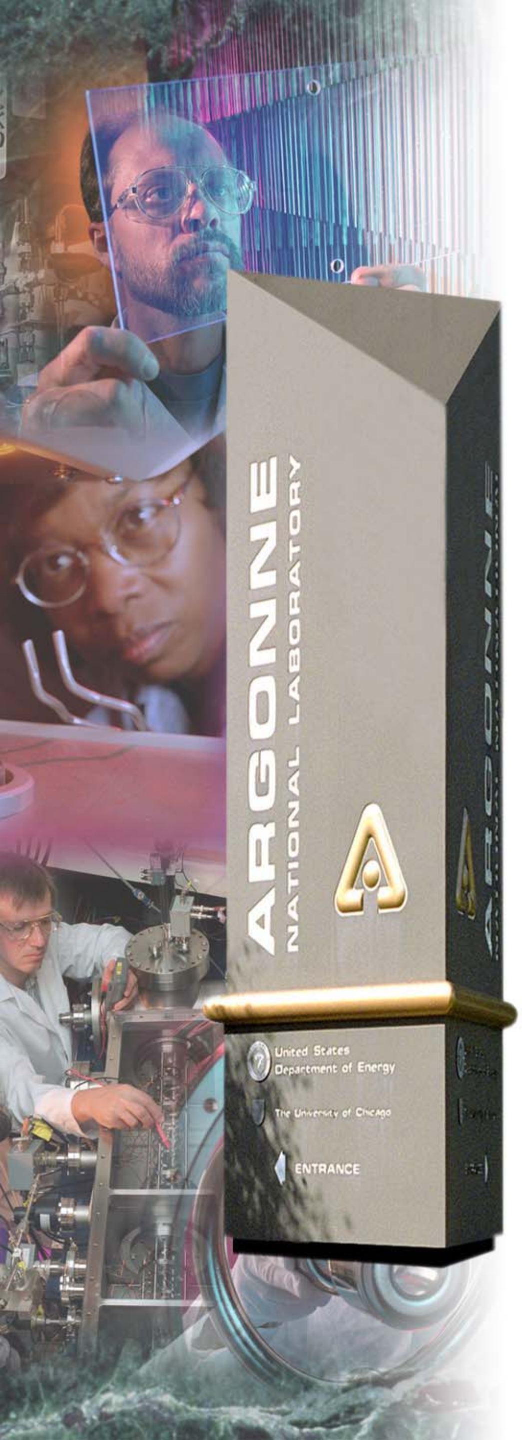

Stability and Machine Performance Improvement at the Advanced Photon Source

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The University of Chicago Review
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at Argonne National Laboratory

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Outline

- **Orbit stability**
  - Importance of orbit stability to users
  - Time scales of orbit motion
  - Recent measures to address orbit motion on different time scales
- **Beam performance**
  - Lower emittance to increase on-axis brightness
  - Optics correction for improved lifetime
  - Reduction of radiation damage of insertion devices (IDs)

Importance of Orbit Stability

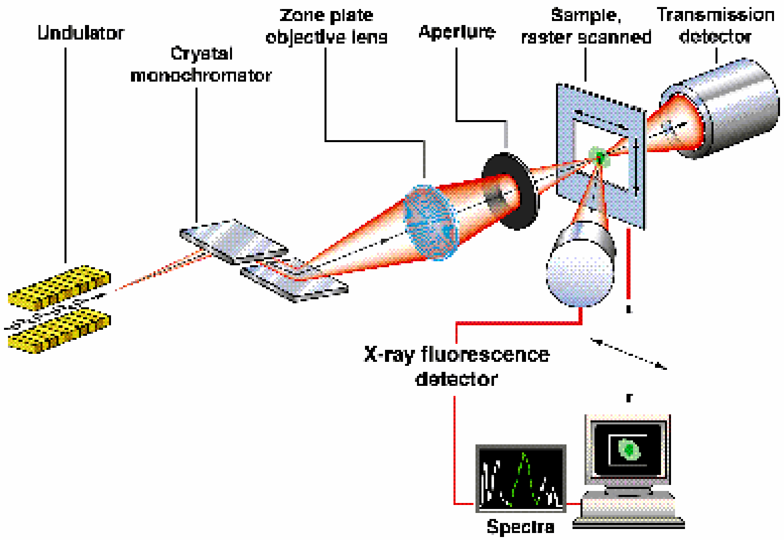
- **May 2000 user survey lists improvement of beam stability as their primary requirement (37%)**
- **Other survey question: The beam stability requirements for my experiments fall in the following time scale:**
  - > 100 Hz 5%
  - 0.1 Hz to 100 Hz 14%
  - 10 s to 10 min. 22%
  - 10 min to hrs 36%
  - fill-to-fill 25%

  } **Interest in long-term** (10 s to 10 min., 10 min to hrs, fill-to-fill)
- **Requests by individual CATs that are particularly sensitive to "long-term" photon beam motion**

