Filling patterns and timing modes with passive bunch lengthening cavities in APS-U

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March 25, 2015
Outline

- Comparison of APS now and APS-U plans
- Modeling methods
- Bunch duration, shapes, and lifetime
- Effects of bunch population variation
- Simulation of effects of loss of a bunch
- Effects of ID gap motion
- Hybrid mode and other options
- Conclusion and plans
Hybrid 7BA Lattice Compared to APS Now

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<th>APS</th>
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H7BA lattice based on L. Farvacque et al., IPAC13, 79.
Present APS fill and operating modes

- 24-bunch uniform, 100 mA
  - 75% of time
  - 6.5 MHz bunch rate
  - 120s top-up

- 324-bunch uniform, 100 mA
  - 15% of time
  - 88 MHz bunch rate
  - 12 hour “fill-on-fill” interval

- Hybrid (camshaft), 100 mA
  - 10% of time
  - One 16 mA bunch
  - 60-s top-up

Diagram courtesy L. Emery, APS.
Planned APS-U fill and operating modes

- Minimum beam current of 200 mA
- Swap-out injection
  - Single bunch swapping only
  - 5-15 s interval
- Two fill patterns being advertised
  - 324-bunch uniform
    - Limit of present kicker technology
    - Desirable for long lifetime and possible flat beam operation
  - 48-bunch uniform
    - Desirable for timing experiments
    - Round beam operation required for lifetime reasons
- Possible hybrid or non-uniform modes under study
- Bunch-lengthening needed to reduce IBS, improve lifetime
  - Passive higher-harmonic cavity (HHC) planned
  - 4th harmonic (of 352 MHz)
- Extensive simulations performed to verify effectiveness, beam stability, practical issues
Modeling methods

- Used parallel **elegant** for tracking
  - Latest release (v27.0) has significantly improved performance for bunched beams
  - Domain decomposition shares bunches across processors for best performance with multi-particle bunches

- To make tracking faster and concentrate on relevant physics
  - ILMATRIX element for the ring itself
    - Can include chromatic and amplitude detuning (not relevant here)
    - Can include first- and second-order momentum compaction
  - SREFFECTS for lumped synchrotron radiation

- Turn-by-turn, bunch-by-bunch\(^1\) diagnostics included as needed
  - Phase space coordinates
  - Beam moments
  - Histograms
  - Beam- and generator-induced voltages, phases in cavities
  - Rf feedback system data

\(^1\): Available in next release.
Collective effects and rf modeling

- **RFMODE**: Beam- and generator-driven rf cavity mode
  - Beam-induced part
    - Uses loss factor plus phasor addition/rotation/damping
    - Implicitly includes the compressive single-turn wake corresponding to the mode
      - Can be turned off if desired
  - Generator-driven part
    - PID feedback seeks to maintain specified net cavity voltage and phase
    - User provides filter coefficients for the controllers
    - Can add other cavity longitudinal and transverse modes if desired (not in present work)

- **ZLONGIT\(^1\)**: Longitudinal short-range impedance
  - Present instance includes
    - Short range wake from rf cavity HOMs but excluding fundamental
    - Geometric impedance of vacuum chamber computed with GdfidL\(^2\) and ECHO2D
    - Resistive wall impedance computed analytically

- Part of **elegant** since 1994, but recently
  - Improved parallel performance for multi-bunch beams
  - Added rf feedback

\(^1\)Data courtesy R. Lindberg, A. Blednykh, and Y.-C. Chae.
\(^2\)www.gdfidl.de
RF Feedback

RF feedback:
- Regulates the RF cavity fields
- Rejects disturbances including beam loading
- Changes the impedance that the beam sees
- Note: in Bunch Lengthening System, main RF contributes to Robinson damping while the harmonic RF cavity contributes to growth

Example: Direct RF Feedback
- Simple Proportional Gain
  \[ \text{Controller} = \frac{\beta}{R} \]
  \( \beta \) = Loop Gain at resonance
- R and Q are reduced by \( (1 + \text{Loop Gain}) \)
- R/Q stays the same
Longitudinal phase space without HHC

