Accelerator Physics Overview

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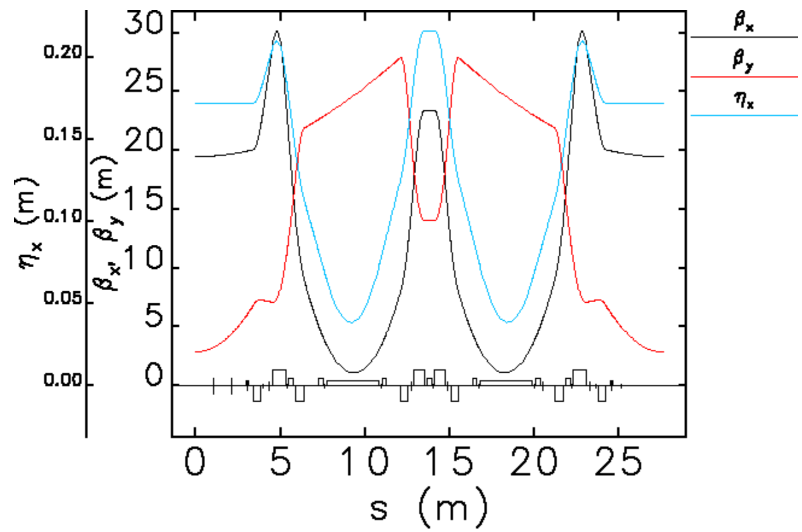
DOE Lehman CD-2 Review of APS-Upgrade
4-6 December 2012

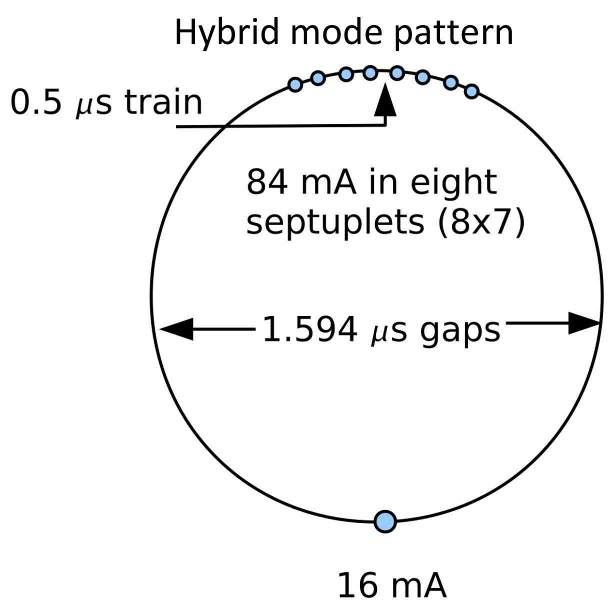
Outline

- Overview of APS accelerators and operation
- Upgrade components and mission need
- Lattice and beam dynamics
- Beam stabilization
- Insertion devices
  - See K. Harkay's talk for superconducting undulator
- Higher current
- Short-pulse x-rays (SPX) not covered (see V. Sajaev's talk)

Accelerator Operations Overview

- 7 GeV light source operating at 100 mA
  - 1104 m circumference
  - 40 sectors, 35 ID straights
  - Effective emittance of 3.1 nm
  - Vertical emittance of 40 pm
- Two fill modes support timing studies
  - 100 mA, 24 bunch mode:
    - 65% of time (~9 h lifetime)
  - 100 mA, hybrid mode
    - 15% of time (~6 h lifetime)
  - Both require top-up
- 100 mA, 324 bunch mode does not require top-up (~60h lifetime)





Accelerator Upgrades are Driven by Mission Need

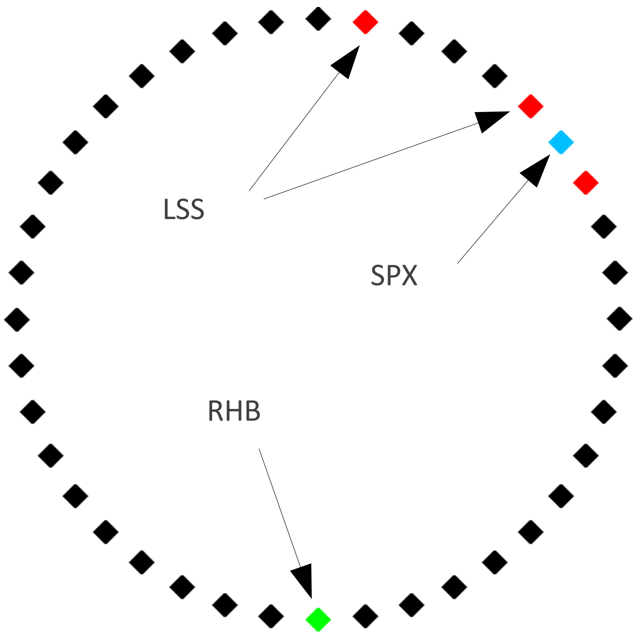
- *Need for additional beamline capacity*
  - Provision of additional canted straights
  - Provision of several long straight sections
- *Need for more stable beams to allow demanding, state-of-the-art experiments to be performed*
  - Multi-pronged approach
  - Goal is a two-to-four-fold improvement in short- and long-term stability
- *Need for higher brightness and flux above 10 keV*
  - Optimized insertion devices
  - Superconducting undulators
  - Several long straight sections
  - Increase beam current to 150 mA
    - All new equipment should be 200 mA compatible
- *Need to provide intense, tunable, few-picosecond x-ray pulses with high repetition rates*
  - Addressed by use of Zholents' deflecting cavity scheme ("SPX")
  - Also, maintain existing bunch patterns at higher current

Major Lattice Requirements

- 3 long straight sections at sectors 1, 5, and 7
  - Reduced from 8 previously by adoption of revolver IDs
  - Increases useful ID length
  - Provides room for SPX cavity cryostats
- SPX requires specific linear and nonlinear optics
  - Deflecting cavities are separated by 2 sectors – need exactly 2π phase advance
    - LSS in sectors 5 and 7 accommodate cryostats
  - Sextupoles require special adjustment (V. Sajaev's talk)
- Reduced Horizontal Beamsize (RHB) at Sector 20 for wide-field imaging
  - Reduction from 280 μm to $\leq$120 μm
- Careful nonlinear dynamics tuning required
  - Maintain good injection efficiency (>80%)
  - Maintain lifetime >3.8h
- Constrain emittance increase to ~10%
- Need adequate chromaticity: ξ=9 for hybrid mode and ξ=4 for 150 mA 24-bunch mode

