Challenges and Solutions for the APS-U Design

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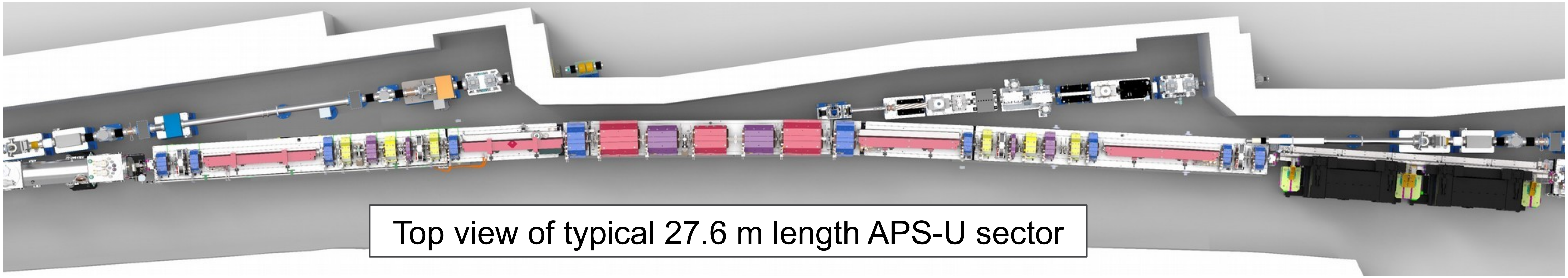
APS Upgrade project is ambitious and challenging

- Entirely new 6-GeV, 200-mA ring, including
  - Multi-bend-achromat lattice
  - 1320+ high-strength conventional magnets
  - 1104 m of vacuum systems
  - Orbit correction system with 1 kHz bandwidth
  - Superconducting insertion devices
  - New and upgraded x-ray beamlines
- Will exceed brightness of 3rd-generation storage ring light sources by 2 to 3 orders of magnitude

Advanced Photon Source (APS)



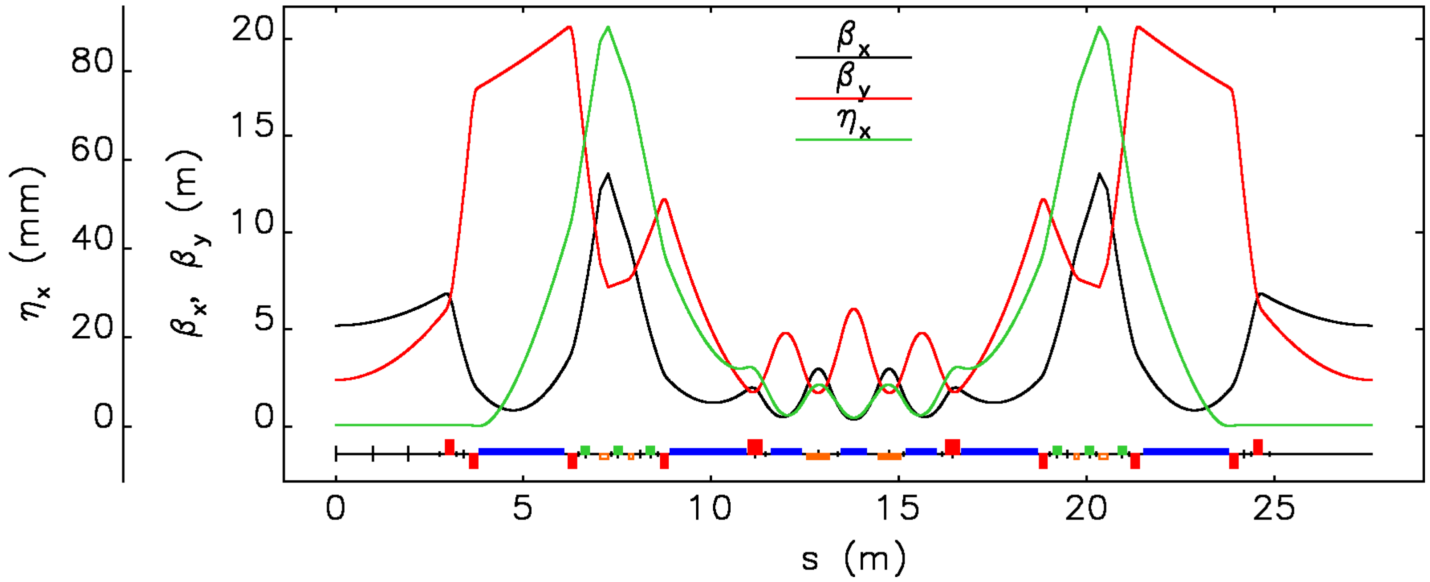
Top view of typical 27.6 m length APS-U sector

Outline

- Overview of APS-U lattice development
- Beam physics challenges include
  - Requirement for rapid commissioning
  - Sufficient confidence in design to dismantle a working ring
  - Injection into small acceptance ring
  - Ensuring sufficient single-bunch current for timing mode
  - Ensuring sufficient beam lifetime
  - Controlling ion effects
  - Limiting beam dump damage
- Acknowledgments

Lattice targets ultimate performance for APS-sized ring

- Final lattice[1] emerged after ~five years of development



42-pm natural emittance in 40-sector ring with 1.1 km circumference at 6 GeV

- Chose Hybrid 7-Bend Achromat (H7BA)[2] with reverse bends[3,4]
  - Higher brightness than alternatives we explored[5,6]
  - Workable injection aperture and lifetime
- Appears to be the brightest operable ring we can build today that fits in the APS tunnel

1: M. Borland et al., NAPAC16, 877.
2: L. Farvacque et al., IPAC13, 79 (2013).
3: J. Delahaye et al., PAC89, 1611 (1990).
4: A. Streun, NIM A 737:148 (2014).
5: M. Borland, et al., IPAC15, 1776.
6: Y. P. Sun et al., NAPAC16, 920.

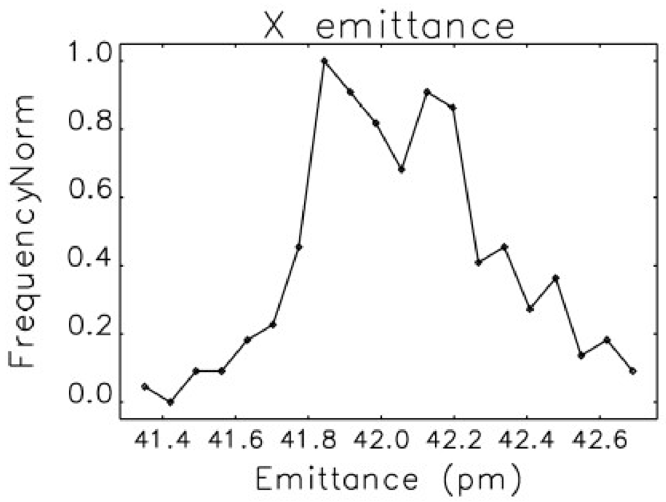
Lattice optimization combines good design with evolution

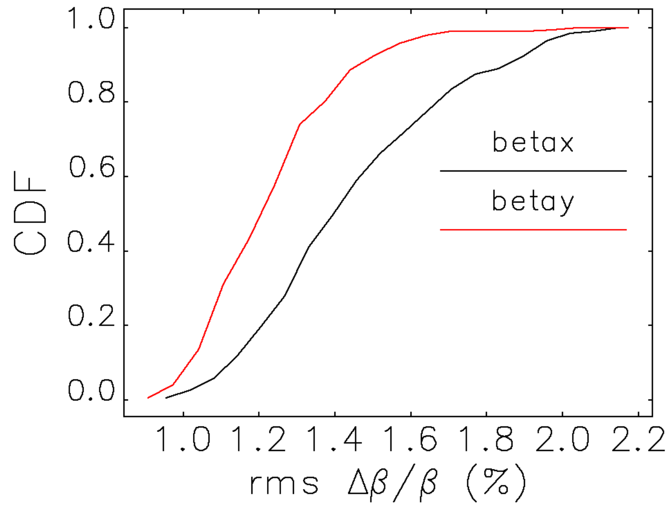
- Started with ESRF-developed HMBA concept
  - Dispersion bumps give 2-3 fold reduction in sextupole strengths
  - Near-cancellation of leading-order geometric sextupole effects
- For APS-U, use tracking-based optimization[1,2,3] with multi-objective genetic algorithm[4] (MOGA) to evolve linear and nonlinear lattice properties, including
  - Particle tracking to determine injection aperture, Touschek lifetime, and momentum-dependent tune footprint
  - X-ray brightness calculation to determine performance at 10 keV
  - Optimize within constraints provided by engineering designs
- Technique proven in applications to present APS
  - Lattices with high chromaticity, broken symmetry, but high performance[3,5]
  - Similar techniques in wide-spread use[6-10]