An Experiment Requiring Beam Stability

Beam stability is critical for x-ray nanoprobe

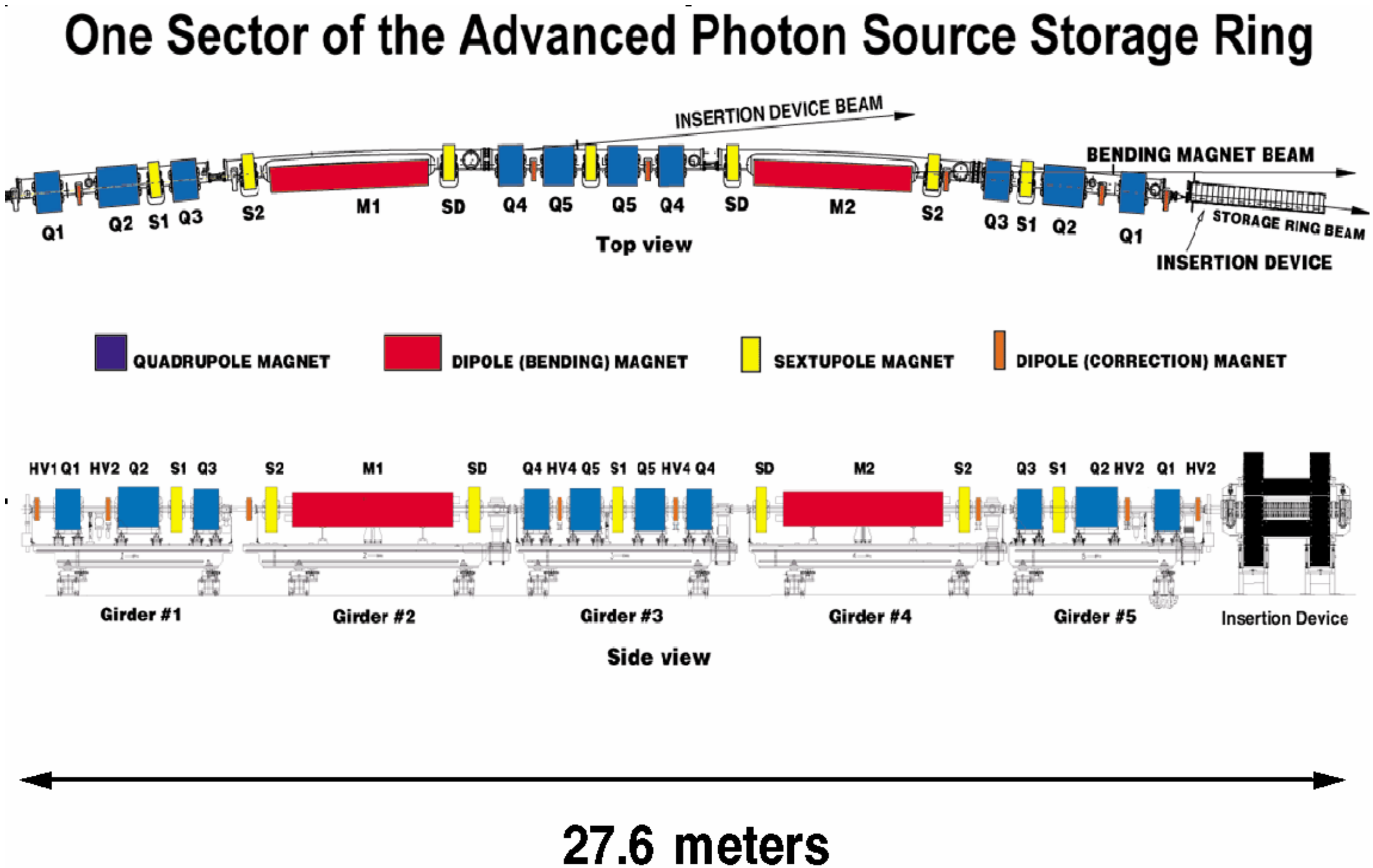
- **X-ray nanofocusing is highly sensitive to e-beam motion**
- **Example: $\sigma_{y'}$ = 3 µrad just fills 200 µm zone plate at 70 m from source**
- **Short/long-term stability <<1 µrad essential for nm-scale microscopy**



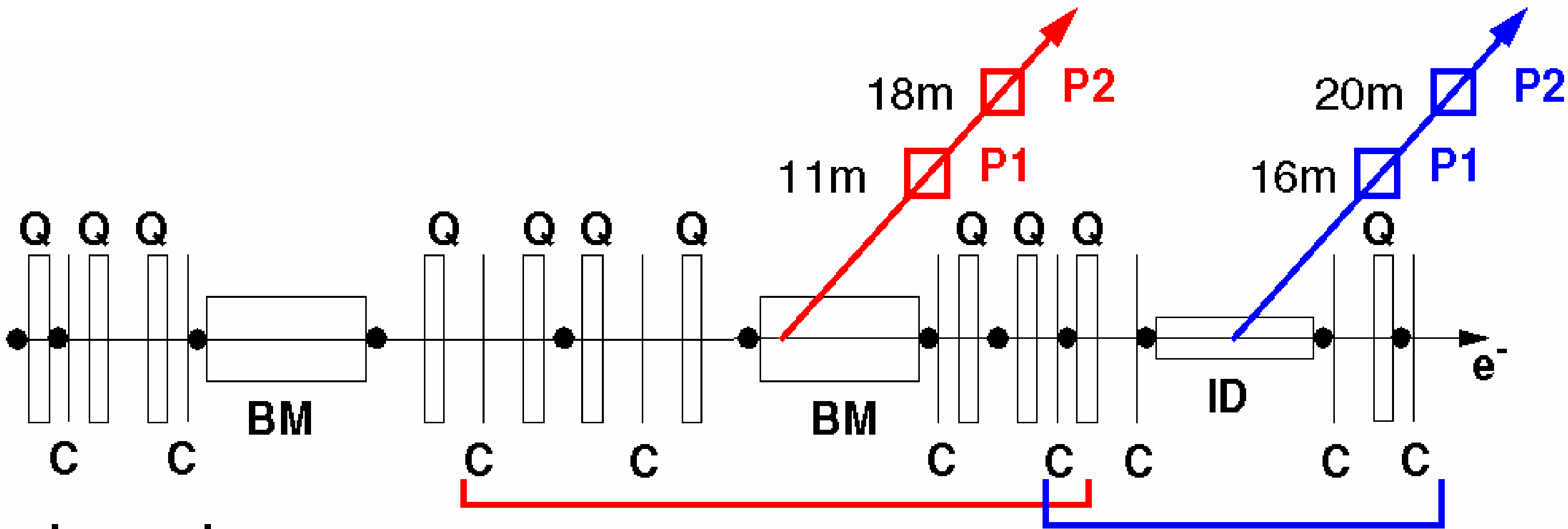
Goal: x-ray beam stability exceeds optics, stages, vibration limits by 10x.

Z. Cai, B. Lai, D. Legnini, I. McNulty, J. Maser, D. Paterson, S. Vogt (XFD/ANL)

Lattice Layout



Orbital Control Configuration



Legend:

C: Steering Corrector Magnet

●: RF Beam Position Monitor (BPM)

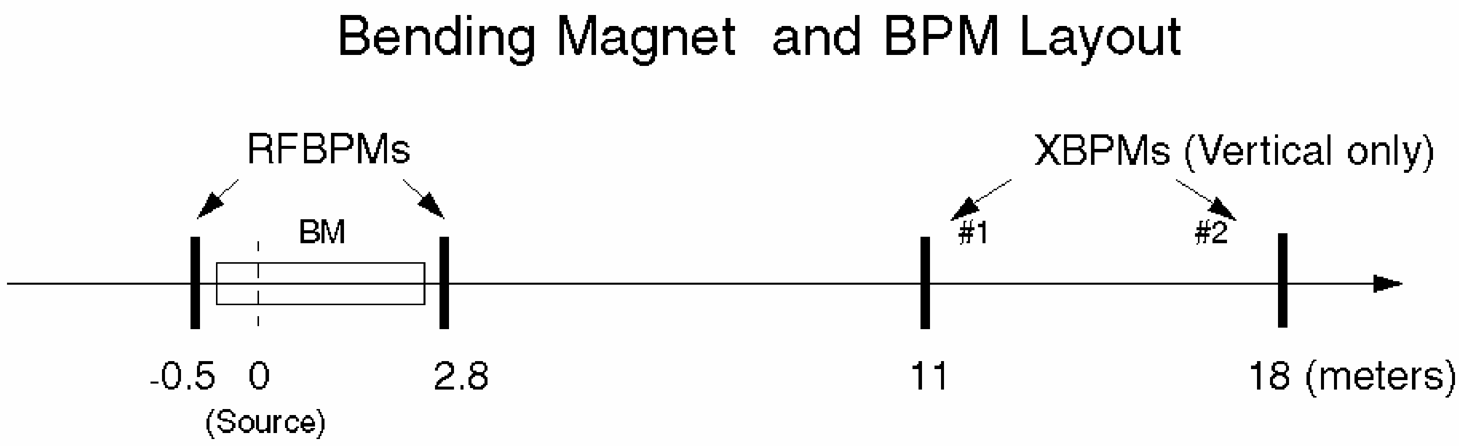
P1,P2 : X-ray Beam Position Monitors (XBPMs)

