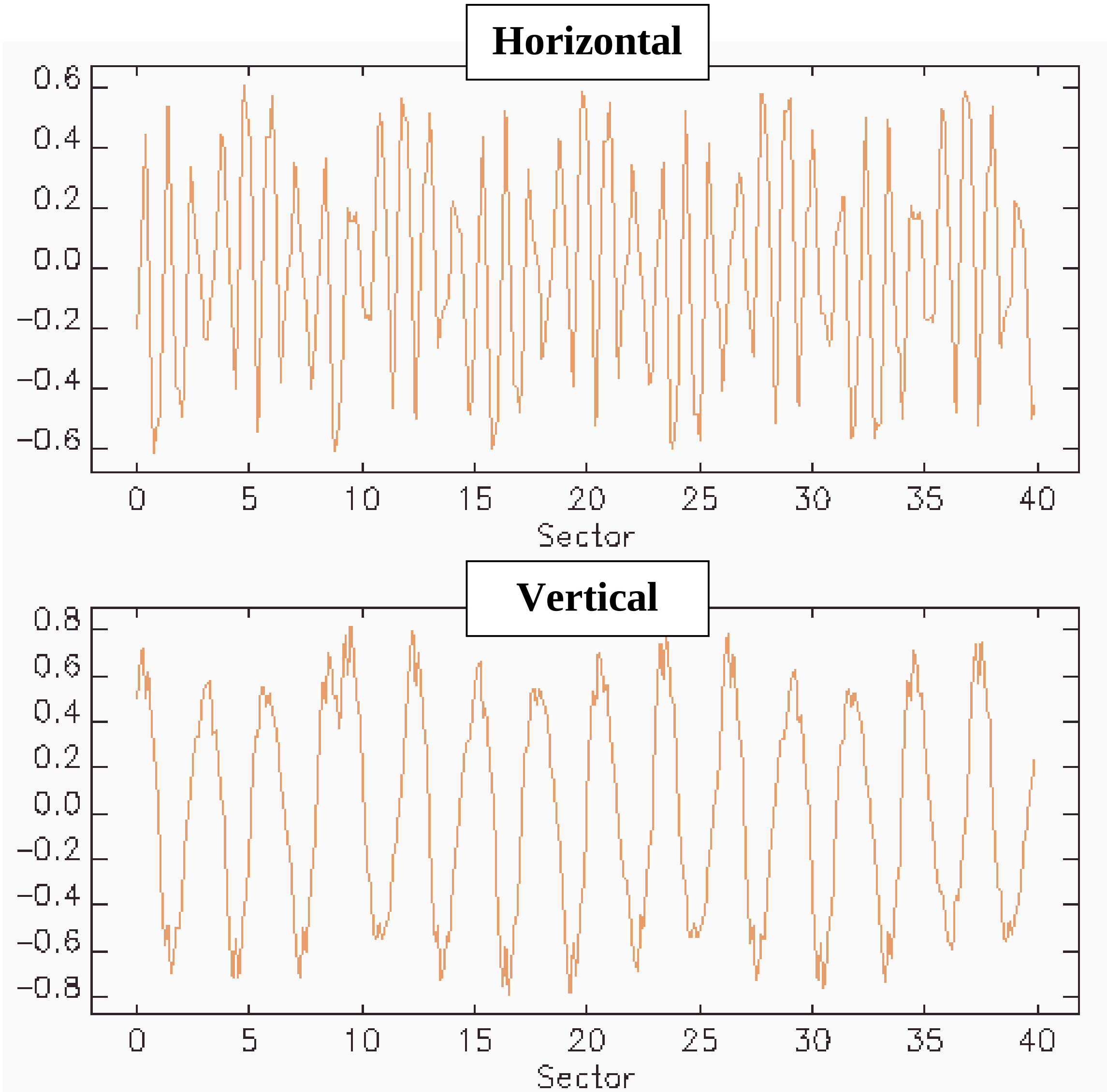
Present Status

- **The global orbit feedback system was put into operation with users in June 1997.**
- **Local feedback is yet to be implemented.**
- **With orbit feedback running, orbit stability up to 30Hz is typically 8µm horizontally and 3.5µm vertically.**