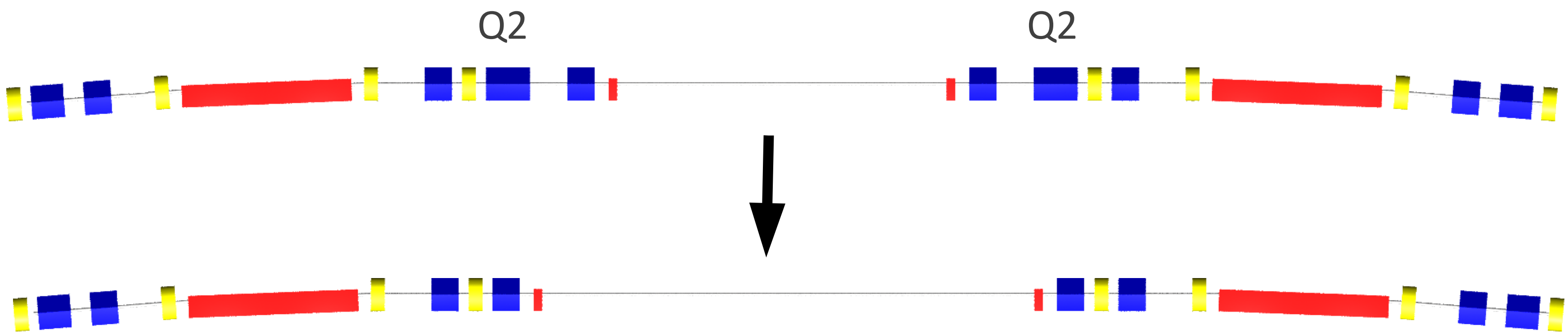
Lattice Optimization

- Multi-objective genetic algorithms used to develop lattices employ tracking, directly tuning for
  - Large Touschek lifetime
  - Large dynamic aperture
  - Adequate chromaticity
- Variables include linear optics and dozens of sextupole knobs
- Use ANL and APS parallel computing resources
- Lattices developed include
  - 3 LSS + RHB at sector 20
  - 3 LSS + RHB + SPX insertion (Sector 6)
  - Earlier versions with 4 and 8 LSS



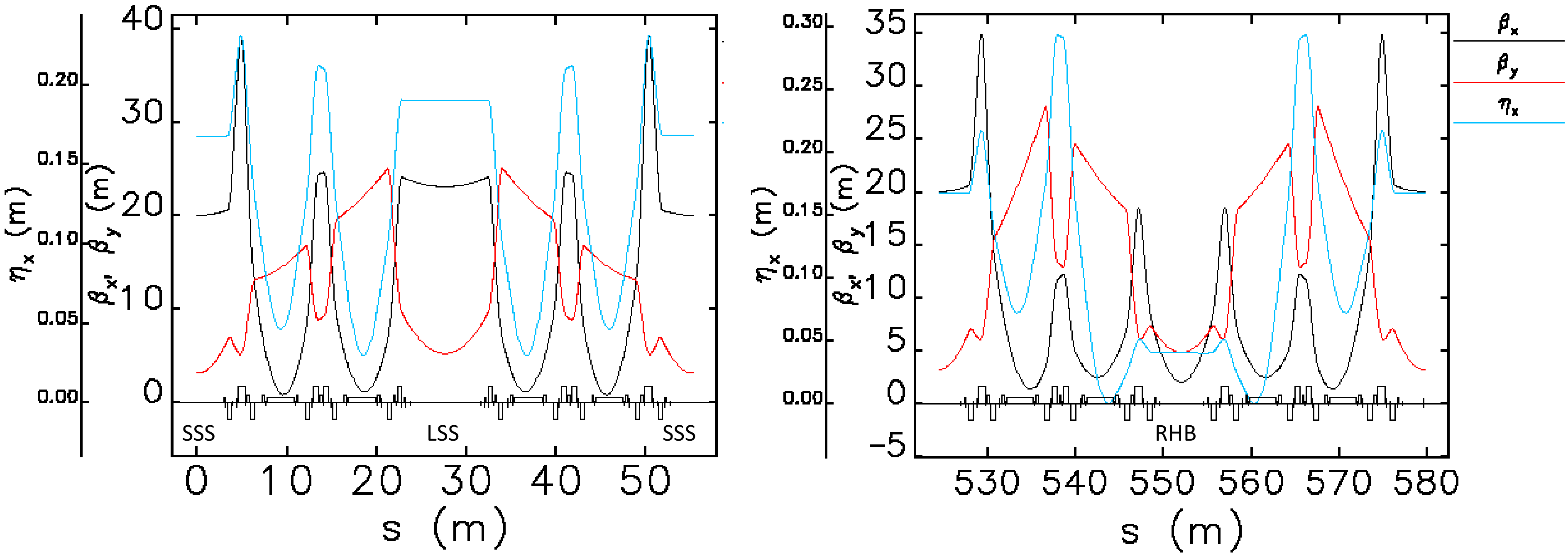
Long Straight Section (LSS) Scheme

- LSS can be implemented at APS with a simple scheme
  - Remove the Q2 magnets on either side of SS
  - Remove the adjacent correctors
  - Remove the adjacent BPMs
  - Slide other components away from the ID



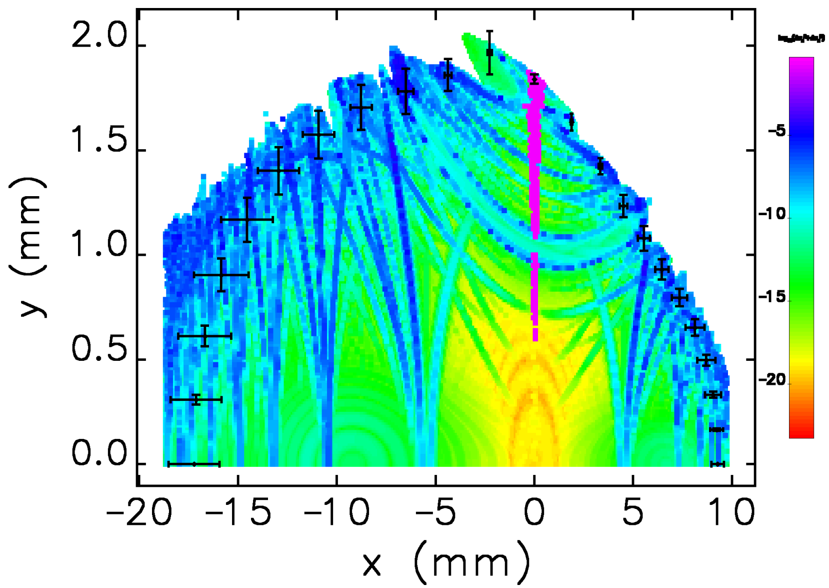
- Increases space available for ID from 4.8 to ~7.7m
- Most cost-effective option for LSS
- Can use existing spare magnets for installation