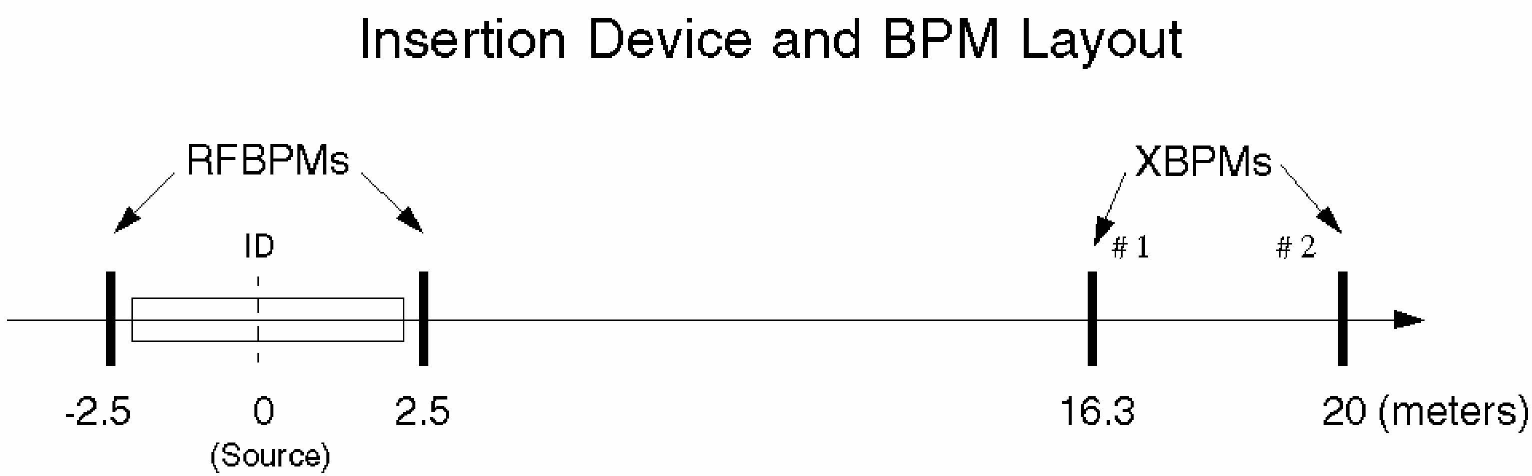
Q: Quadrupole

BM: Bending Magnet

ID: Insertion Device

X-ray BPM Layouts





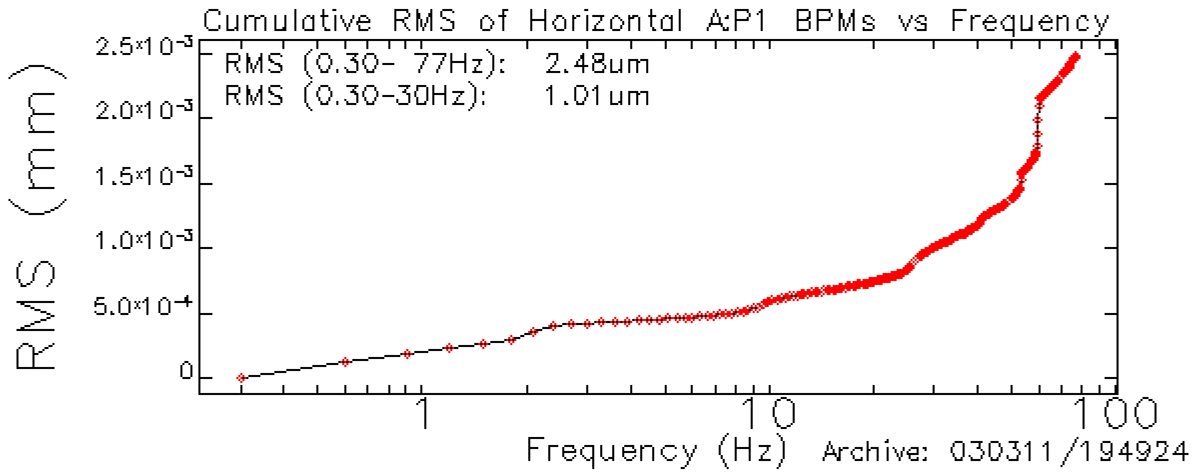
Time Scales of Beam Motion

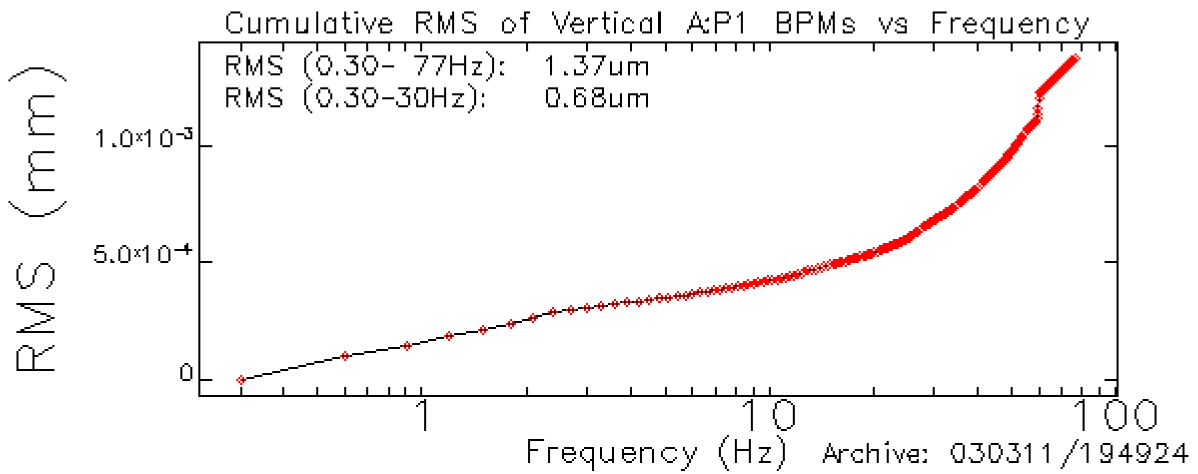
- **Useful to categorize time scales of beam motion according to effect on user experiments**
- **High-frequency (100 Hz–271 kHz, i.e., revolution frequency)**
  - For most users increases effective emittance rather than interferes with data collection
- **Medium-frequency (1 Hz-100 Hz)**
  - Interferes with user experiments
- **Short-term (1 second – hours)**
  - Momentarily steers the center of the beam away from experiment during data collection.
- **Long-term (1 day–1 run)**
  - Requires frequent re-steering of the photon beam or re-aligning of x-ray optics.