1: I. Bazarov et al, PRSTAB **8**, 034202 (2005).
2: H. Shang et al., PAC 2005, 4230.
3: M. Borland et al., PAC 2009, 3850.
4: K. Deb et al., IEEE Trans. on Evol. Comp. **6**, 182 (2002).
5: V. Sajaev et al., NAPAC16, 907.
6: L. Yang et al., PRSTAB 14, 054001 (2011).
7: W. Gao, PRSTAB 14, 094001 (2011).
8: C. Sun, PRSTAB 15, 054001 (2012).
9: M. Ehrlichman, PSTAB 19, 044001 (2016).
10: Y. P. Sun, NAPAC16, 924.

Fast lattice commissioning facilitated by automation

- Challenge: only three months to commission the ring
- Detailed lattice commissioning simulation developed[1,2]
  - Error generation
  - First-turn, then global trajectory correction
  - Rf setup
  - Orbit correction
  - Lattice measurement and correction
  - Coupling adjustment
- This software will be used for actual APS-U commissioning
  - Partial test on the existing APS succeeded in achieving stored beam

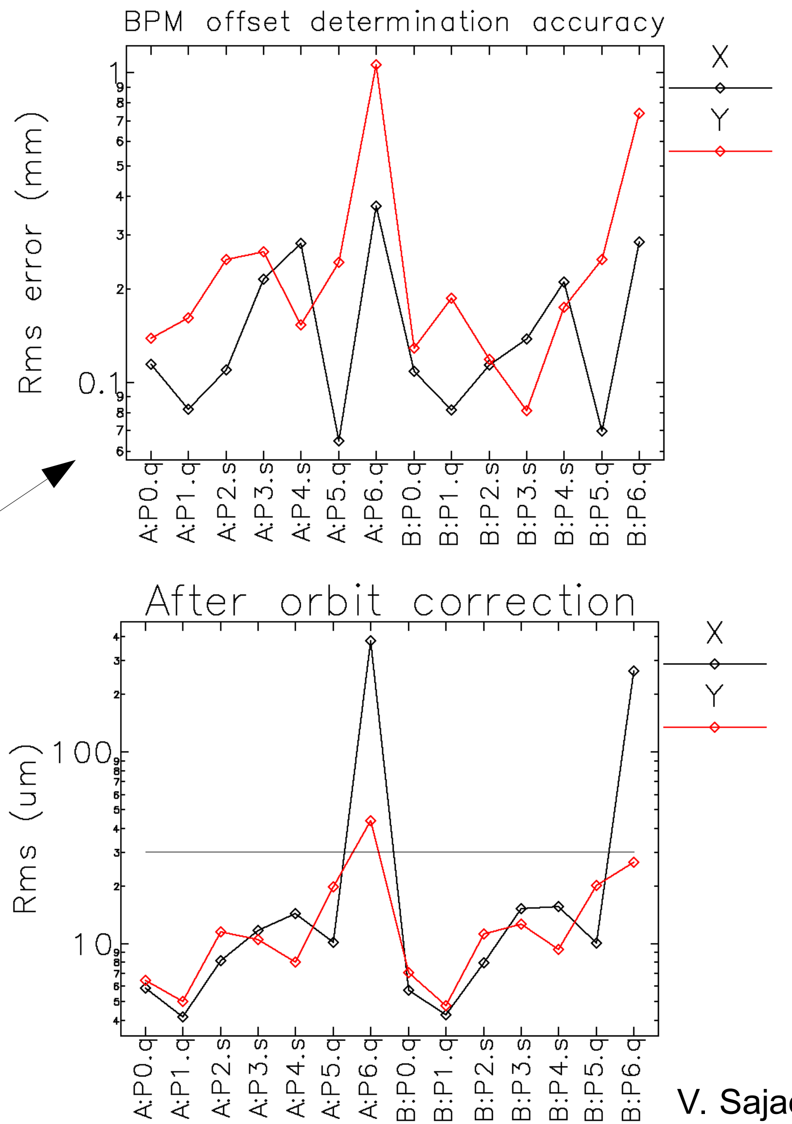




1: V. Sajaev et al., IPAC2015, 553.
2: V. Sajaev, PRAB 22, 040102 (2019).

Accurate BPM offset measurement possible

- Challenge: need 30 µm rms BPM offset accuracy to enable accurate lattice correction
  - Having many reverse bends and too few pure quads makes this problematic
- A scheme was developed to measure BPM offsets relative to nearby sextupoles
  - Form closed x, y bumps around sextupole
  - Scan bumps in 2D grid
  - At each grid point, measure change in corrector strength needed to keep bump closed when sextupole current is reduced 50%
- Initial results don't meet 30 µm requirement
  - Iterating with orbit correction allows beating requirement in most cases
  - Expect entire process to take up to 50 hours



V. Sajaev

Commissioning simulation has many benefits

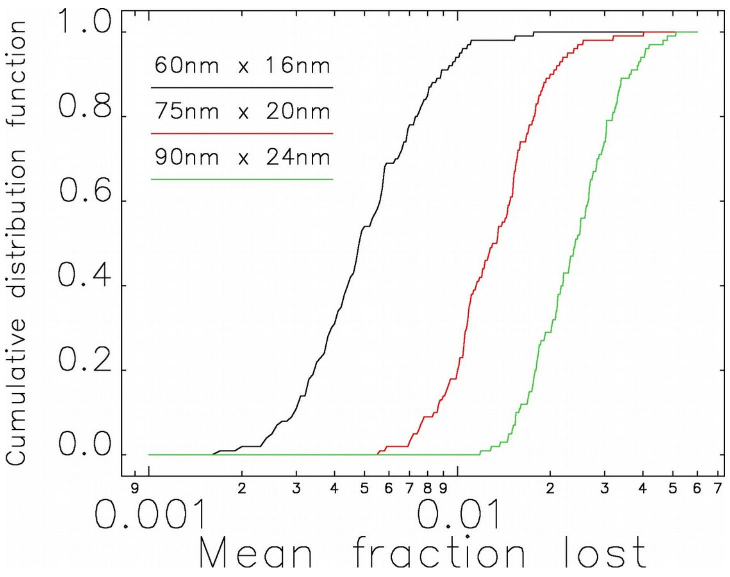
- Challenge: engineering specifications must be no tighter than necessary or cost, schedule issues may arise
- By running commissioning simulation with different assumptions
  - Determined alignment tolerances
  - Evaluated support alternatives
  - Provided power supply calibration and magnetic measurement requirements
- Commissioning simulation provides many "ensembles" of post-commissioning conditions
  - Used in tracking-based prediction of post-commissioning lifetime, injection efficiency, loss distributions, instabilities

Girder misalignment	100 μm
Elements within girder	30 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	0.4 mrad
Quadrupole tilt	0.4 mrad
Sextupole tilt	0.4 mrad
Corrector calibration error	5%
Initial BPM offset error	500 μm
BPM calibration error	5%
BPM single-shot measurement noise	30 μm
BPM orbit low-current noise	3 μm
BPM orbit high-current noise	0.1 μm
BPM and corrector tilts	1 mrad