Real-Time Feedback Hardware Configuration



Betatron Orbit Motion



- **Orbit disturbances produce an orbit error which follows a closed sinusoidal path relative to the reference orbit in the machine.**
- **This is true for static disturbances (e.g., magnet alignment errors) and for dynamic disturbances (e.g., power supply ripple).**
- **The number of sinusoids per revolution is fixed by the machine lattice (the betatron tune).**
- **In the APS, the horizontal betatron tune is 35.2, and the vertical betatron tune is 14.3.**

The Global Orbit Correction Algorithm

- **The global orbit correction algorithm solves a set of linear equations which describe betatron orbit motion:**

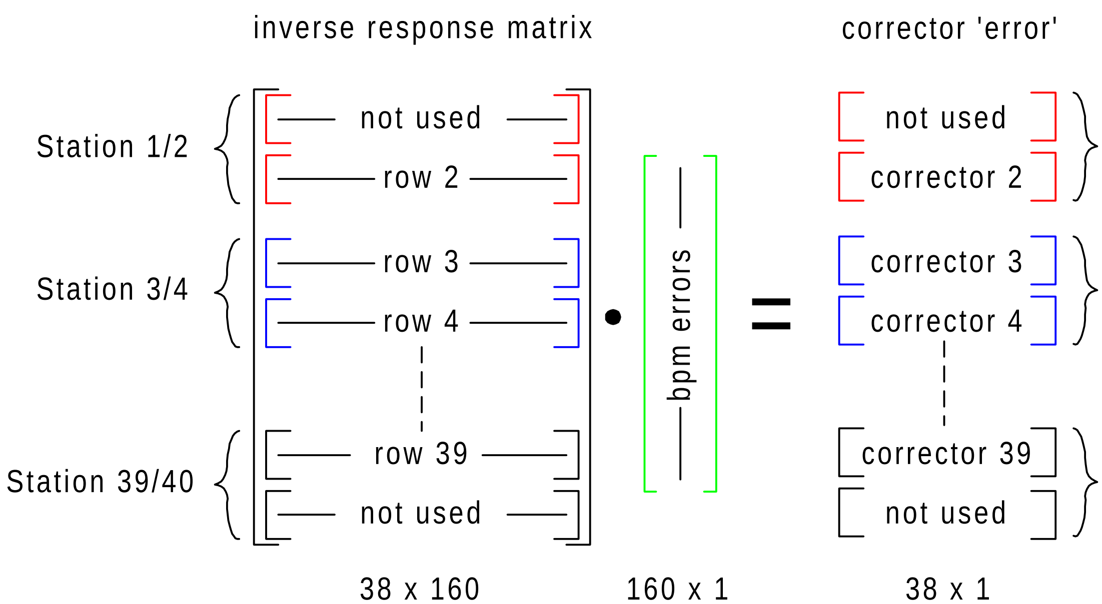
$$R \cdot \Delta c = \Delta x$$

where *R* is the response matrix, *Δc* is a vector of corrector magnet currents and *Δx* is the vector of positional changes at the BPMs.

- **In the APS global orbit correction system, there are many more measurements (BPMs) than unknowns (correctors).**
- **The (least-squares) solution to the response matrix equation is in the form of another matrix and is generated offline. The 'inverse response matrix' maps bpm errors to corrector changes:**