Time Scales of Beam Motion (Cont'd)

- **Each time scale has distinct**
  - sources of motion
  - methods of characterization
  - target specification of stability and
  - strategies of remediation and compensation
- **Above applies generally to all light sources**

Orbit Motion Characterization Example





Recent Orbit Stability Improvements

- Long-term stability: inclusion of dipole radiation and insertion device x-ray beam position monitors
- Short-term stability: integration of the "DC" orbit correction into real-time feedback orbit correction system (RTFS), which allows > 10-Hz correction rate
- Medium-frequency stability: Transient compensation of circurlarly polarized undulator
- Ease-of-operation: Extensive use of data and file management for orbit correction and operator interfaces
- Characterization of medium-frequency: RMS orbit motion (0.01 Hz–30Hz): 1.1 μm and 0.9 μm in the horizontal and vertical planes

X-ray Beam Position Monitors

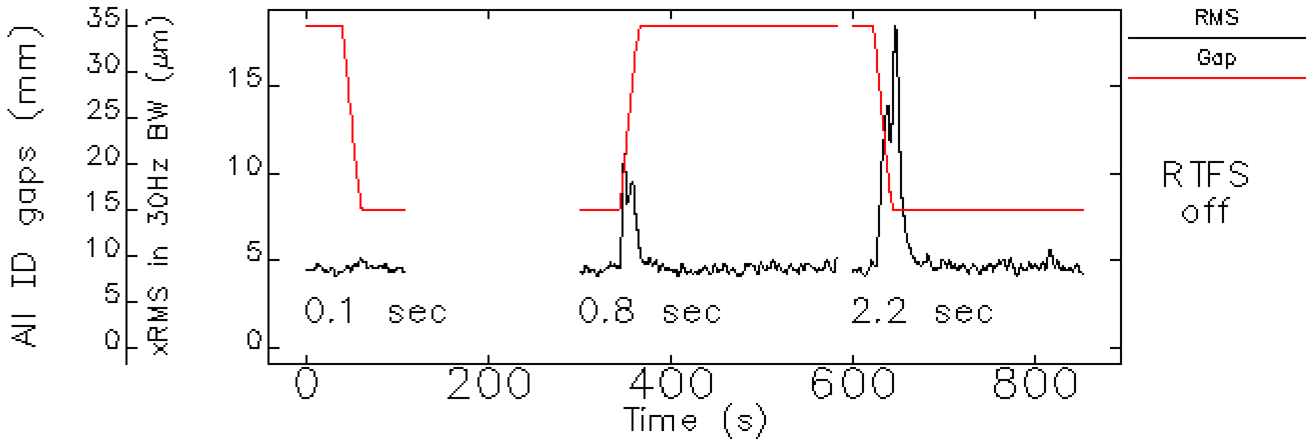
- **APS uses ID XBPMs in orbit correction, providing long-term stability for ID beamlines**
- **Long term beam stability < 200 nanoradians rms over a 48-hour period on three ID beamlines so far**
- **Eventually all sectors with special magnet girder realignment will have long-term stability**
- **Poster:**
  - "Routine Achievement of 200 Nanoradian rms Pointing Stability of Insertion Device Beams using x-ray Beam Position Monitors"
    - G. Decker and O. Singh
- **All 20 dipole beamline XBPMs used in orbit correction, which provide long-term orbit stability in the vertical plane**

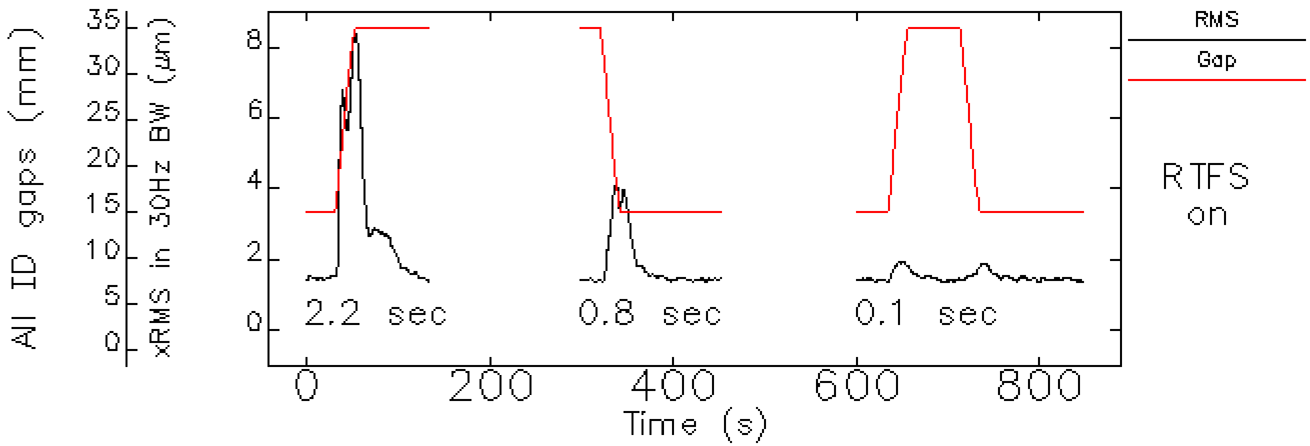
Faster DC Orbit Correction

- **Ported the robust general-purpose feedback software from UNIX workstation to an IOC that is part of the RTFS**
- **Network wait times eliminated**
- **DC orbit correction is 25 times faster than a few years ago; practically eliminates short-term orbit change from ID gap motion**
- **Posters:**
  - "APS Storage Ring Orbit Correction at 10 Hz" - L. Emery
  - "Real-time Feedback System" - F. Lenkszus