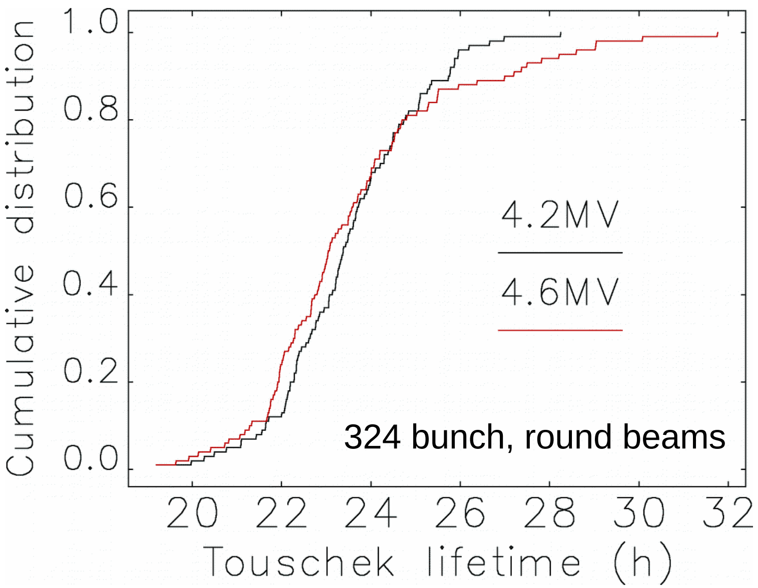
Error tolerances validated through commissioning and robustness simulations

Detailed simulations provide confidence in design

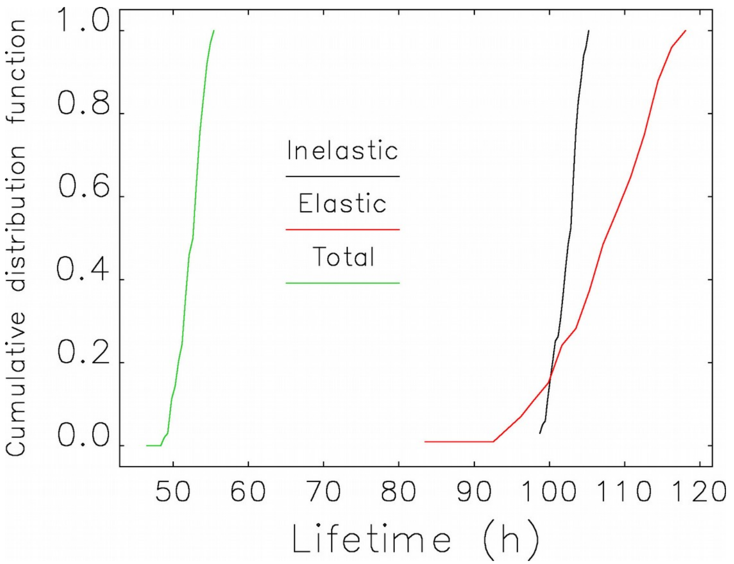
Injection loss fraction distribution for 100 ensembles (30 shots each) for three emittance assumptions



Touschek lifetime distribution for 100 ensem., incl. LMA evaluation, optimized passive harmonic cavity, longitudinal impedance, and IBS



Gas-scattering lifetime distribution for 100 ensem. using local angular and momentum acceptances, detailed gas pressure model

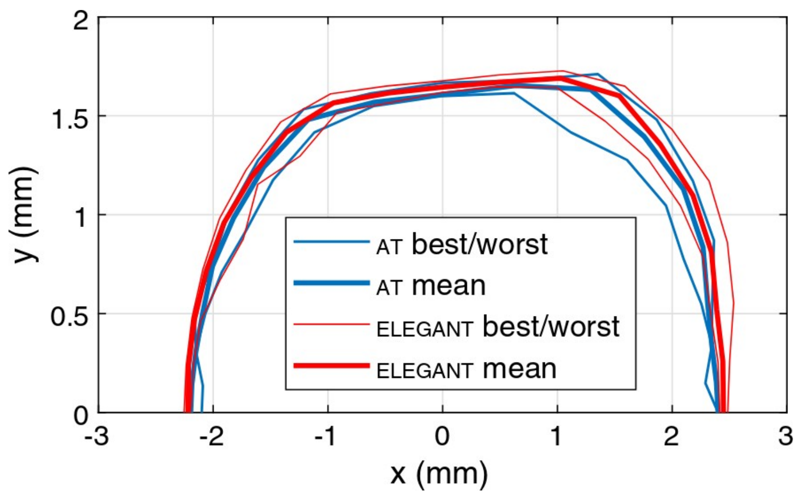


N_b	Charge nC	κ	ϵ_x pm	ϵ_y pm	σ_δ %	τ_{10th} h	ΔT_{inj} s	τ_{50th} h	ΔT_{inj} s
48	15.34	0.99	31.9	31.6	0.145	3.7	28.0	4.0	30.3
324	2.27	0.99	29.8	29.5	0.136	15.0	16.7	16.1	17.9
324	2.27	0.13	41.7	5.6	0.138	7.3	8.1	9.1	10.1

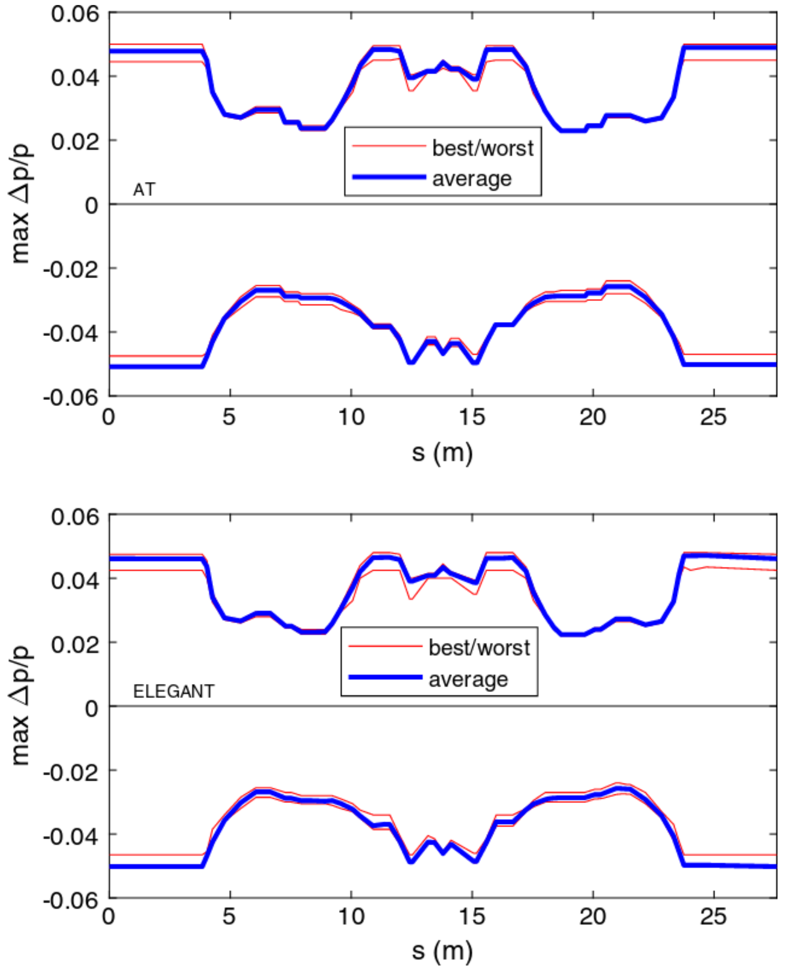
APS-U elegant/AT comparison gives further confidence[1]

Parameter	elegant	AT
Horizontal tune, ν_x	95.0999	95.0993
Vertical tune, ν_y	36.0999	36.1007
Momentum compaction, $\times 10^{-5}$	4.0406	4.0399
Chromaticity, ξ_x	8.1183	8.1704
Chromaticity, ξ_y	4.7221	4.8739
Natural chrom., ξ_x^{nat}	-133.6488	-133.5874
Natural chrom., ξ_y^{nat}	-111.6335	-111.4689
Emittance (pm)	41.6612	41.6434
Energy loss per turn (MeV)	2.8688	2.8700
Momentum spread, σ_δ, $\times 10^{-3}$	1.3499	1.3494
Damping partition, J_x	2.2497	2.2495
Damping time τ_x (ms)	6.8446	6.8424