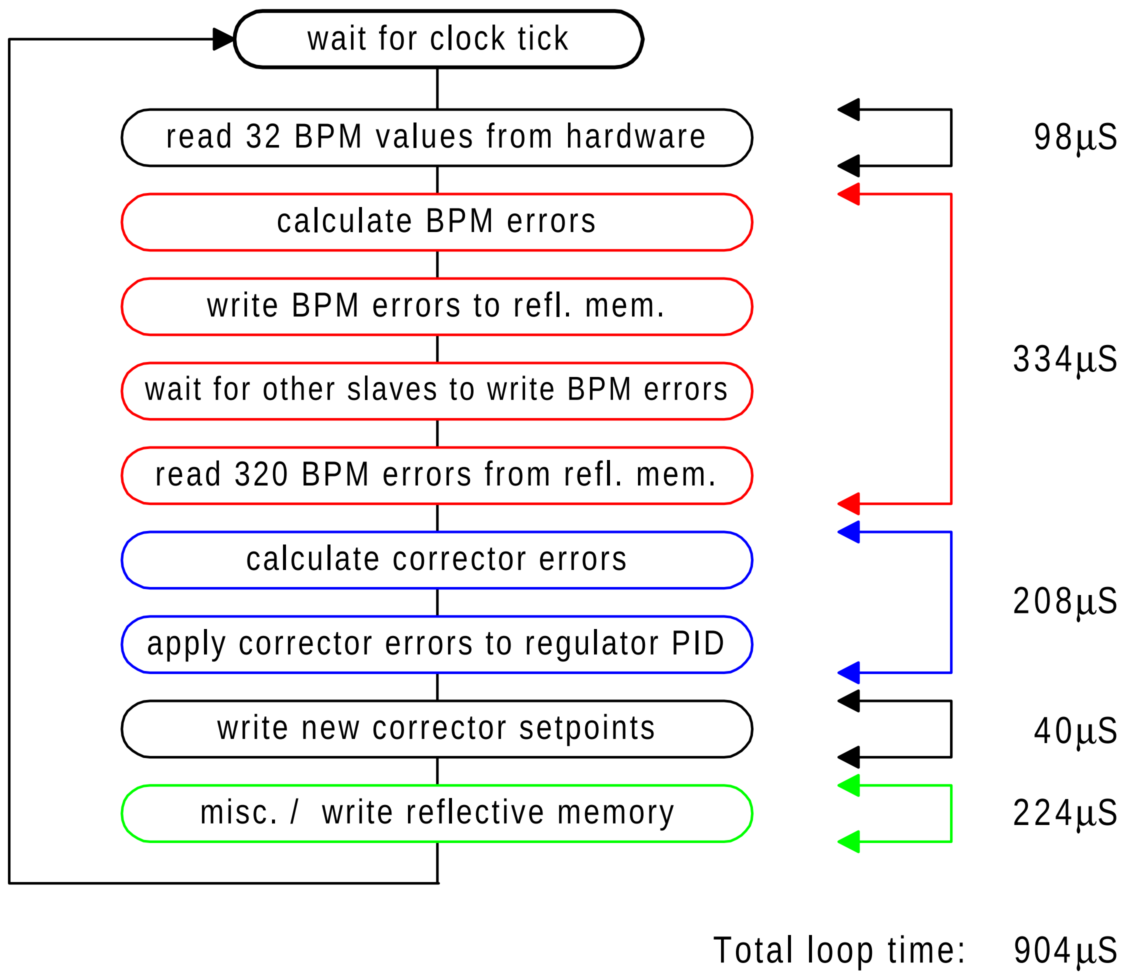
$$R^{-1} \cdot \Delta x = \Delta c$$

- **The APS real-time orbit feedback system uses a 160-bpm by 38-corrector inverse response matrix. The matrix calculation is conveniently divided into 38 vector dot-products for computation in 20 separate stations.**