Faster DC Orbit Correction

Effect of shortening the iteration interval of DC orbit correction

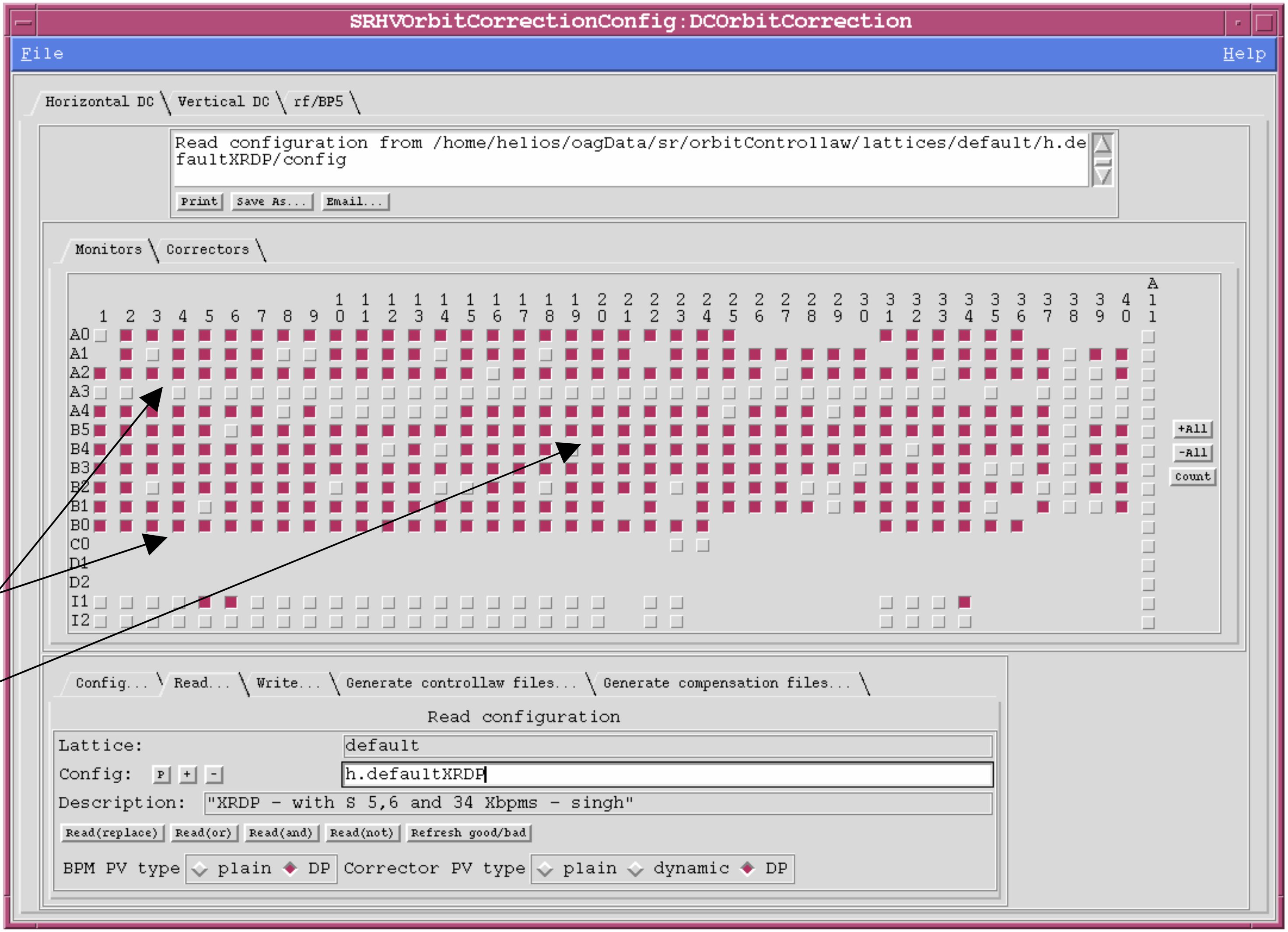




High-Level Software

Application for selecting devices in orbit correction

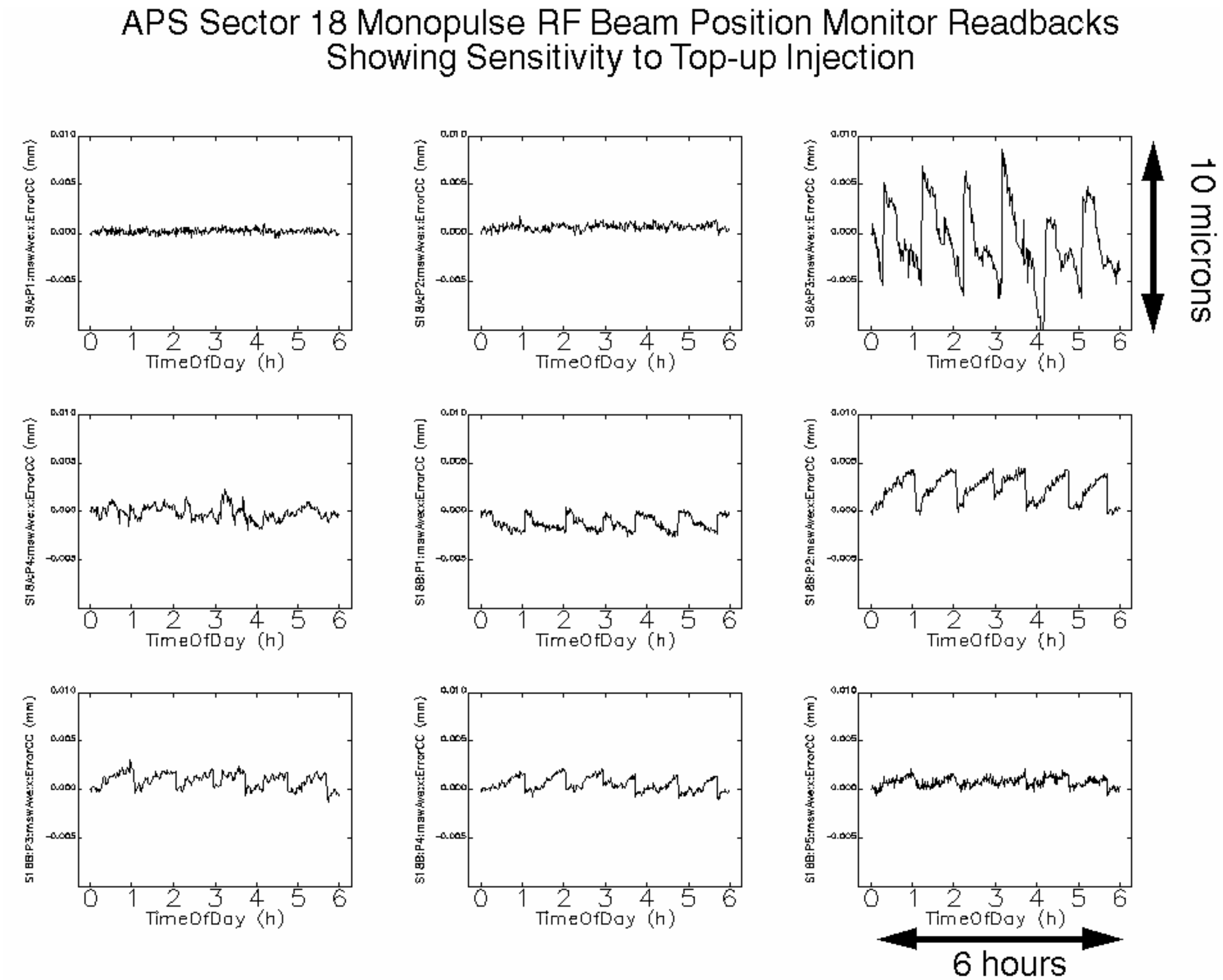
Database configures which BPM is non-existent or not "ok" for orbit correction