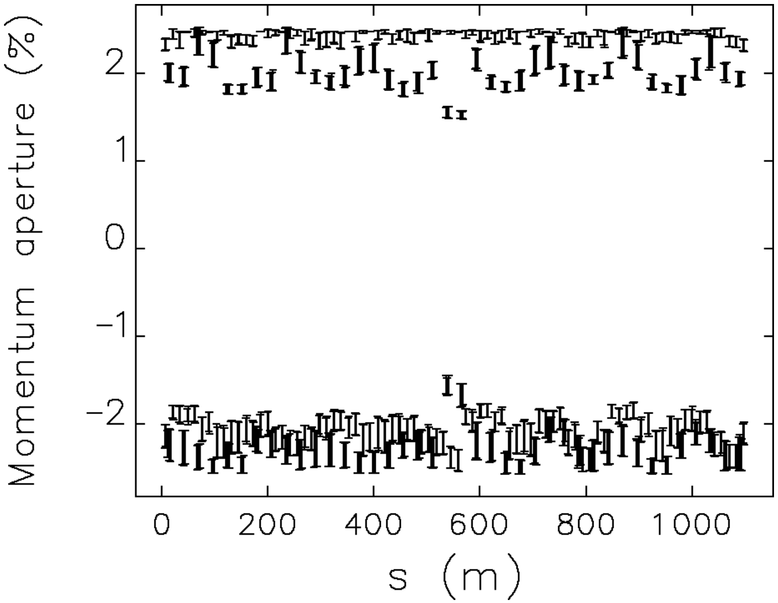
3LSS+RHB Lattice Functions



- LSS:
  - Horizontal lattice functions little changed
  - Vertical beta function increases from 3 m to 5 m
- 85 μm rms beam size at RHB sector ($\leq$120 μm required)
- Effective emittance of 3.4 nm

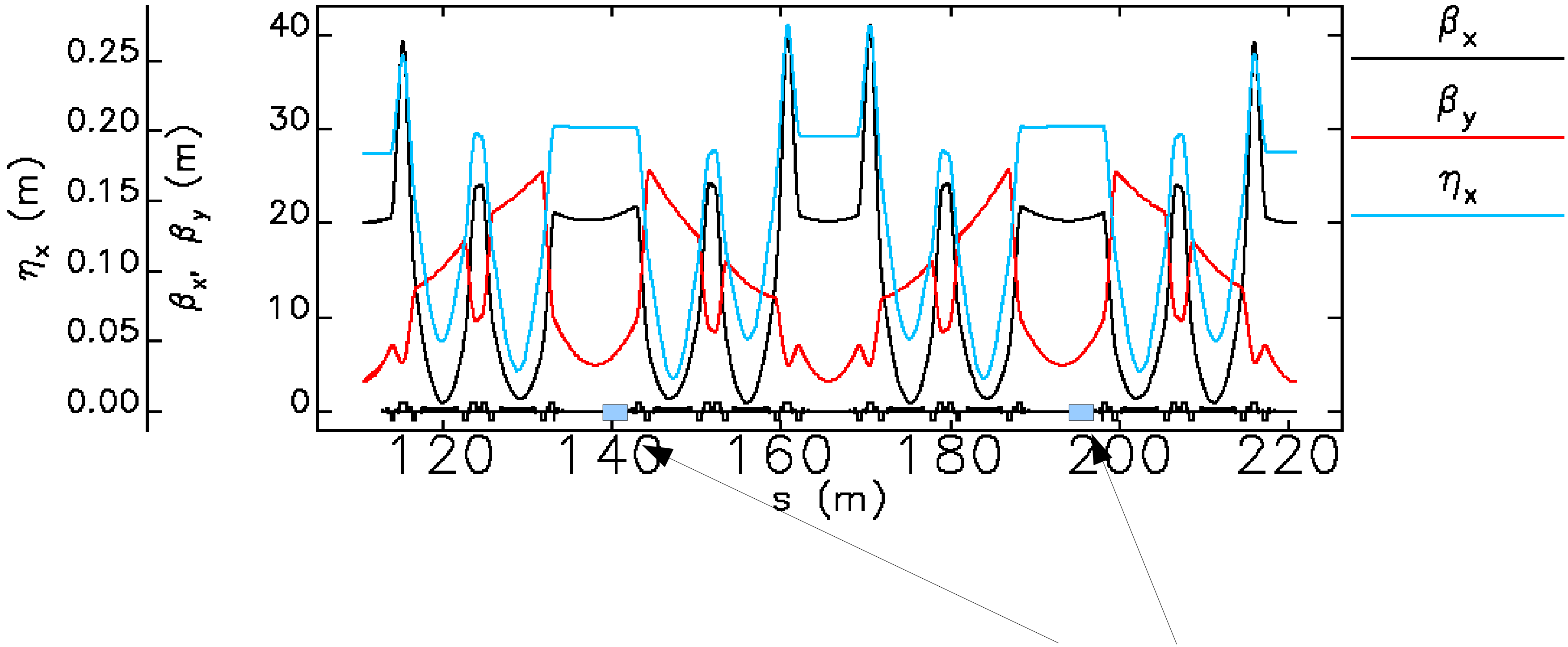
3LSS+RHB Predicted Performance (ξ=9)





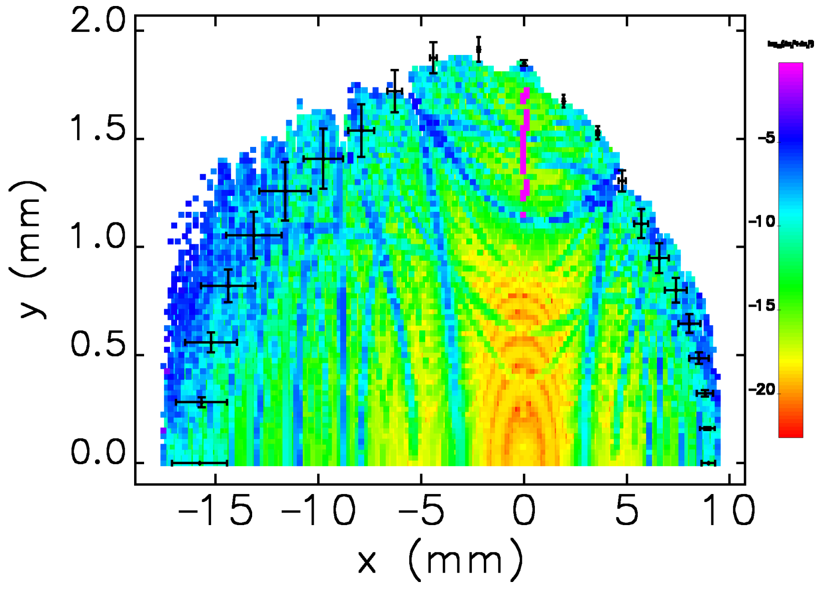
- Evaluated with 50 error ensembles
- Dynamic acceptance more than sufficient
- Local momentum acceptance is adequate for 150 mA hybrid mode
  - >2.7 h lifetime (95% confidence) for 16 mA
  - >8 h lifetime (95% confidence) for other bunches