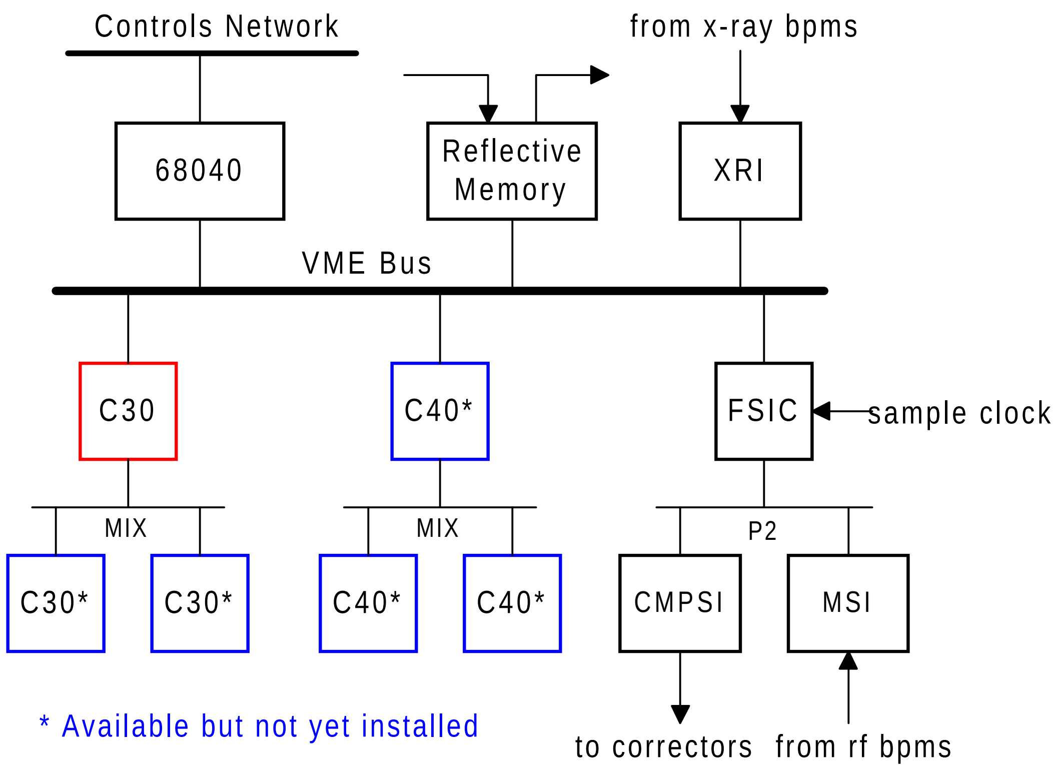


Slave Station Flowchart

- **Each slave station needs 160 BPM values to compute the new corrector setpoints, but only has direct access to 8 BPMs.**
- **Reflective Memory is used to transfer the required BPM values from each slave to every other slave.**