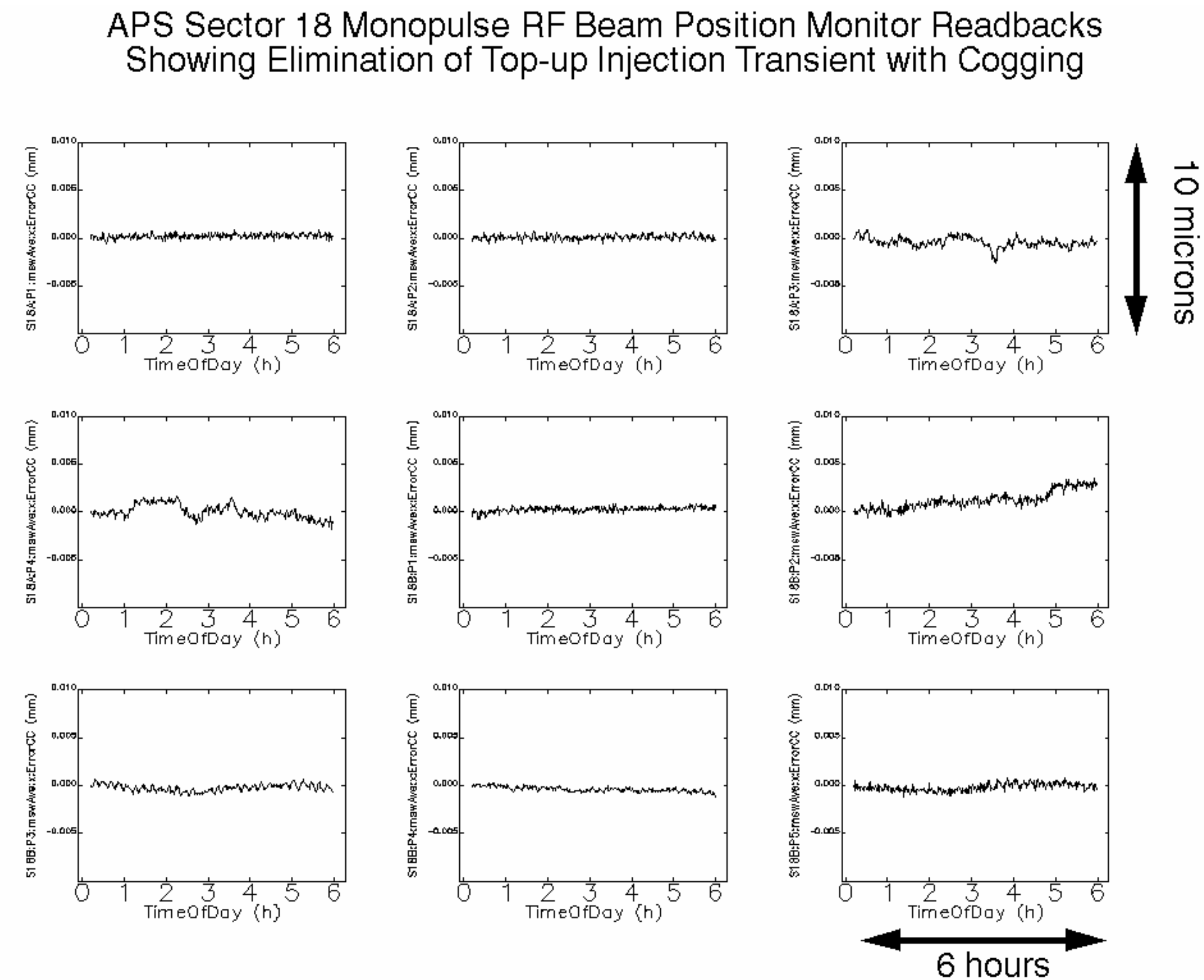
Other Stability-Enhancing Improvements

- **Adding a second pair of narrowband BPMs in sectors to improve the overall stability from intensity effects and bunch pattern changes**
- **Related poster: "Improvement of Storage Ring Beam Position Missteering Interlock Reliability by Using Narrowband BPMs and Digital Beam Position Limit Detectors" - O. Singh**
- **Cogging timing mode for monopulse receiver BPMs: sampling of a different bunch (or different part of the beam) at every turn, which virtually eliminates the offset change during top-up operations**