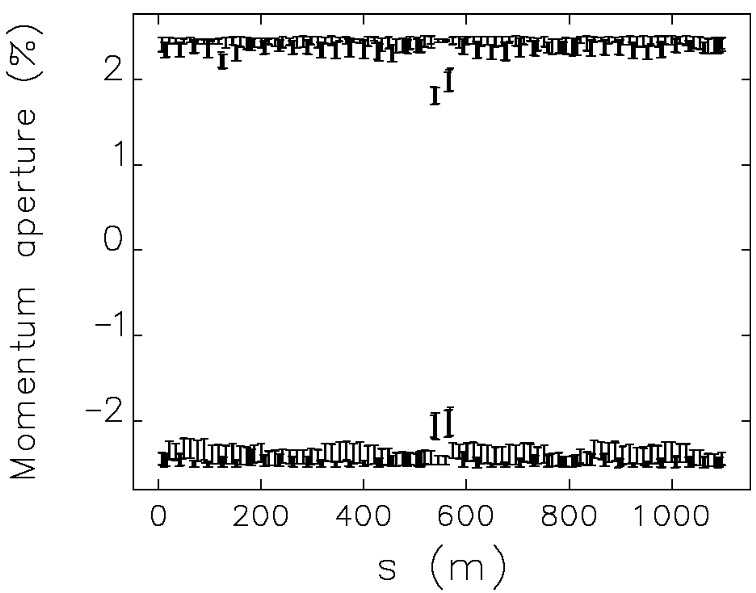
3LSS+RHB+SPX Lattice Functions



- Crab cavities in downstream part of sectors 5 and 7
  - Required vertical phase advance achieved
- 97 μm rms beam size at RHB sector ($\leq$120 μm required)
- Effective emittance of 3.5 nm

3LSS+RHB+SPX Predicted Performance (ξ=5)





- Evaluated with 50 error ensembles
- Deflecting cavities are on at full strength (0.5 MV/cavity)
- Dynamic acceptance more than sufficient
- Local momentum acceptance is good
  - >7 h lifetime (95% confidence) for 150 mA/24 bunches

Mockup Lattice Testing

- Turning off Q1 magnets allows mocking up removal of the magnets to make an LSS
- Tested several lattices with 4 LSS[1]
  - 4 non-symmetric LSS (1, 5, 7, 11)
  - 4NLSS + SPX
  - 4NLSS + RHB
- General findings
  - Lattices are acceptable for operations
  - Need to steer close to centers of sextupoles to avoid driving skew sextupole resonance
    - Implies significant reduction in local steering for beamlines (in progress)
  - Need to work close to the normal tunes 36.16 and 19.22
    - Optimizer recommends ~36.10 and ~19.30

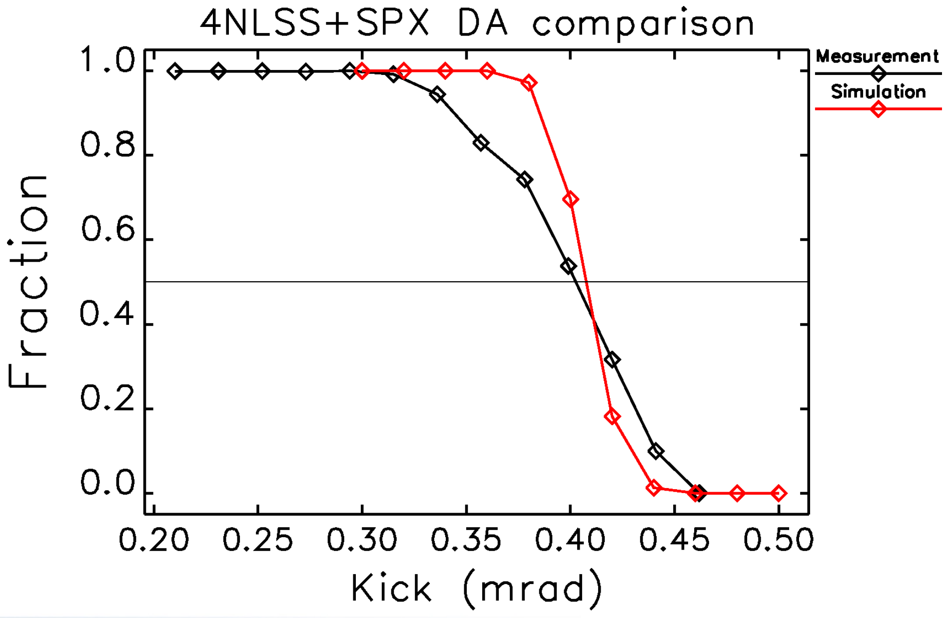
[1]3LSS is a recent change.

Mockup Lattice Testing

- Good agreement with expected linear optics
- Stored 100 mA in 24 bunches in all lattices
- Lifetimes at bottom of expected range, but workable

	4NLSS	4NLSS+SPX	4NLSS+RHB
Design chromaticity (x and y)	9; 9	8; 8	9; 9
Predicted median lifetime	7.1	8.6	7.9
Predicted 5th percentile lifetime	6.1	6.6	5.9
Measured lifetime	6.0	6.0	5.4

  - 4NLSS+SPX chromaticity higher than needed now
- Dynamic aperture close to expectations
  - Difference in slope is result of collective effects