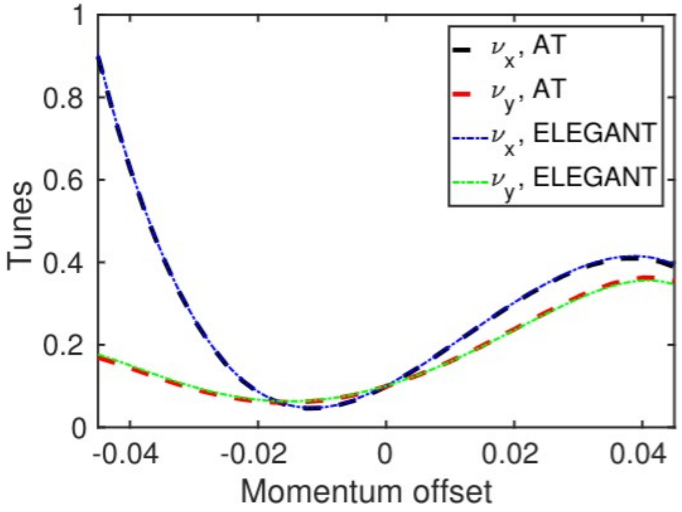
DA with errors



LMA with errors



Chromatic tune variation



DA and LMA results shown here use notional errors, rather than commissioning sets.

1: M. Borland et al., PRAB 22, 114601 (2019).

On-axis swap-out takes over where top-up left off

- Challenge: Lower emittance leads to poor lifetime, small injection aperture[1]
- Top-up operation[2,3] helped 3rd -generation light sources maximize performance
  - Accommodates shorter lifetime, but requires sufficient injection aperture for efficient beam accumulation
- Swap-out[4,5] accommodates drastically reduced injection aperture
  - Enabling technology now available: fast, high-voltage kickers

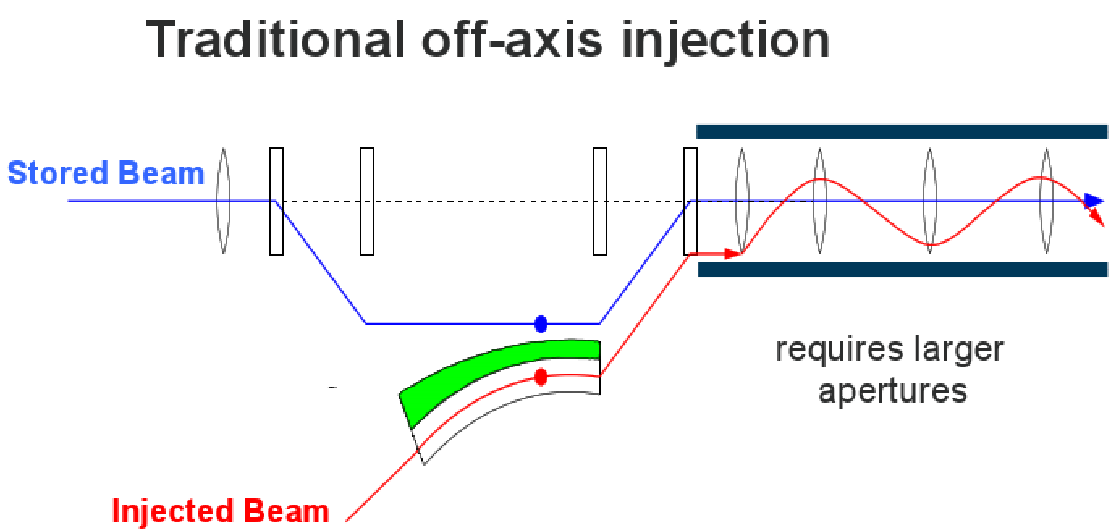
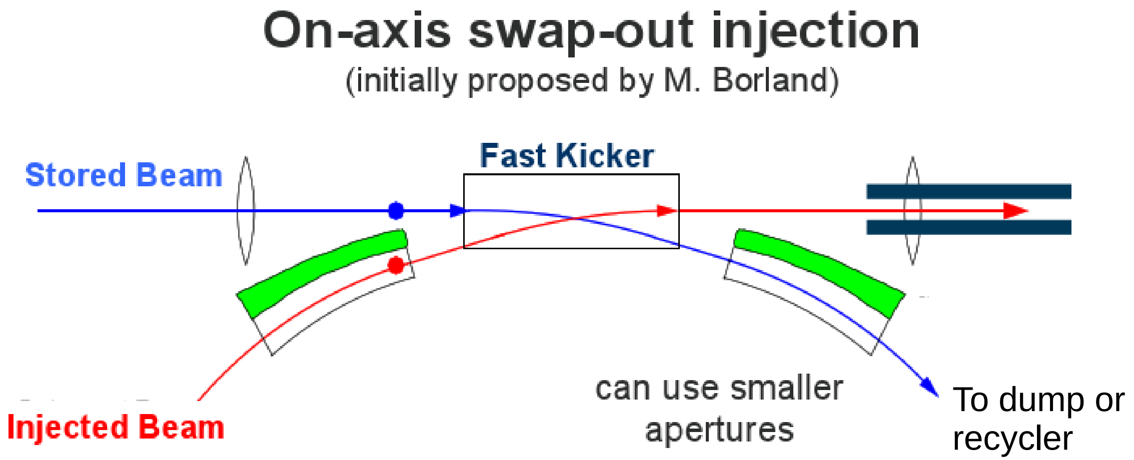


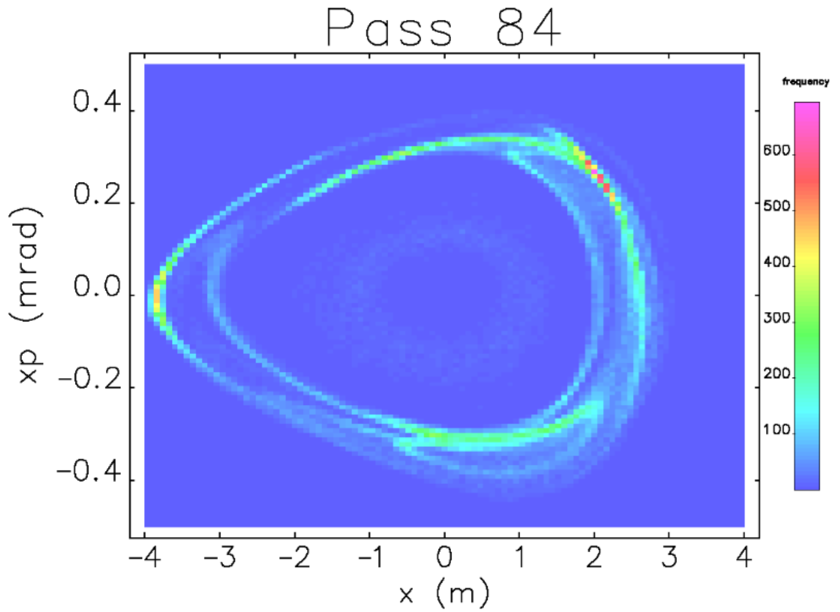
Diagram courtesy C. Steier (ALS-U).