- Results similar with $10^4$-$10^6$ simulation particles/bunch
- Microwave instability threshold is at ~0.5 mA/bunch
  - In APS, threshold is ~7 mA/bunch
- Increased energy spread has a small impact on brightness
Scan of HHC detuning

- As expected, bunch lengthens as HHC cavity is tuned toward resonance
- “Beneficial” effect of MWI visible for 48-bunch mode
- As bunch lengthens with decreased detuning, MWI is suppressed and energy spread drops
- Expected optimum bunch length from theory (without impedance) is 50 ps with ~16.5 kHz detuning
  - 324-bunch results agree with this expectation
  - Seems we can go beyond that...
Longitudinal density averaged over 2000 turns (48B)

- 10.00kHz
- 10.50kHz
- 11.00kHz
- 11.50kHz
- 12.00kHz
- 12.50kHz
- 13.00kHz
- 13.50kHz
- 14.00kHz
- 14.50kHz
- 15.00kHz
- 15.50kHz
- 16.00kHz
- 16.50kHz
- 17.00kHz
- 17.50kHz
Longitudinal density is noisy, but rms is stable (48B)

- Results on previous slide average out the effect of MWI
- Turn-by-turn variation seems mostly MWI-driven
  - Present with cavity detuned by $+136\text{kHz} \ (f_{\text{rev}}/2)$ as well
- Not related to rf feedback
- How much do users care about this?
Touschek lifetime analysis

- Touschek lifetime is main reason for introducing HHC
- Normally, one just uses gaussian bunch duration
- Using tracking results improves fidelity of calculations
  - Tracking results give bunch distribution turn-by-turn
  - Slice analysis of bunch on each pass gives current density and slice energy spread
    - Slice energy spread includes MWI
  - Program `touschekLifetime` allows slice-based Touschek lifetime calculation
- Also included IBS effect on emittance and energy spread
  - Computations used `ibsEmittance`
- In addition, need local momentum acceptance
  - Used 100 error ensembles with lattice correction as input to tracking
- Computations provide a Touschek lifetime value for each error ensemble, averaged over many bunch samples
- Method not fully self-consistent, but allows combining effects of intrabeam scattering, HHC, and microwave instability

1: A. Xiao and M. Borland, PRSTAB 13 074201 (2010); and A. Xiao, to be published.
4: V. Sajaev, to be published.
Touschek Lifetime Improvements due to HHC

- In both cases, have 200 mA, $Q_L = 600k$, $\kappa \approx 1$

- For 48 bunches, get factor of ~2 for 13.5 kHz detuning
  - Bunch is already significantly lengthened by the ring impedance
  - Do not reach the desired 7.5 h value
  - Has implications for shielding, TBD

- For 324 bunches, get factor of ~3 for 13.5 kHz detuning
  - Total lifetime (including gas scattering) expected to meet goal for round beams
  - Flat beams (2x higher brightness) more challenging

Symbols show 10th (lower) and 50th (upper) percentile points in lifetime distributions.
Effect of bunch population variation

- Bunches will be swapped out when they fall to 90% of initial charge
- Expect to have randomly-ordered (in time) bunches with uniform distribution of charge between 105% and 95% of the average value
- Simulated 10 random 48-bunch fills of this type
- Modest variation among bunches within a fill and over time
Effect of lost bunch (48 bunches, minus 1)

- Swap-out involves kicking out one bunch and immediately injecting replacement
  - May fail sometimes to inject the replacement
- Simulated kicking out of last bunch in 48-bunch fill, then return to equilibrium
  - No particle loss observed even with ±2% momentum acceptance
- Real part of beam-induced field in main cavity has ~160-230 kV sawtooth
  - Forces bunches to shift phase
  - Changes effect of HHC
The effect of lost bunch (48 bunches, minus 1)

- Variation in the bunch centroid is a significant fraction of the bunch length
  - Is this a problem for users?
- ~7 degree phase shift on main rf system
  - May want to adjust injector phase to hit the optimum point in the bucket
- Bunch length variation is under 10%, presumably tolerable
- Could provide gate to users to indicate when a bunch is missing
Effect of variation in energy loss per turn