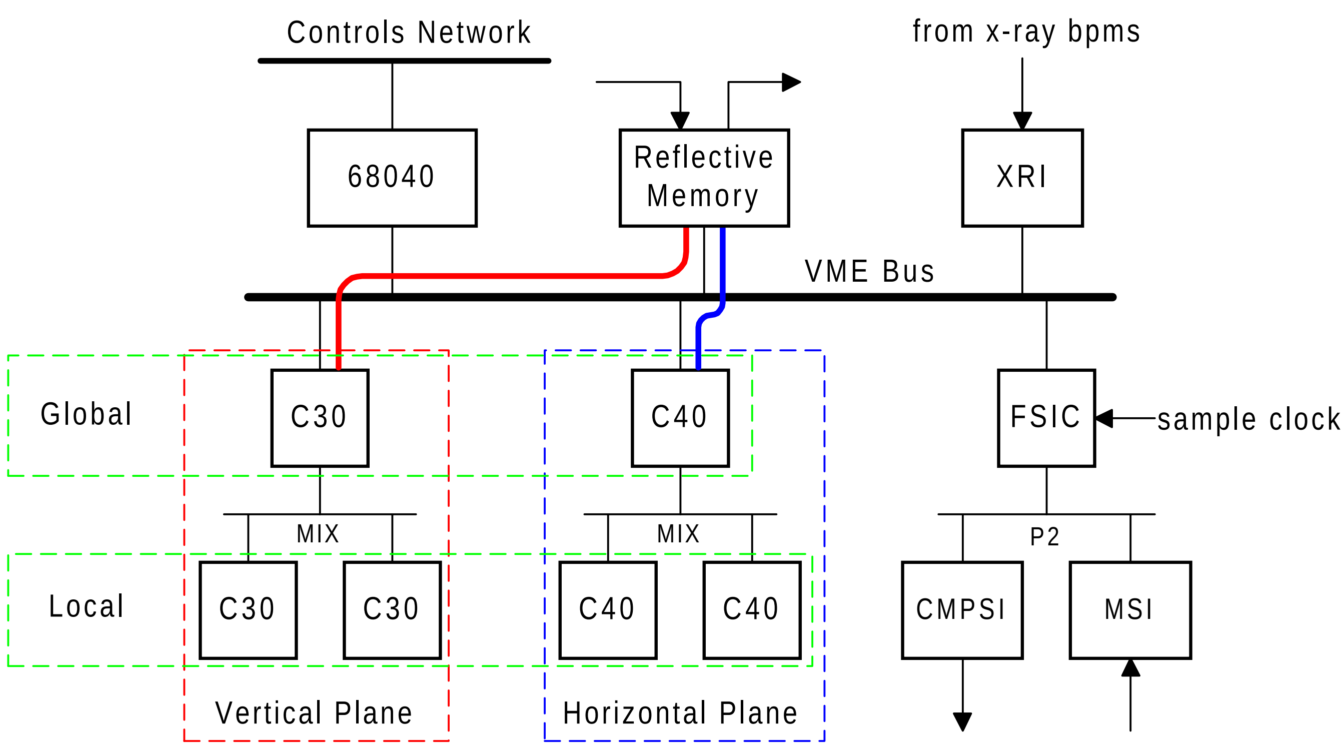
Slave Station Hardware



- **The 68040 processor runs EPICS core routines and each slave appears on the controls net as an IOC.**
- **Real-time processing is performed using Texas Instruments TMS320 C30 & C40 floating-point DSPs.**
- **Each station accesses 16 BPMs and controls up to 32 correctors.**
- **X-ray BPMs on each beamline will be used for ‘local’ feedback.**
- **The Reflective Memory network provides deterministic data transfer between the stations at 29.6Mbytes/second.**

Slave Processor Utilization

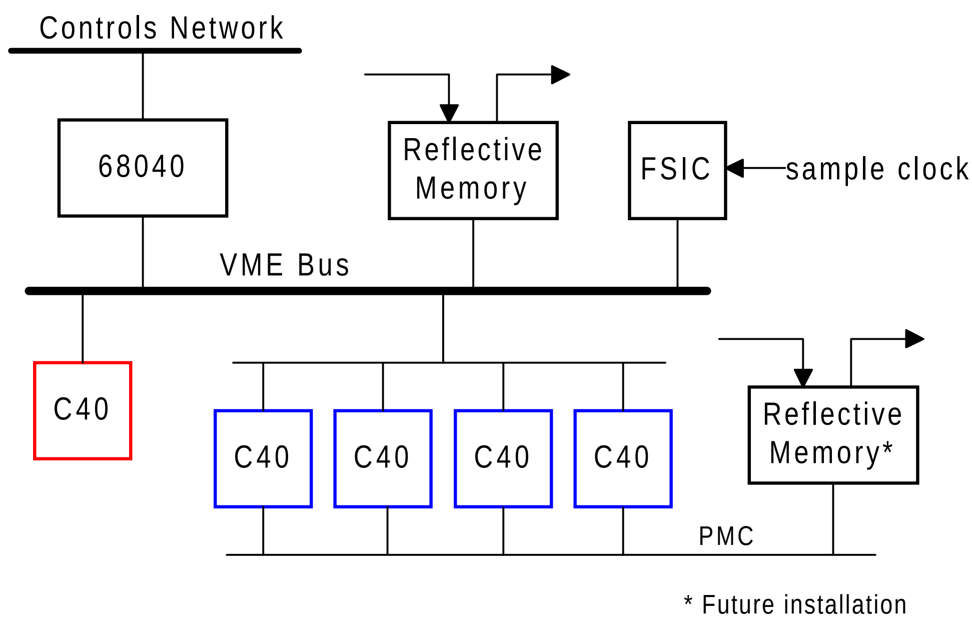
- **The present system uses a single C30 DSP to perform global orbit correction in two planes at a 1kHz rate.**
- **Ultimately there will be six DSP processors in each slave station that perform both global and local correction at a 2kHz rate.**
- **The two main processors will be staggered in time to reduce the bottleneck of reading bpm values from Reflective Memory.**



- **One group of DSPs will handle the horizontal plane, the other will handle the vertical plane.**
- **The main DSPs will handle global orbit correction, with the auxiliary DSPs computing local orbit corrections.**

Master Station Hardware

- **The master station has no hardware interfaces and relies on the Reflective Memory for data transfer.**



- **One C40 DSP performs supervisory functions and implements some data analysis functions.**
- **The array of four C40 DSPs is used for real-time data analysis**
- **A second Reflective Memory card (on PMC bus) will improve effective throughput of the data analysis algorithms.**

Code Development

General

- **The DSP code is developed under Unix using the Texas Instruments TMS320 code generation tools.**
- **Most of the code is written in ‘C’, with speed-critical functions written in C-callable assembler.**
- **DSP Code is downloaded over the controls LAN from the control system file server using *SwiftNet* tools that run on the VME controls processor under *VxWorks*.**

C Code Optimization

- **We use compiler optimization where possible.**
- **This can cause unexpected behavior, e.g., when the compiler rearranges code to minimize DSP pipeline conflicts.**

Debugging

- **Rather that using extensive debugging tools, we have used reserved “test” locations in dual access RAM on the DSP to pass debugging information to the VME controls processor.**
- **This method has the little impact on the DSP algorithm and allows us to debug at normal DSP operating speeds.**