Other Stability-Enhancing Improvements



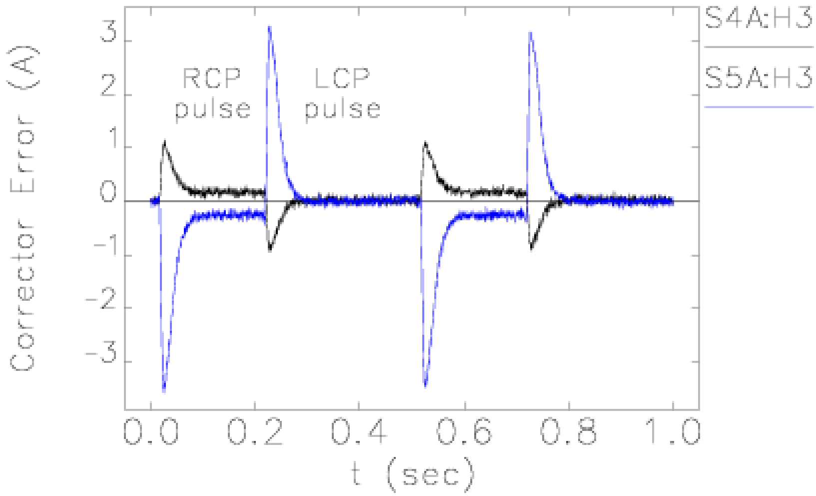
Other Stability-Enhancing Improvements



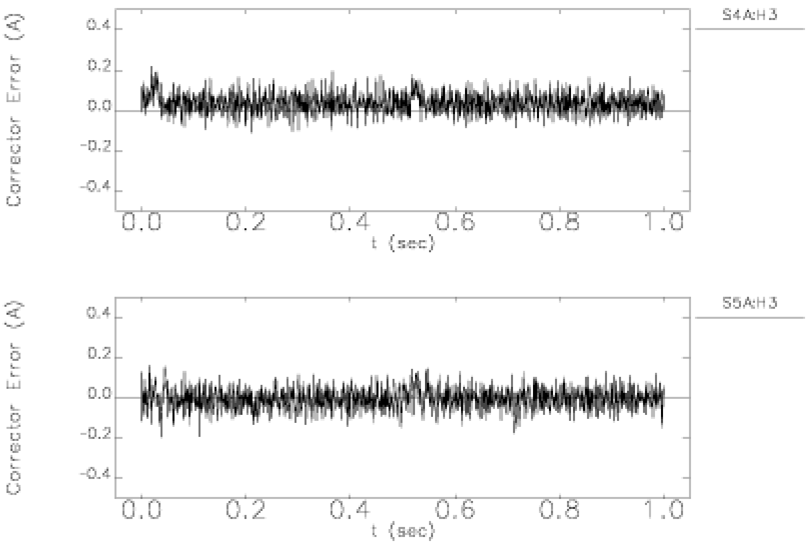
Pulsed Circularly Polarized Undulator

Orbit Perturbations as Seen by RTFS Signals

Uncorrected



Corrected



Beam Emittance

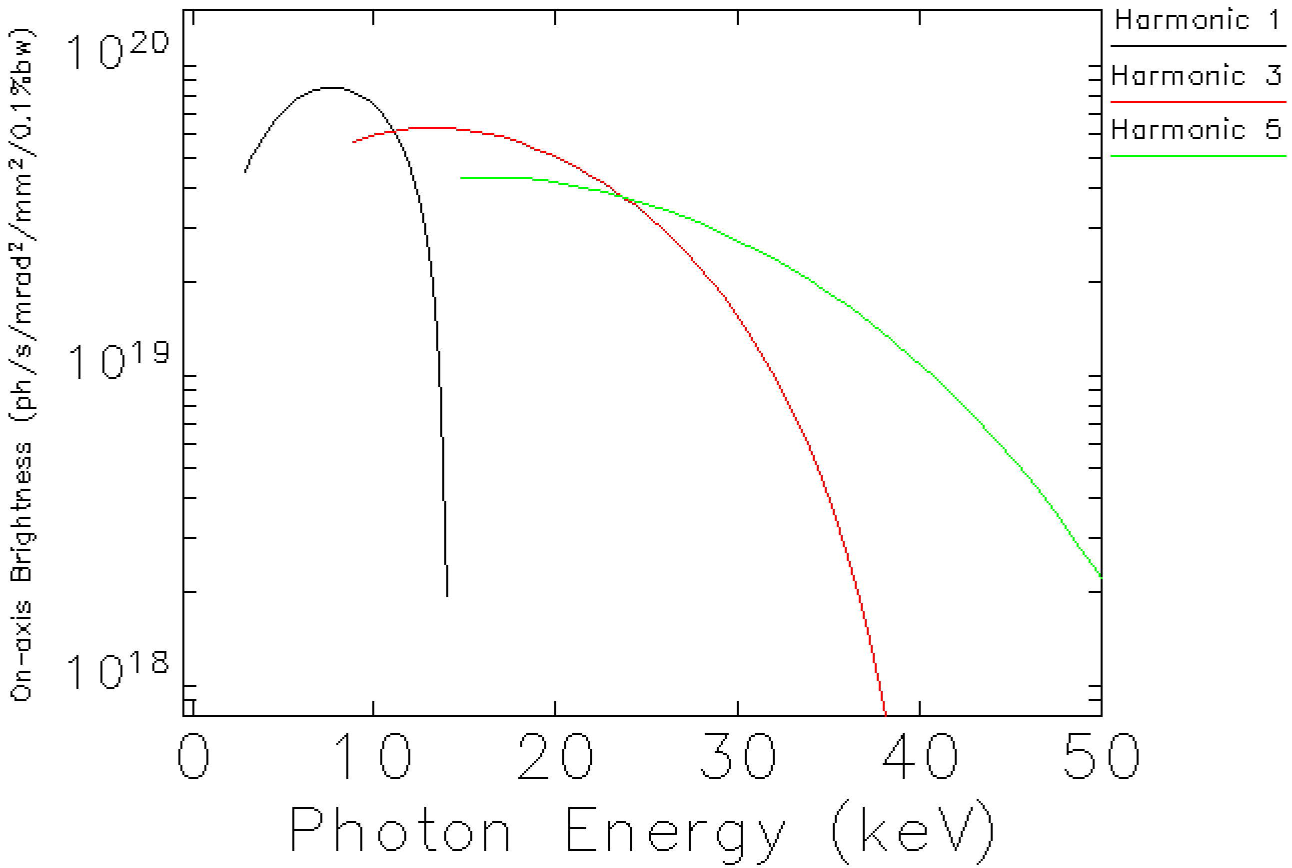
- On-axis brightness increases with smaller electron beam sizes, i.e., lower equilibrium emittance

$$B \propto \frac{I}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \quad \text{where, for example,} \quad \Sigma_x^2 = \sigma_x^2 + \sigma_r^2$$

- Effective horizontal emittance ($\varepsilon x = \sigma x \ \sigma x'$) has been reduced by a factor of 2.5 in comparison with the original design specification (8.0 nm-rad →3.1 nm-rad), thus increasing on-axis brightness
- Vertical emittance (εy) is typically set in the range 0.02 εx to 0.025 ε_x to maintain a certain lifetime (~6 h) in top-up mode
- ε_x can be reduced to a minimum of 0.005 εx (producing σx = 6 μm) when bunch pattern and lifetime permit, increasing the relative photon brightness to the maximum operationally possible

Photon Brightness

- **On-axis photon brightness is calculated and logged every 15 minutes, e.g., U33 shown below for 102 mA and $\varepsilon_y / \varepsilon_x = 0.004$.**