- As ID gaps are varied, the energy loss per turn varies
  - Could vary by a significant fraction of the 2.27 MeV/turn nominal loss
  - Presently, without pre-conditioning APS rf systems trip when closing all ID gaps rapidly

- Feedback will maintain cavity voltage and phase relative to the source, but
  - Beam will move to a different rf phase
  - Incoming bunches may suffer losses from energy oscillations due to phase offsets
  - Bunch duration will change

- Simulated unrealistically rapid variation of energy loss per turn by 0.6 MeV
  - Took 10 equal steps at 10k turn intervals
  - Ramped loss between levels over 1000 turns
  - Included effect on damping times and energy spread
  - Kept (slow) tuners for main, HHC fixed
Effect of variation in energy loss per turn

- Increased energy loss moves beam higher on the main rf waveform
- Reduced slope of main rf means longer bunches
  - Good news for beam lifetime
- For 13.5 kHz bunches begin to take double-humped appearance
- Shifting phase complicates injection
  - Booster may need to track SR bucket
Hybrid mode

- Looked at two possible hybrid or camshaft modes with 4.25 mA/bunch
  - Mode 1: 47 bunches at 12 bucket spacing with ±1.05 μs gap from single bunch
  - Mode 2: 47 bunches at 18 bucket spacing with ±0.66 μs gap from single bunch

- As expected, significant non-uniformity in bunch properties
  - Do not achieve >67 ps bunch duration seen in uniform 48-bunch mode
  - Already-difficult lifetime situation made significantly worse

- Results shown have detuning of 15.5 kHz
  - Variations are slightly worse for 13.5 kHz
Hybrid mode

- Main cavity voltage shows a significant modulation
- Present rf feedback system is not fast enough to counteract this
  - Response time is about 20 ms
- Studying a faster system that should better compensate
RF Feedback: Other Types of Feedback

- Polar (Amplitude / Phase) or Cartesian (in-phase / quadrature): can be narrowband or wideband
- Comb Filters: reduce impedance & beam-loading at revolution harmonics & synchrotron sidebands
- Feed-Forward: feed wall-current monitor to generator to cancel the beam-current directly

Example of Transient Beam-Loading Compensation for Hybrid Fill
(can be achieved with combination of above)
Another possibility: 24 doublets

- Could fill 24 pairs of buckets with uniform separation between pairs
  - Pair forms a “super-bunch” 2.9 ns in duration
  - 151 ns gap between pairs
- This actually works pretty well
  - 13.5kHz: 70-76 ps rms bunch duration
  - 15.5kHz: 63-67 ps rms bunch duration
X-ray Pulsed Brightness Compared to APS Today

- Assumptions:
  - APS: existing insertion devices and front ends; 24-bunch, 100 mA mode
  - APS-U: 4.8-m HPM and 3.7-m SCUs, high-heat-load front ends, 200 mA

- Increases of 40-80 fold for hard x-rays

Pulsed brightness is $\frac{p}{\text{pulse/mm}^2/\text{mrad}^2/0.1\%\text{BW}}$
Conclusions

- APS presently runs in timing modes about 85% of the time
- APS MBA upgrade seeks to preserve timing capabilities
  - 48-bunch, 200 mA mode
  - Pulsed brightness shows a significant increase
  - Exploring hybrid modes, other possibilities
- The necessity for a bunch-lengthening cavity complicates matters
- Extensive simulations show little issue with
  - 48-uniform, 324-uniform, and 2x24 fill modes
  - Accidentally kicking out a bunch
  - ~10% variation in bunch-to-bunch charge
  - Rapid ID gap variation
- Beam-phase detectors seem advisable to keep booster and ring synchronized
- On-going work includes
  - Simulation of filling from zero
  - Use of faster rf feedback with goal of improving results for hybrid mode
  - Modeling of multi-bunch instabilities with additional cavity HOMs
  - Add transverse impedance and verify single bunch stability limits
Acknowledgments

- Impedance model: R. Lindberg, A. Blednykh (BNL), Y.-C. Chae
- Error enembles for lattice evaluation: V. Sajaev
- Computing: Argonne Laboratory Computing Resources Center (LCRC)