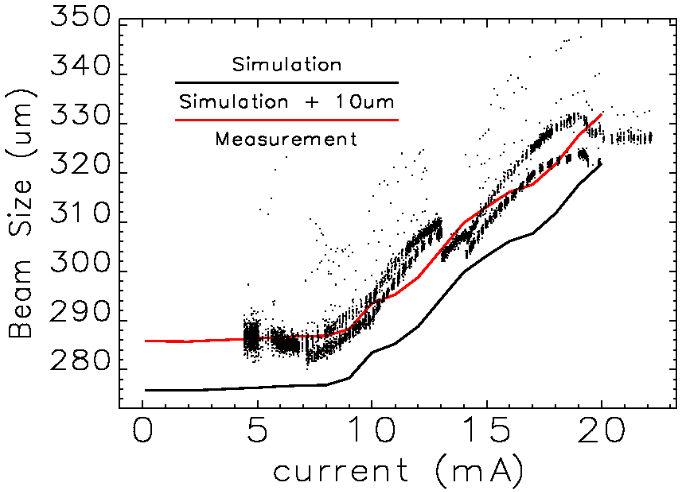


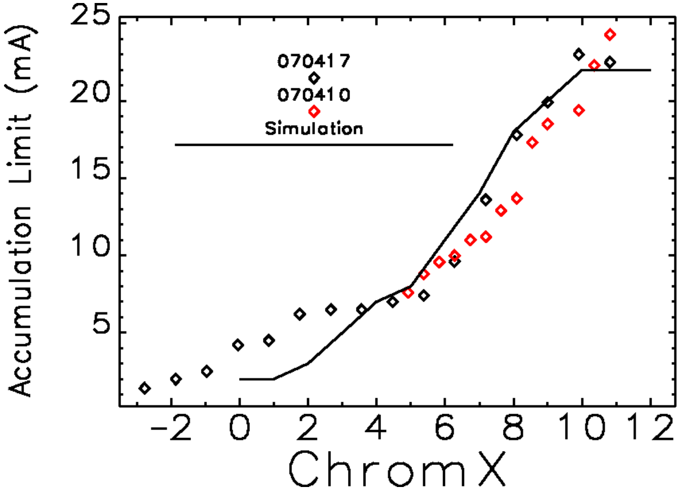
Lattice Alternatives

- Replacement triple-bend achromat lattice
  - Explored in detail, 1 nm emittance possible
  - Cost, interruption of user operations considered unacceptable
- Replacement multi-bend achromat lattice
  - Too costly and disruptive for present upgrade
  - LDRD to explore as a potential future upgrade
- Lower energy operation
  - Emittance scales like E^2
  - Detailed study indicates no advantage over 5~100 keV range
- Damping wigglers
  - APS lacks needed real estate, rf voltage
- Damping partition change via systematic orbits
  - Potential for 1.5 nm effective emittance
  - No hardware changes
  - Planning experimental studies
  - *May* be compatible with several LSSs as special operating mode

Collective Effects

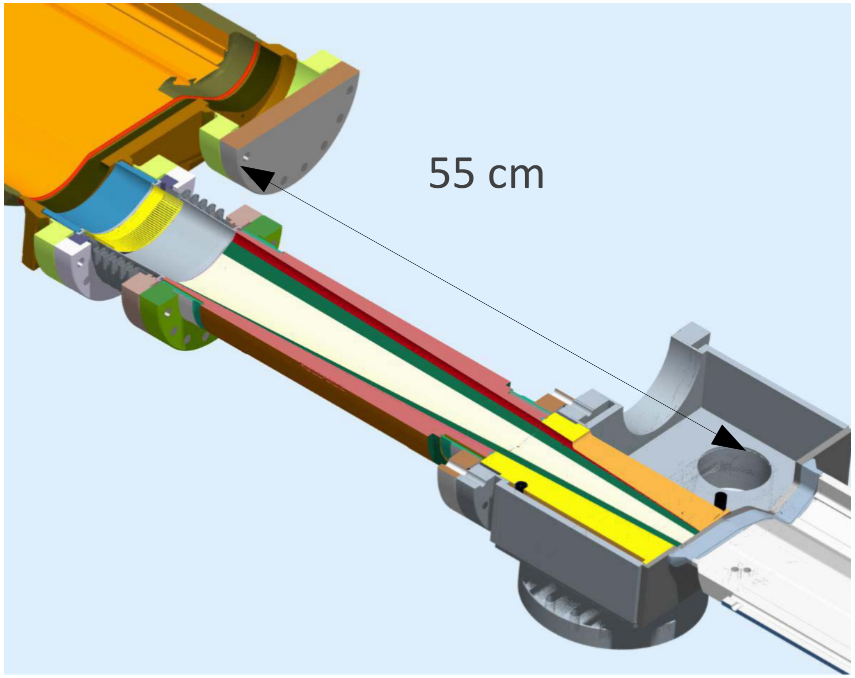
- High single-bunch current essential to APS timing users
- Impedance model allows prediction of single-bunch effects
  - Detailed 3D modeling of chambers with GdfidL
  - Tracking with elegant
- Model successfully predicts
  - Bunch lengthening
  - Energy spread increase
  - Accumulation limit, including need for high chromaticity w/out feedback
- Provides essential guidance as we make changes, e.g.,
  - LSS
  - IDs in undeveloped sectors
  - Deflecting cavities





Long Taper Development

- LSSs will increase effective vertical impedance
  - Longer chamber → more resistive wall impedance
  - Larger beta functions → more geometric impedance
  - Single bunch limit 16 mA → 12 mA
  - Exacerbated by problems obtaining very high chromaticities in non-asymmetric lattices
- Evaluated nonlinear tapers but found they did not resolve the problem
- Longer (linear) tapers will reduce impedance
- APS-U involves replacing tapers at LSS and 4ID (small-gap chamber)



Beam Stabilization

- Targeting two-to-four-fold improvement in beam stability

		AC rms motion 0.01-200 Hz		AC rms motion 0.01-1000 Hz		Long-term drift (One Week)	
		μm rms	μrad rms	μm rms	μrad rms	μm rms	μrad rms
Horizontal	Present	5.0	0.85	5.0 - 7.0*	NA	7.0	1.4
	Upgrade	3.0	0.53	6.0	1.14	5.0	1.0
Vertical	Present	1.6	0.80	3.7*	NA	5.0	2.5
	Upgrade	0.42	0.22	0.84	0.44	1.0	0.5

* Measurement up to 767 Hz.