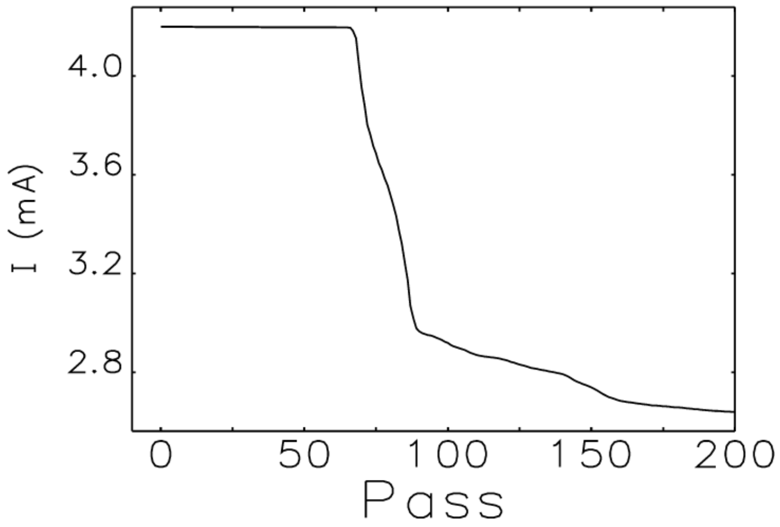


1: M. Borland et al., JSR 21, 912 (2014).
2: S. Nakamura, EPAC90, 472.
3: L. Emery et al., PAC99, 200.
4: R. Abela et al., EPAC 92, 486.
5: L. Emery et al., PAC03, 256.

Swap-out helps APS-U compete on two fronts

- Alternative design[1] allowed accumulation, but
  - 90-pm emittance too high in light of intense international competition
  - Collective effects at injection would prevent 200-mA, 48-bunch timing mode[2]
- APS-U has two concepts for swap-out
  - Default[3]: vertical-plane injection with DC Lambertson septum
  - Alternative: Horizontal-plane injection with pulsed septum, emittance exchange in transport line
  - See A. Xiao's talk on Thursday





1: Y. Sun et al. NAPAC16, 920.
2: R.Lindberg et al., NAPAC16, 901.
3: A. Xiao et al., PAC13, 1076.

APS-U impedance model developed early in design

- Challenge: understand collective effects early enough to guide decisions
- Early impedance model based on notional "pre-engineering" chamber concept
  - ID transitions, resistive wall, plus other components scaled from APS[1]
- Added and assessed details as engineering design progressed
- Results include
  - Choice of swap-out injection
  - Specification of required chromaticity
  - Keeping MWI under control
  - Refining rf gasket design and tolerances
  - Specifying NEG-coating thickness
- Margin is ~3x when feedback is included
  - Stability at injection is limiting factor

1: Y. C. Chae et al., PAC07, 4336.

Geometric contributions

Sector ($\times 40$) Element	Number	Ring Element	Number
In-line absorber	17	Inj/Ext kicker	3
BPM-bellows	14	Other kickers	3
Gate valve	4	352 MHz rf-cavity	12
Flange	47	Rf transitions	3
ID transition	1	4^{th} harmonic cavity	1
Crotch absorber	2	Collimators (H/V)	5/2
Pumping cross	5		
Small gap ID BPMs	0.5		

Dominant sources of longitudinal wakefields

Resistive wall

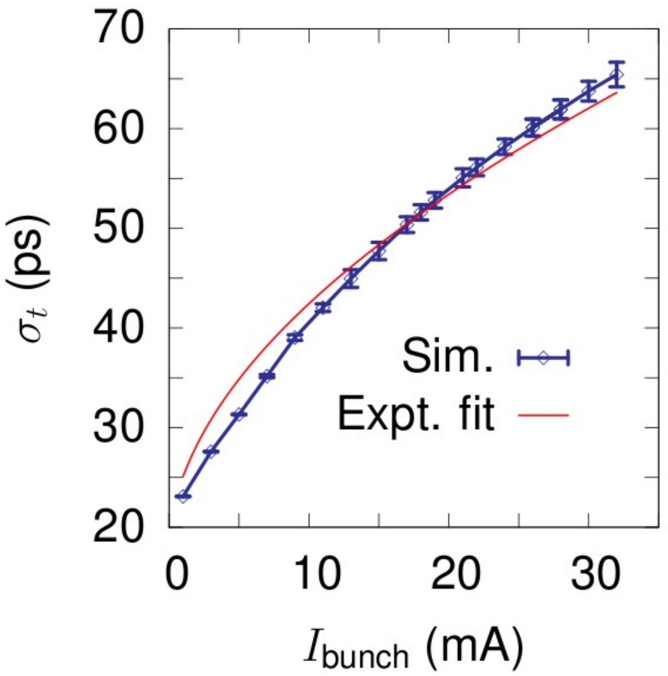
Metal	Diameter	Length
Cu	22 mm	224 m
Al	22 mm	625 m
SS	22 mm	80 m
Al	6 mm	50 m
Al	16×6 mm (H$\times$V)	125 m

Dominant driver of transverse instabilities

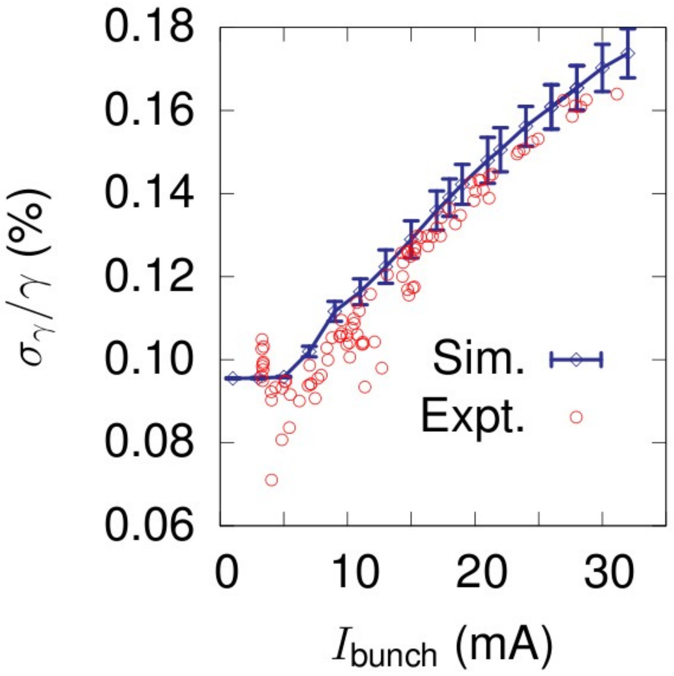
R. Lindberg

Tracking-based predictions of collective effects for the present APS agree with measurements[1,2,3]