Real-Time DSP Kernel

- **To date we have not used a DSP real-time kernel, but have chosen to run a single task that linearly executes the orbit feedback code.**
- **The issue will be re-addressed when we have several DSPs running in each slave station.**

Control System Interface

- **The DSP operation is controlled and monitored through data structures residing in dual-access RAM on the DSP board.**
- **Elements of these data structures are interfaced to EPICS process variables through EPICS sequence programs. Since the process variables are control system entities they are accessible by all the standard EPICS tools.**
- **A sequence program on the controls processor periodically scans the data structure and deposits data such as BPM readings into corresponding process variables.**
- **A separate EPICS sequence program transfers local control information such as inverse response matrix rows or BPM selections to the DSP resident data structure and sets a flag commanding the DSP to load the new values into its local SRAM.**
- **Global control parameters such as feedback loop open/close, filter cutoff frequencies, etc., are delivered to the master station as process variables. Reflective Memory is then used to pass these parameters to the slave stations.**

Operational Issues

- **Some considerable effort has been put into making the orbit feedback system seemless with machine operations.**

- **Orbit feedback control loops can be opened and closed completely transparently, with no impact on stored beam, e.g., when the control loops are opened the corrector setpoints revert to their original DC setpoints.**

- **The real-time orbit feedback system is presently used in conjunction with a workstation-based ‘DC’ orbit correction system, with a highpass filter removing the DC component from the real-time correction to prevent the systems from ‘fighting’.**

- **APS machine status information (e.g., the Machine Protection System interlock) allows the orbit feedback system to respond to changes in machine conditions in a graceful manner (e.g., by turning off the control loops when beam is lost).**

Real-Time Beam Diagnostics

'DSPscope'

- **Simultaneous collection of 40 channels of time-domain data from bpms, correctors, or regulator error signals.**
- **Data is provided as EPICS waveforms records.**

'AC Voltmeter'

- **Simultaneous sliding Fourier transforms of 40 selectable data channels through the DSPscope interface.**
- **Simultaneous sliding Fourier transforms of all 320 BPM channels in either plane.**

AC Lock-In Measurements

- **Drive a corrector at some frequency (e.g. 83.3Hz), and measure only that frequency component in the orbit response.**
- **Used for fast measurements of the response matrix.**
- **Recently used for lattice tuning.**

Corrector Error Statistics

- **Sliding estimates of the *mean* and *variance* of the corrector errors are computed at each sample tick.**
- **Used to detect problems with the orbit feedback system itself and to detect problematic BPM channels.**

Corrector Error History Buffer

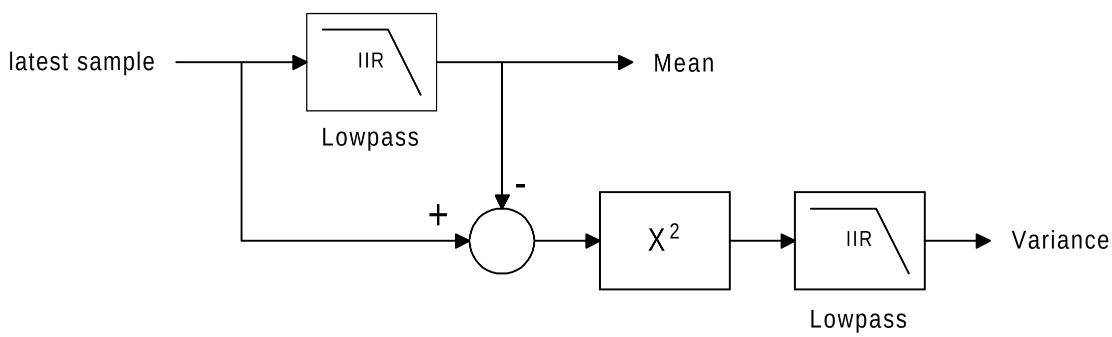
- **Maintain a circular buffer of the past 128mS of corrector errors.**
- **Used to detect and locate sources of unwanted beam motion e.g., following a beam dump.**

'Sliding' Algorithms

- **The orbit feedback system is not well suited to algorithms that operate on blocks of time-sequence data (e.g., FFT)**
- **We have implemented 'sliding' algorithms that use the latest data sample to update previous results on each sample tick.**