- Components of the beam stability upgrade
  - New BPM electronics
  - Front-end hard x-ray BPMs
  - Real-time feedback system upgrade
  - BPM position sensing

Allocation of Beam Motion "Power"

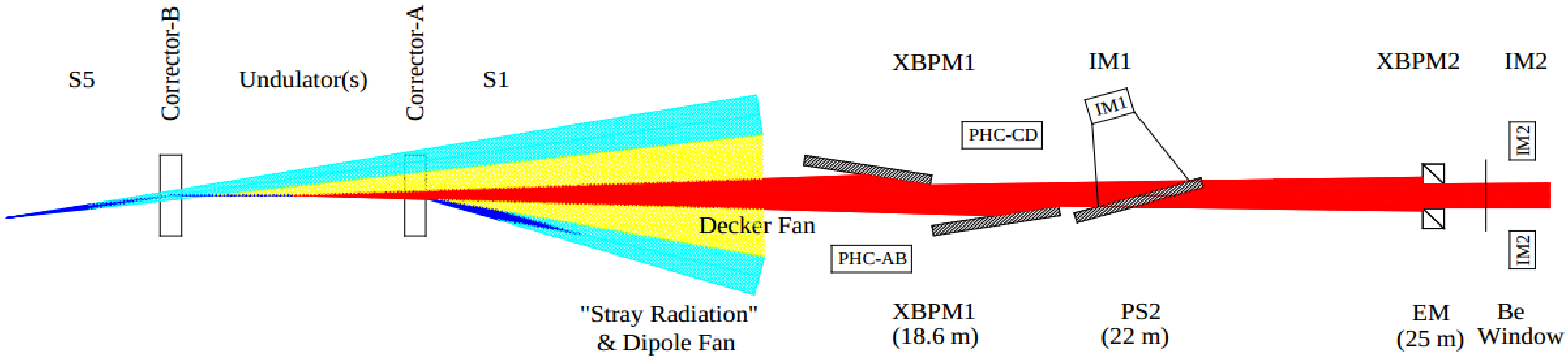
- Based on the beam stability goals, we allocate the available beam motion among difference possible sources
- This is based on the plane and bandwidth affected by different sources
  - IDs primarily affect the horizontal plane at relatively low frequencies
  - SPX will primarily affect the vertical plane with a potentially broad frequency content
- These may drive specifications for the systems in question or derive from anticipated/historical performance

System	$\int P_x df$ $(\mu m)^2$	$\int P_{x'} df$ $(\mu rad)^2$	$\int P_y df$ $(\mu m)^2$	$\int P_{y'} df$ $(\mu rad)^2$
Total	9.0/36	0.33/1.30	0.18/0.71	0.048/0.194
SR baseline	7.0/34	0.27/1.24	0.08/0.34	0.023/0.096
PM and IEX IDs	1.0/1.0	0.03/0.03	0.01/0.01	0.001/0.001
Pulsed EMVPU	1.0/1.0	0.03/0.03	0.01/0.01	0.001/0.001
SPX	0.0/0.0	0.00/0.00	0.08/0.34	0.023/0.096

Two values in each column are for the 0.01-200 Hz and 0.01-1000 Hz bands, respectively

Enhanced X-ray BPM System

- High-power grazing incidence BPM (XBPM1)
  - Intercepts undulator beam outside central cone
  - Pinhole cameras measure vertical position
  - Left-right absorbers measure horizontal position
  - Far less sensitive to soft bending magnet radiation background
- Intensity monitor 1 (IM1) uses scattered photons from the closed photon shutter (PS2) for beam centering during machine setup
- Non-invasive IM2 uses scattered photons from the exit window
- XBPM2 uses x-ray fluoresence from the exit mask to verify beam position



Real-time feedback system upgrade

PDR 3.3.8

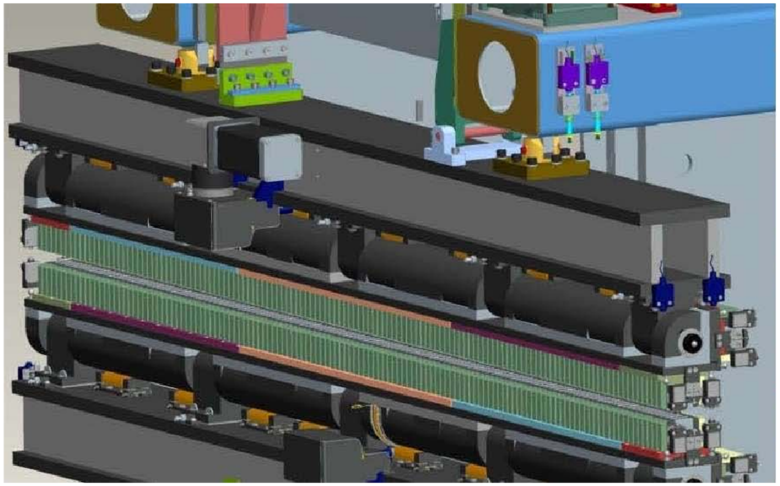
- Originally commissioned in 1997
- Limited to 1.5 kHz sample rate ⇒ 60 Hz closed-loop bandwidth
- Scope:
  - Develop comprehensive simulator to guide changes
  - Complete replacement of existing DSPs & reflective memory system
  - Double the number of BPMs interfaced to the system
  - Double the number of fast steering correctors (interface to existing correctors)
- Benefits:
  - Increase closed-loop bandwidth to 200 Hz
  - Improve AC stability four-fold
  - Improve feedforward system that mitigates top-up disturbance
- Staged upgrade, must be compatible with existing system