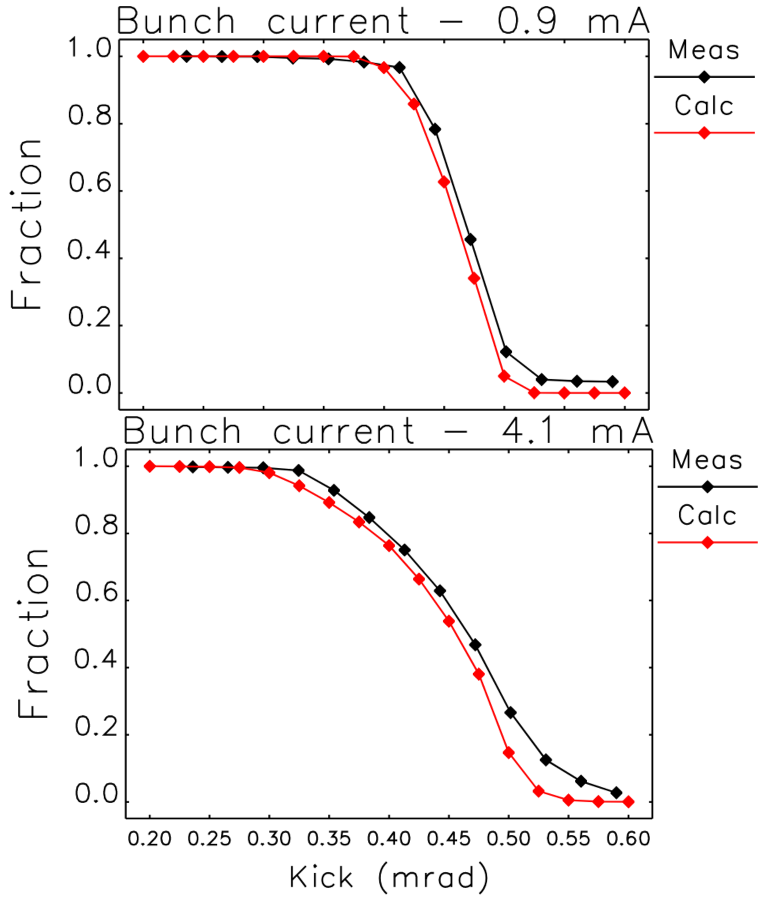
Longitudinal collective effects



Bunch lengthening is well captured by simulation



Microwave instability onset and energy spread growth closely predicted



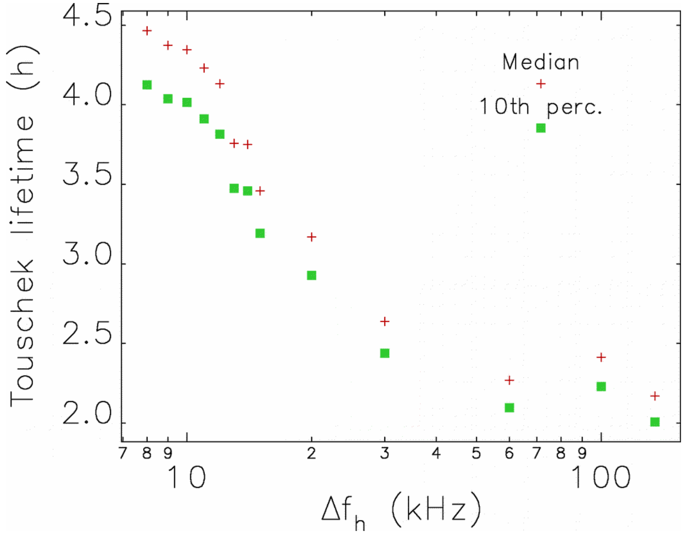
Effect of impedance on dynamic acceptance is captured well by simulations

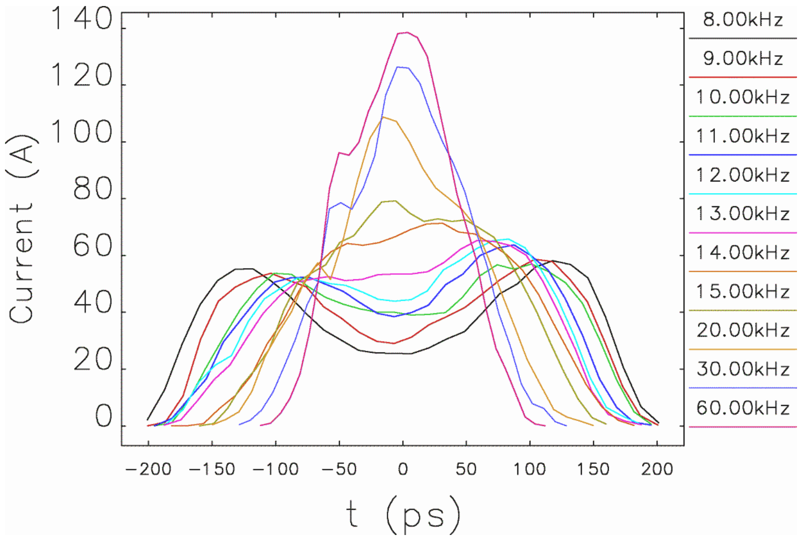
1: V. Sajaev et al., PAC13, 405 (2013).
2: R. Lindberg et al., IPAC15, 1822 (2015).
3: S. Shin et al., PRAB 22, 032802 (2019).

Overstretching increases Touschek lifetime ~25%

- Challenge: obtain 3 h lifetime to stay within limits of existing shielding at 200 mA[1]
- Long Touschek lifetime requires
  - Sufficient rf voltage
  - Accurate lattice correction to preserve LMA
  - "Round beam" operation: $\varepsilon_y = \varepsilon_x$
  - Bunch-lengthening cavity (BLC)
- Modeling incorporates many details
  - Slight emittance increase due to IBS
  - Variation in LMA among commissioning ensembles
  - Non-gaussian longitudinal distribution from self-consistent model with impedance and passive BLC

200 mA in 48 bunches

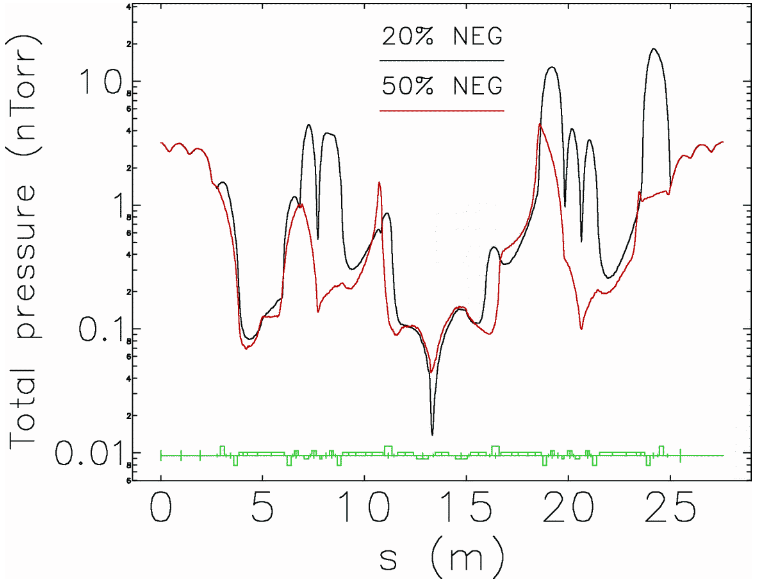


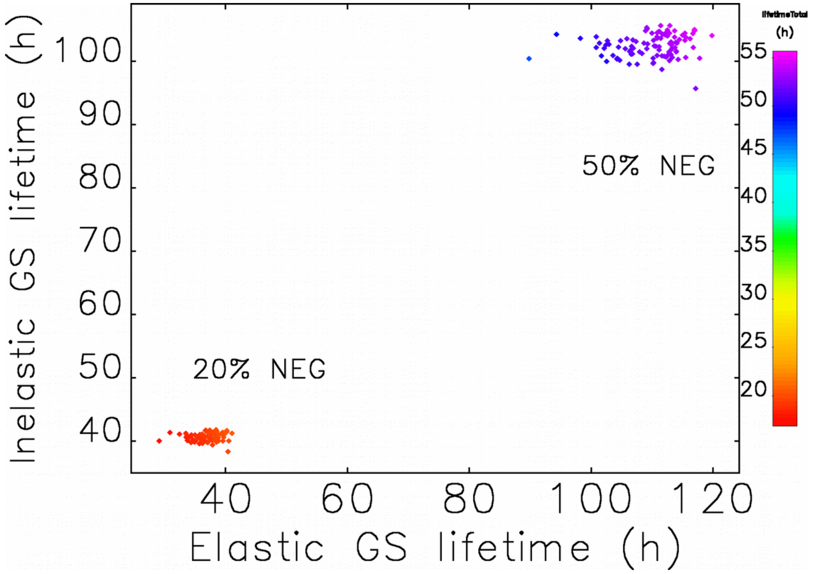


1: B. Micklich, private communication.