Sliding Statistics

- **The *mean* value is simply the output of a lowpass IIR filter.**
- **The *variance* is computed from the instantaneous value and the mean value**



Sliding *N*-point Fourier Transform

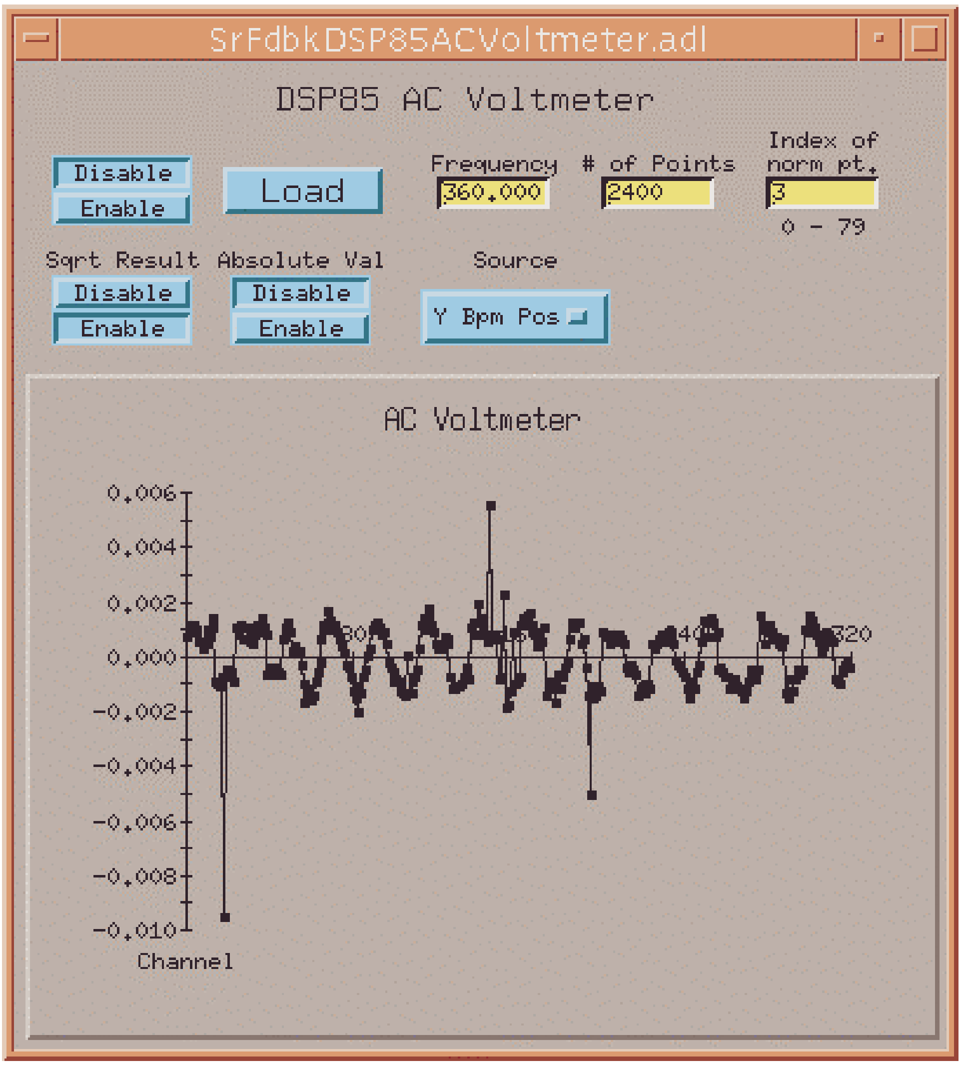
- **Updates the previous result from the difference between the latest sample and the sample *N* points ago**

$$Y_k(n) = \left[Y_k(n-1) + x(n) - x(n-N) \right] . e^{-j2\pi \frac{k}{N}}$$

- **The algorithm requires *N* sample ticks to compute a result, but thereafter the result is updated on every sample tick.**

On-Line Sliding Fourier Transform

(‘AC Voltmeter’)



360Hz Fourier Component of 320 bpms

(Vertical betatron orbit motion and bad bpms are visible)