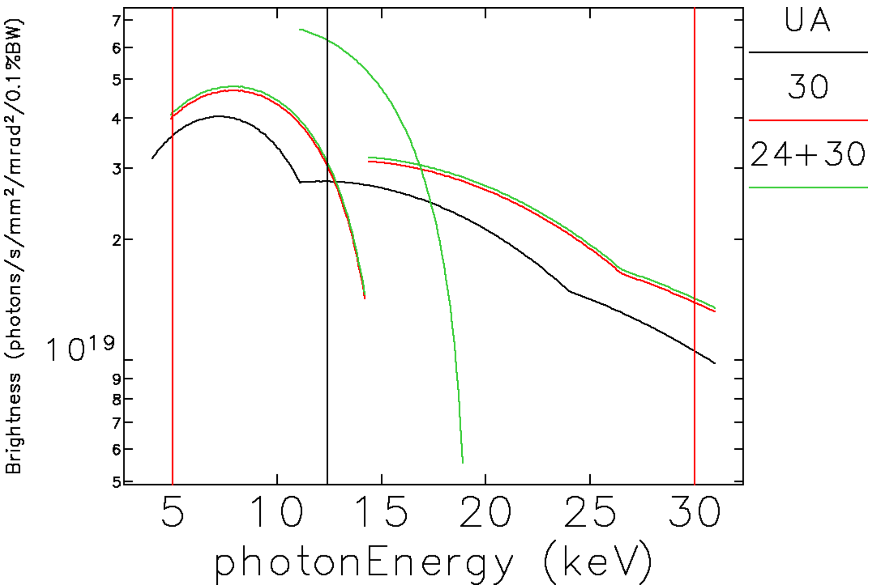
Optimization of Undulators

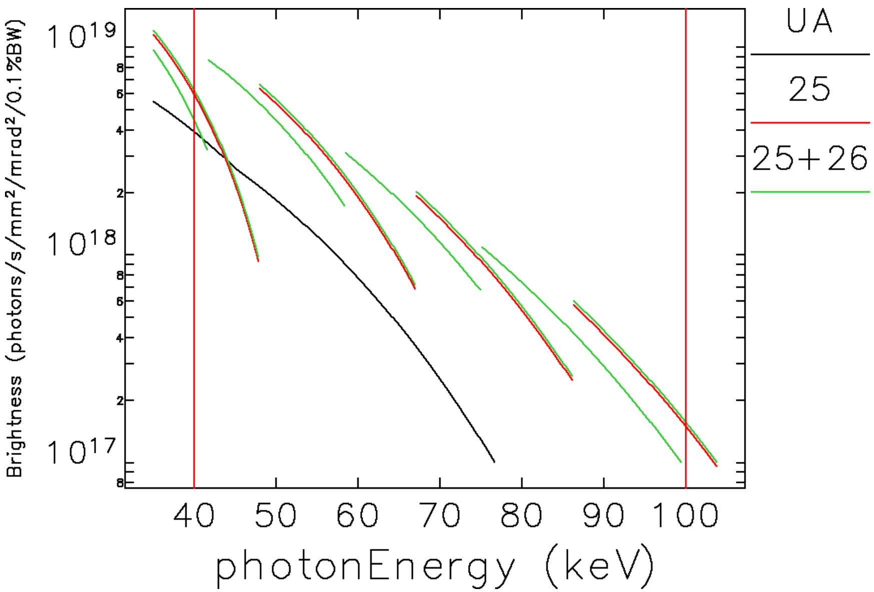
- 30 APS “Undulator A” (U33) devices still in use
  - 33 mm period, 2.4 m long, with K<2.75
  - General-purpose ID with continuous coverage above 3.3keV
- Also a selection of other periods in use
  - 18, 23, 27, 30, and 55 mm
- Goal is to maximize brightness or flux in specific energy band(s)
  - Constrained by power and power density limits in front ends
- Options for brightness improvement
  - Customized period
  - Revolver
  - Higher current
  - Longer device in LSS
  - Superconducting device

Revolver Undulators

- Revolvers have two or more magnetic structures, one support
- In use at, e.g., ESRF, SPRing-8
- More space-efficient than multiple in-line devices
  - Reduced need for LSSs
- Brightness gains relative to single devices



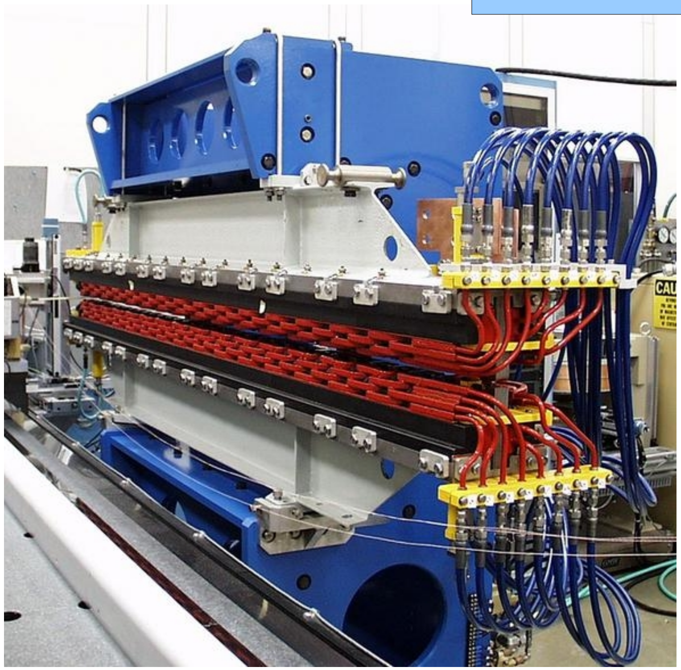




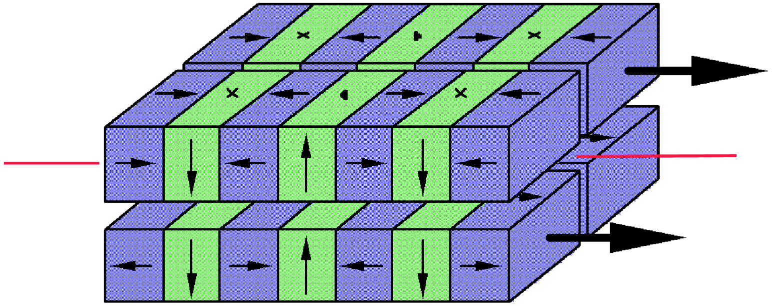
Other Types of Devices

PDR 3.4.3

- Variable-polarization EM undulator
  - Somewhat similar to existing "CPU" device
  - Want to increase switching frequency from present 0.5 Hz to ~10 Hz
  - Extend lower limit of CP radiation from present 500 eV to 400 eV
  - Innovative single-turn coil concept developed and to be tested
  - Copper-coated stainless steel chamber required



- APPLE-II undulators
  - Two devices needed
  - Provides variably polarized radiation
  - Intended approach is to purchase devices