Gas scattering lifetime dramatically improved

- Challenge: obtain sufficient gas-scattering lifetime to preserve margin relative to 3 hour target
- Long (e.g,. >30 h) GS lifetime requires
  - Sufficient local DA and MA
  - Sufficiently low pressure, particularly for heavier gases
- Went beyond simple estimates[1,2]
  - MOLFLOW[3]/SYNRAD[4] for vacuum system modeling
  - Parallel elegant for local DA and MA computation
  - Per-species determination of local out-scattering rates, local loss rates
- Outcome: NEG coating expanded to encompass ~50% of the circumference (~20% activated)
  - Min. predicted GS lifetime increased from ~17h to ~47h

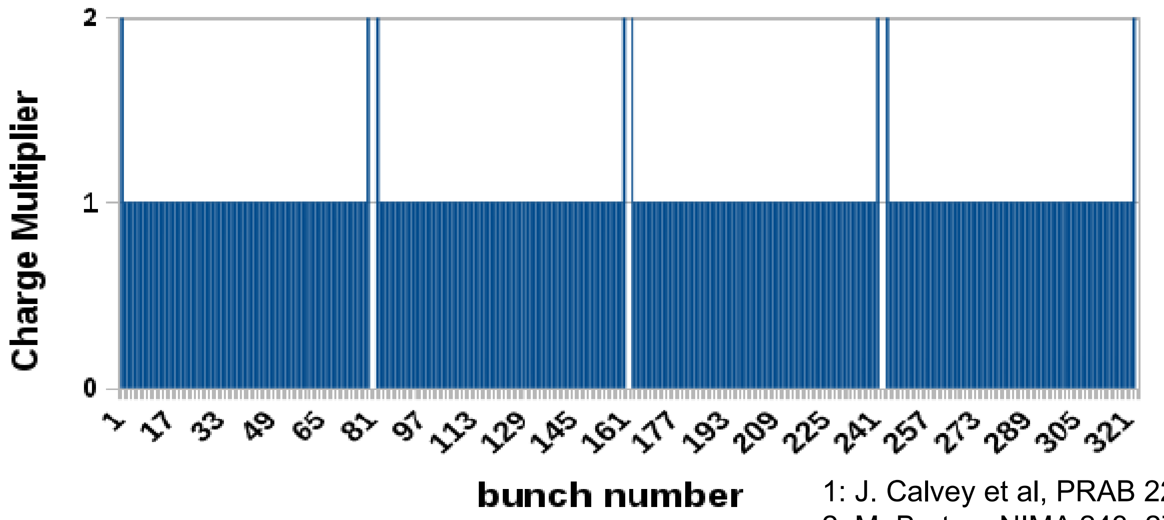




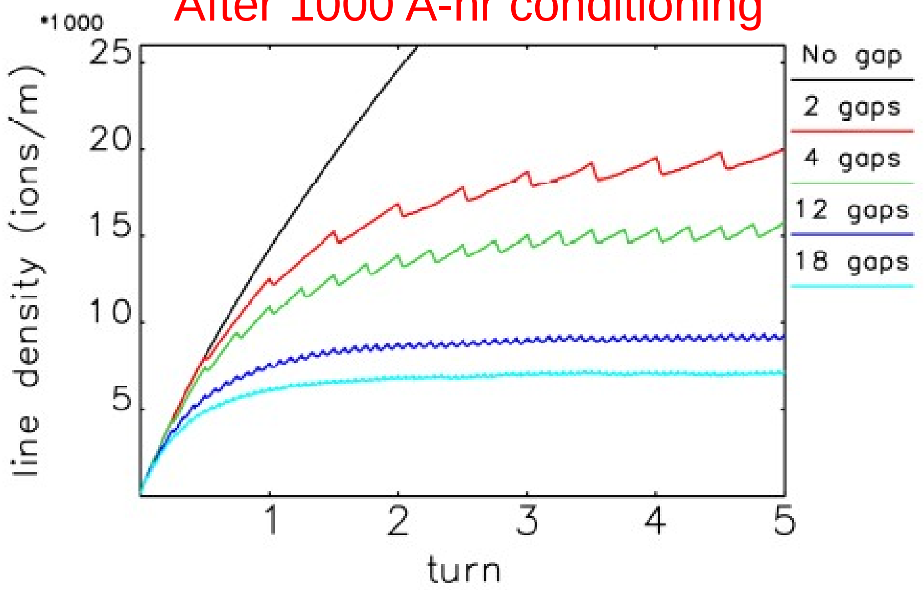
1: M. Borland et al., IPAC15, 546.
2: M. Borland et al., NAPAC19, WEPLE08.
3: M. Ady et al., IPAC14, 2348.
4: R. Kersevan, PAC93, 3848.

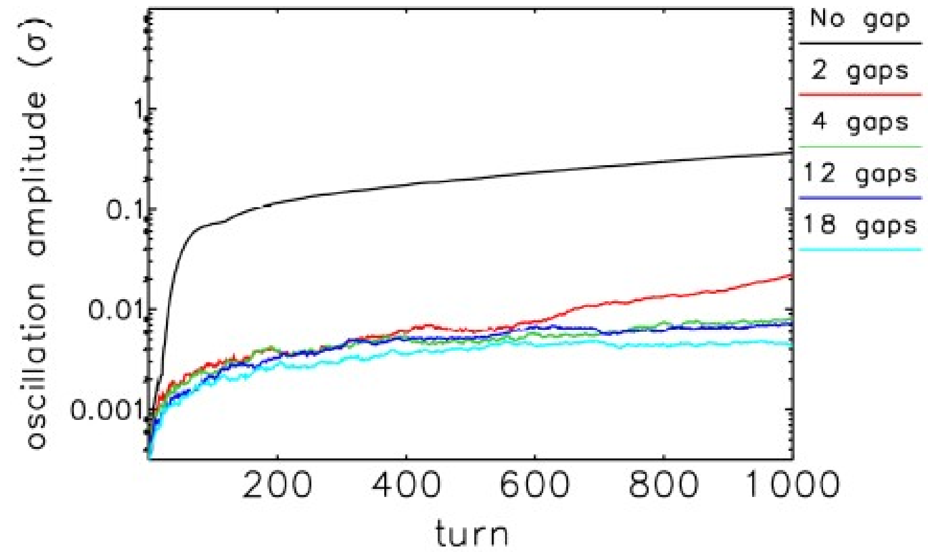
Compensated gaps can control the ion instability[1]

- Gaps between bunch trains allow time for ions to escape[2,3]
- Minimize rf transients by distributing "missing" charge to bunches adjacent to gaps ("guard bunches")
  - High charge bunches before gap provide a stronger kick to ions
  - Simulations show modest impact on bunch distribution and Touschek lifetime, no impact on MBI growth rates
- Ion simulations show that even 2 gaps of 2 bunches each greatly reduces ion trapping and eliminates the ion instability
- More trains can be used if necessary



After 1000 A-hr conditioning



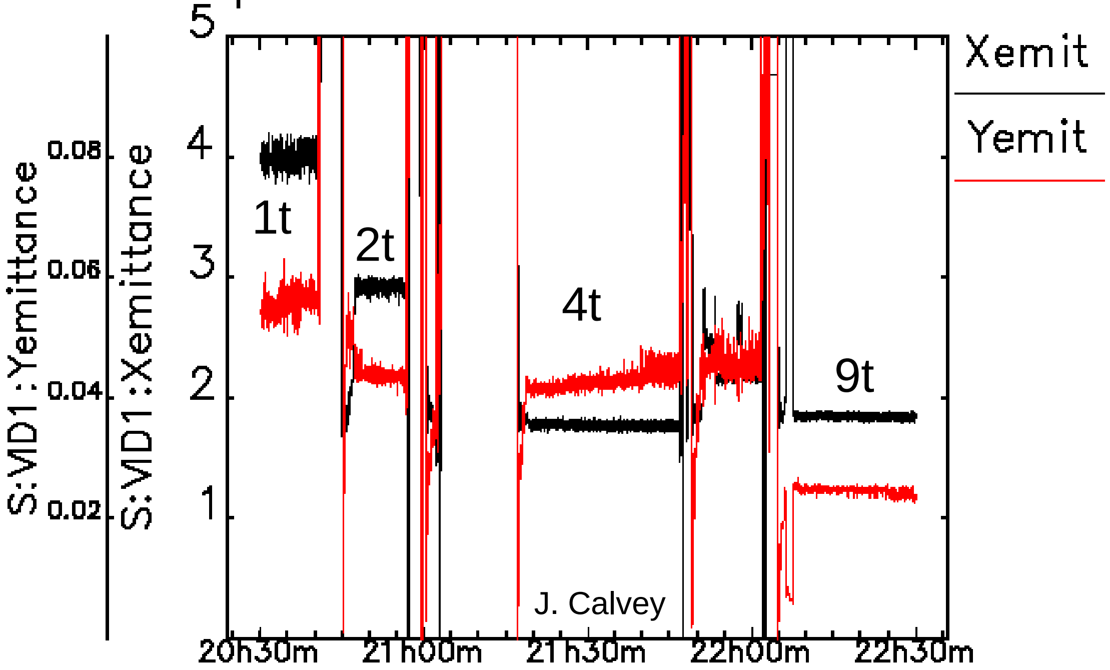


1: J. Calvey et al, PRAB 22, 114403 (2019).
2: M. Barton, NIMA 243, 278 (1986).
3: D. Villevald et al., SLAC-TN-06-032 (1993).