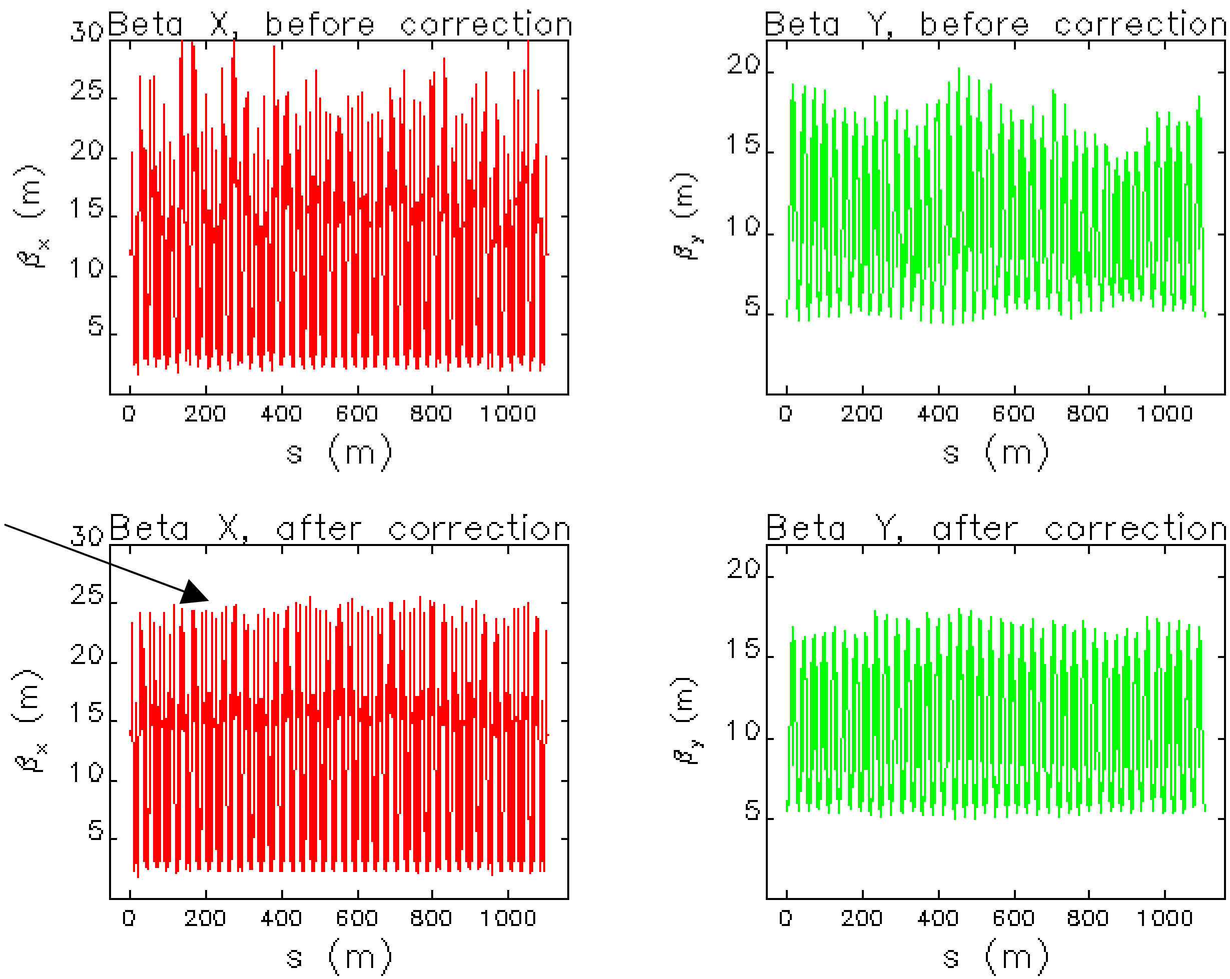


Lattice Optics Correction

- **Lifetime and injection efficiency are reduced by linear optics perturbation, which increase non-linear optical effects**
- **Now-routine optics characterization and correction (quadrupole magnet adjustments) restores lifetime**
- **Optics correction is required after shutdowns where about three sectors at a time are re-aligned for long-term orbit stability purposes**
- **Routine correction allows special lattice investigations, such as "missing-Q1" lattice that simulates an extended straight section**
- **Poster:** "Optics Correction Using Orbit Response Matrix Technique" - V. Sajaev

Lattice Optics Correction

Decreased modulation of lattice function



Other Improvements to Performance

- **Reduction of booster equilibrium emittance (from 130 nm-rad to 93 nm-rad) with the goal of reducing beam loss in storage ring and magnetization loss in IDs**
- **Injection section upgrade designed by Mechanical Engineering and Diagnostics groups for improved aperture and for diagnosing transfer-line optics**

Summary

- Large continuing effort to reduce orbit motion over several “time scales”
- Increased on-axis brightness through optimization of effective emittance
- Routine optics correction for lifetime recovery

Back-up Slides

High-Frequency (100 Hz–271kHz)

- Quantified by power spectral density (PSD) of appropriate beam position monitor readback
- For most users, motion increases effective emittance rather than interferes with data collection; vertical emittance most sensitive because of its already small value
- Sources: magnet power supplies, rf power sources, beam instabilities
- Remediation: Reduction of sources, i.e., improve power supply regulation, adjust rf cavities
- Compensation: Bunch-by-bunch feedback: not required (yet) at APS

Medium-Frequency (1 Hz–100 Hz)

- Quantified by power spectral density of appropriate beam position monitor readback; RMS motion value is given with frequency range of integration of PSD
- Interferes with user experiments
- Sources: ground motion, mechanical vibrations, magnet power supplies
- Remediation: Damping pads for girders, reduction of water flow, stiffening of water pipes (1995)
- Compensation:
  - Apply correction to the orbit with a short iteration interval, i.e., real-time orbit feedback system with 1534-Hz iteration rate; orbit motion is corrected in frequency range 0.1 Hz to 50 Hz
  - In the case of reproducible sources, we can compensate using feedforward (i.e., circularly polarized undulator in pulsed mode - 2003)

Short-Term (1 Second – Hours)

- Quantified by time profile of properly-filtered beam position monitors; single value reported is full range of position distribution.
- Steers the center of the beam away from experiment during data collection
- Sources: ID gap motion, thermal effects
- Remediation: Top-up operation (2001), improve VC water temperature regulation (1999)
- Compensation:
  - In the case of reproducible sources, i.e., circularly polarized undulator ramping in DC mode, we can compensate using feedforward (2002)
  - Apply DC correction to the orbit with a short iteration interval, i.e., 10 Hz; orbit motion from ID gap motion is not longer seen (2003)

Long-Term (1 Day – Run)

- Quantified by time profile of properly filtered beam position monitors
- Requires frequent re-steering of the electron beam in accelerator or photon beam in beamline
- Source: weather, tides, ground settlement, bunch pattern dependence of beam position monitors
- Remediation: none
- Compensation: Include thermally-stabilized x-ray bpms in DC orbit correction

High-Level Software

- Large effort to implement:
  - **Uniform design for operations and machine studies. Graphical user interfaces written in tcl/tk using widget libraries with consistent look and feel**
  - **General enough software structures to prevent extensive rewrites when a complication arises**
  - **Application configuration management from databases, i.e., to easily handle frequent changes in device availability**
  - **Split work of a complex system in simple applications and use a simple file protocol for data exchange (SDDS)**
- APS orbit correction configuration system is by now very sophisticated
- Related poster: “Automation of the APS Linac” - G. Banks, S. Pasky

Pulsed Circularly Polarized Undulator

- Polarization switches fast (5 ms), increases useful data collection time but magnetic transients that perturb the fields are strong
- Compensation with 7 small dipole and multipole magnets controlled by arbitrary waveform generators
- Year-long software and machine studies effort to optimize the waveforms using RTFS as readback
- Operations administratively limited to 2-second period
- Resulting rms orbit motion (0.01 Hz–30 Hz): 1.2 μm and 0.9 μm in the horizontal and vertical planes compared to normal values of 1.1 μm and 0.9 μm