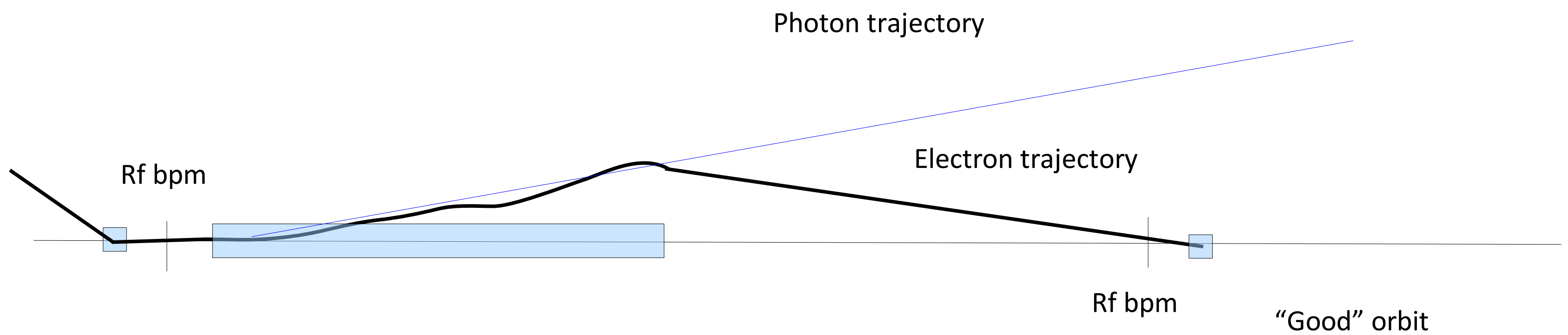
Schematic of an APPLE-II undulator

Requirements on IDs

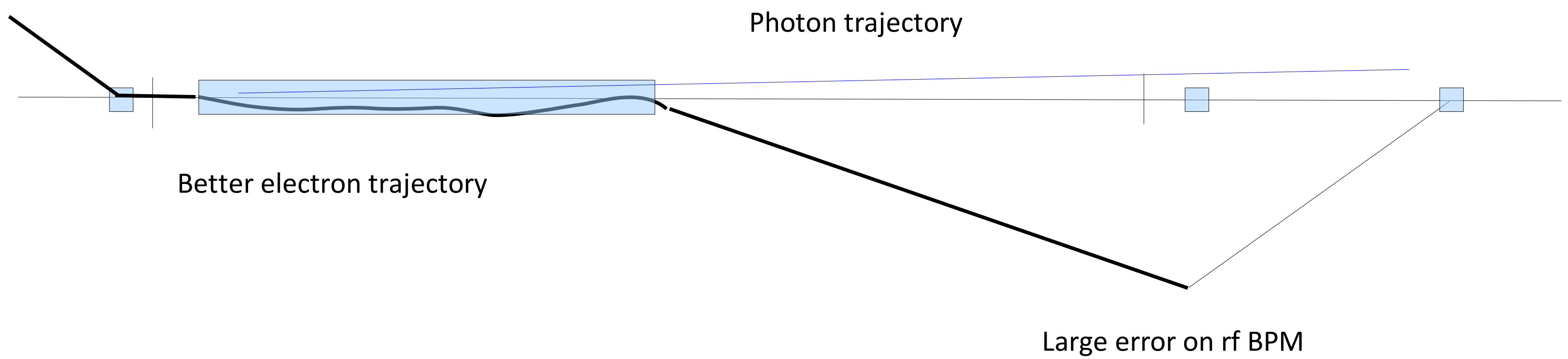
- Insertion devices can adversely impact storage ring
  - Beam motion due to changing of gaps, change of current, or quench
  - Perturbation of the linear optics
  - Nonlinear effects leading to reduced lifetime or injection efficiency
- Requirement on first- and second-field integral errors
  - Based on allocation of allowed beam perturbation in lower band-width from all sources
  - Integrated orbit correction system attempts to control
    - Global orbit: Impact of gap motion in one straight on beam position at another straight
    - Local orbit: Impact of gap motion in one straight on photon beam positions and angles in the same straight
  - Global orbit regulation profits from number and position of BPMs and correctors
    - Primarily gives a limit on rate-of-change of field integrals rather than absolute values
    - Requirements are easily achieved
  - Local orbit regulation is more challenging
    - Correctors are generally not integral to the insertion devices, so errors are inevitable
    - Rf BPMs are not generally at the ends of the devices, but at the ends of the straight
    - May have two IDs in one straight section with insufficient space for a corrector in between
    - Photon BPMs have systematic errors

Requirement on Absolute Field-Integral Errors

Without X-ray BPMs field integrals cause local steering errors



With X-ray BPMs with high weighting, field integral errors have less impact



Requirements on First and Second Field Integrals

PDR 3.4.5

- To provide improved beam stability, will need some combination of
  - Improved correction of field integrals
  - Improved x-ray BPMs (e.g., GRID XBPMS)
    - With reduced contamination and range of gaps, can give XBPMs higher weight
  - Additional correctors and rf BPMs closer to device
  - Specifications that more closely follow user requirements and use patterns
    - E.g., users don't in fact operate at arbitrary gaps, but typically use a limited range within an extended time period

Field Integral	**Single 5-m device**	**Single 2.5-m device**	**One 2.5-m device upstream or downstream**	**Two independent 2.5-m devices**
$\int B_y dz$ (G·cm)	4700	4700	TBD	TBD
$\int B_x dz$ (G·cm)	470	470	TBD	TBD
$\int dz \int B_y dz'$ (G·cm^2)	510,000	130,000	TBD	TBD
$\int dz \int B_x dz'$ (G·cm^2)	170,000	43,200	TBD	TBD

Requirements on Nonlinearities

- All undulators and wigglers have nonlinear-term scaling of roughly $L_w\lambda^2 dB_y^2/dx$, which makes long-period polarizing wigglers problematic
  - Hard to specify limits of these nonlinear terms since they are complicated functions. Need to test designs on a case-by-case basis.
- Each proposed ID is modeled with calculated 3D fields in all polarizing modes (plus static field errors) and tracked in the SR ring (with optics errors) to ensure that dynamic and momentum acceptance are not reduced (significantly)
- Mitigation methods
  - Reduce pole width or limit strength for e.m. devices
  - Use L-shims for APPLE-type device
  - Possible multipole-type correction for partial correction but no room in vertical aperture
- All undulators and wigglers also have static field error that come from construction and individual magnet tolerance
  - Specification for multipole errors in good-field region (i.e. desired dynamic aperture area) are based on various effects on the beam. Multipole limits are unchanged since original study of 1995.

Higher Current

- Accelerator is presently capable of 150 mA operation in all fill modes
  - Recent tests show that only 2 klystrons are needed
- 150 mA operation requires some beamline/front-end upgrades

Dependencies on Programmatic Work

- Development of lattices
  - Improvements possible and new requirements may emerge
  - Transitional lattices must be developed
  - Requires significant computing resources, available from APS and ANL clusters
- Testing of mock-up lattices, code verification
  - On-going using regular ASD studies time
- Improved collimation
  - Desirable in order to protect IDs in light of shorter beam lifetime
  - On-going effort; test of spoiler materials anticipated next run
- Alignment of beamlines
  - Necessary to permit steering to center of sextupoles
  - On-going using existing studies time and shutdowns
- Improved coupling control
  - Offers improved nonlinear dynamics, higher brightness
  - Approach identified by modifying existing six-pole steering magnets

Accelerator Upgrades Serve Mission Requirements

- Need for additional beamline capacity with high brightness
  - Additional canted straights
  - Long straight sections
- Enhanced brightness for 10~100 keV
  - Optimized insertion devices, including revolvers
  - SCUs emphasize 20 keV and above
  - LSSs maintain device length in spite of other changes
  - Higher current
- Allow more demanding experiments to be performed by providing improved beam stability
- Support time-resolved studies at few-ps scale
  - Deflecting cavity system
  - Retention of existing fill patterns
- Extensive analysis finds no show-stoppers

Contributors to PDR Chapter 3 and Related Discussions

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