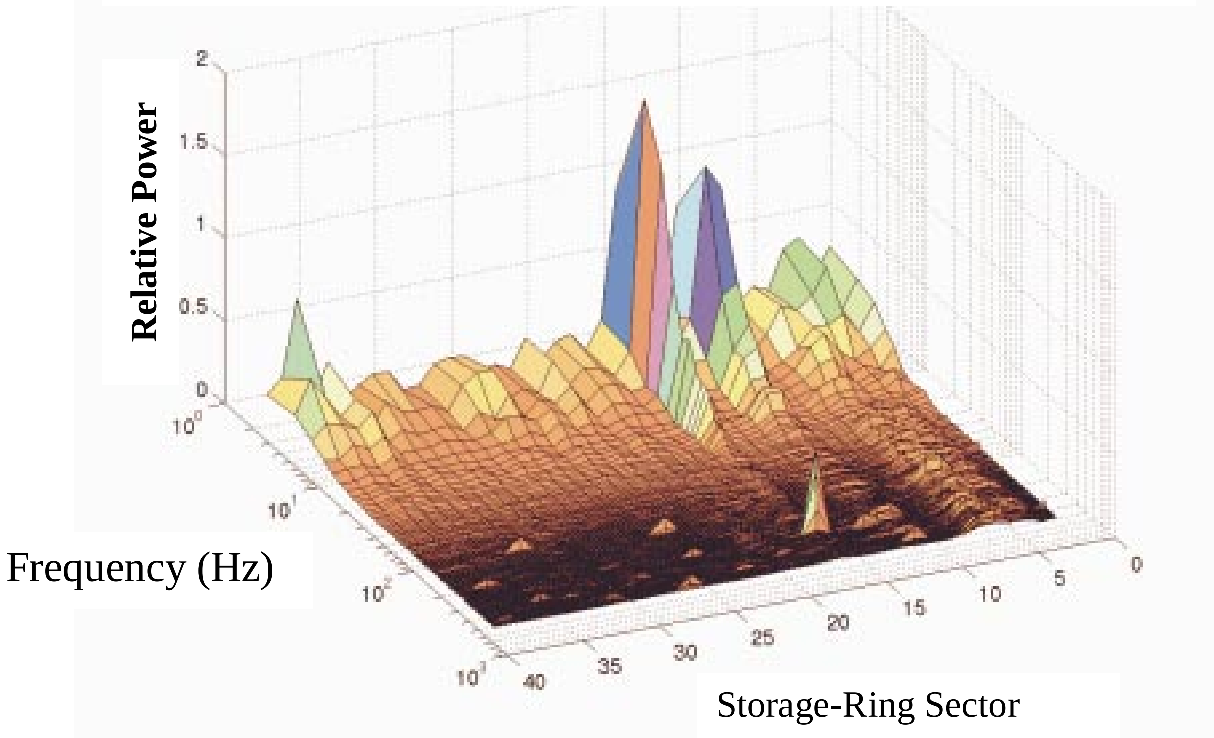
Implementation of the 320-channel AC Voltmeter

- **Four C40 DSPs are used to implement the 320-channel AC voltmeter, each operating on 80 BPMs.**
- **The DSP high speed serial ports are used to transfer control messages between the processors, e.g., for arbitration of access to the reflective memory.**
- **The output of each channel is a magnitude or power (user selectable).**
- **A selectable channel is used as a phase reference for the other channels. The sign of the magnitude is then chosen relative to the sign of the reference channel.**
- **The 320 results are available as an EPICS waveform and can be downloaded from the feedback system at 2Hz.**

Identifying Sources of Orbit Motion

- **A program is underway to identify and eliminate sources of orbit motion from the APS storage ring.**
- **Solving the response matrix equation in real time allows sources of orbit motion to be localized using measured beam motion.**
- **The required solution is already being computed by the orbit orbit feedback algorithm as a 'corrector error'.**
- **The corrector error power spectrum provides a roadmap of sources in frequency and space.**

Corrector Error Power Spectrum vs Storage-Ring Sector



Summary

- **The APS global orbit feedback system is in routine operational during user beam time.**
- **With global orbit feedback, the APS orbit stability is well within specification. Horizontal stability is typically 8µm and vertical stability typically 3.5µm, measured up to 30Hz.**
- **In addition to improving orbit stability, the APS orbit feedback system provides excellent beam diagnostics that are routinely used for diagnosing machine problems and for identifying the sources of orbit motion.**