Dedicated ion experiment further refines understanding

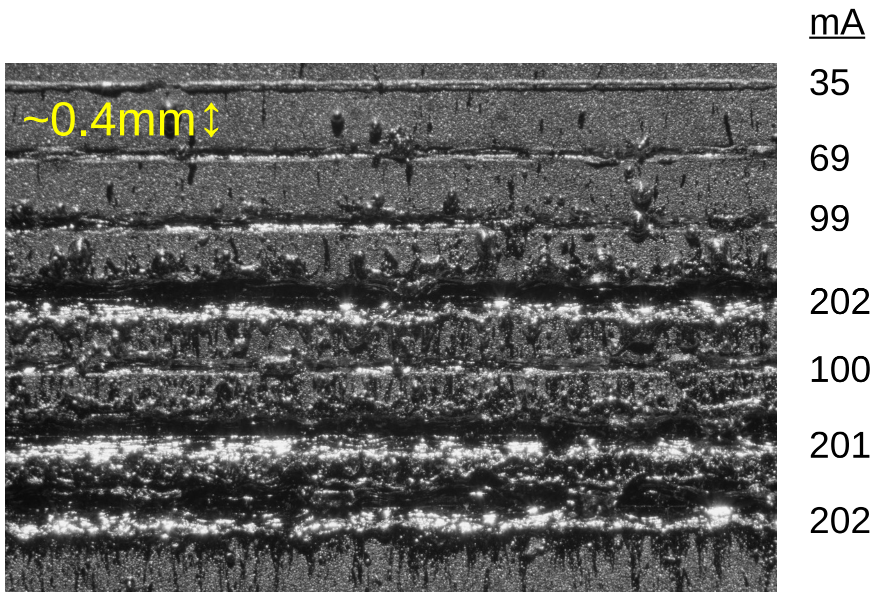
- A gas-injection experiment was performed in APS to gather definitive data
- Injected N_2 into 6-m straight section up to ~100 or ~800 nT
- Measure frequencies of beam motion, emittance increase with various bunch patterns, beam current, etc.
- Simulation initially gets ion frequency wrong (10 MHz instead of 5 MHz)
- Using bi-gaussian model for ion fields gives agreement
  - Sensitive to numerical parameters
  - More study needed
- Application of improved models to APS-U is underway

Measured emittances for 324-bunch pattern with different numbers of trains



APS-U beam is potentially destructive[1,2]

- Concerns for high-current, low-emittance beam
  - Perforation of vacuum chamber
  - Erosion of the swap-out dump
  - Erosion of the whole-beam dumps
  - Spray of metal globules in the chamber
- Recent experiments in APS match APS-U conditions for whole-beam dumps
  - Peak dose as high as 30 kJ/g
  - Damage to Al6061 is evident
- Mitigating strategies, supported by experiment and simulation
  - Use five whole beam dumps to reduce chance of chamber strike
  - Plan for sacrificial surfaces on whole-beam dumps
  - Choose low Z material with high thermal diffusivity
  - Use kickers to decohere or spread the beam

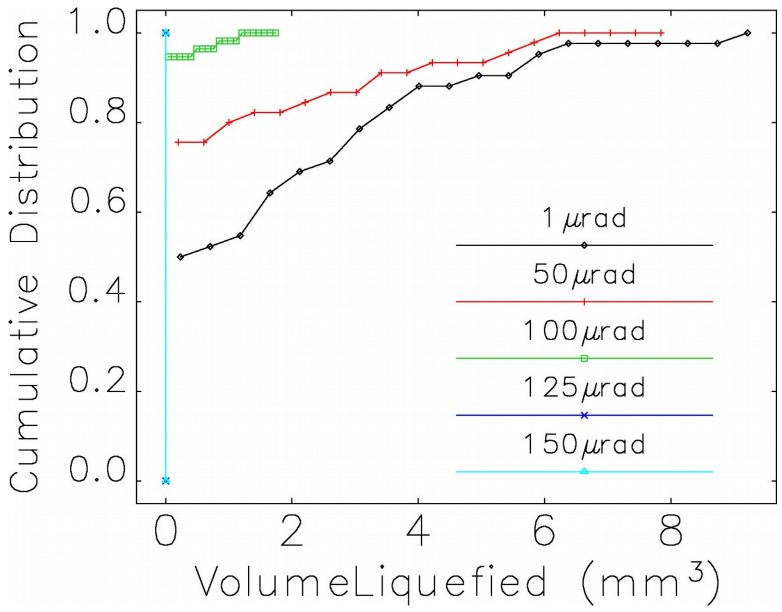


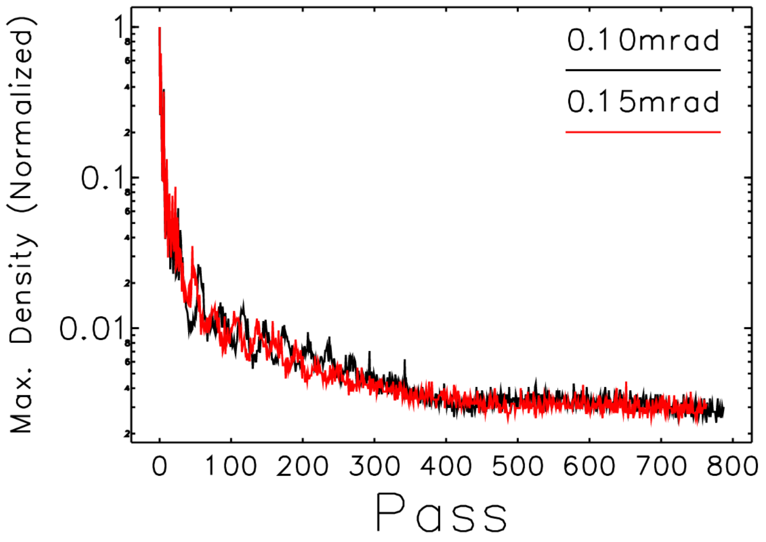
See J. Dooling's talk on Friday for more detail

1: J. Dooling et al., NAPAC19, MOPLM14.
2: M. Borland et al., IPAC18, 1494.

Kickers can protect the various beam dumps

- Whole-beam dump(s) hit by entire beam over ~50 µs
  - Have ~160 µs to act after, say, rf trips
  - Fire a weak kicker when abort is detected
    - Bunches hit dump in different vertical locations
    - Emittance slightly increased by decoherence
    - If kicker fails to fire, dump will be damaged
- APS-U also has a "swap-out dump"
  - One 15-nC, ~100 ps, bunch will melt Al-6061
  - To protect the swap-out dump
    - Pre-kick target bunch with weak kicker ~200 turns before swapping
    - Increases emittance in both planes >100-fold
    - Swap will not occur if decoherence kicker fails to fire





Conclusions

- APS-U design pushed to limits of existing circumference, technology
  - Confidence comes from extensive simulation
- Continue to refine modeling and understanding of single-particle and collective dynamics
  - Make commissioning as fast as possible
  - Ensure a timely transition to user operations
  - Improve ability to react to the unexpected
  - Existing ring provides invaluable opportunity to test codes, understanding
- Hot topics include
  - Choice of injection option (A. Xiao, Thursday)
  - Whole beam dumps (J. Dooling, Friday)
  - Swap-out safety tracking

Acknowledgments

- APS-U Beam Physics Team includes
  T. Berenc, A. Blednykh (BNL), M. Borland, J. Byrd, J. Calvey, J. Carwardine, G. Decker, J. Dooling, L. Emery, K. Harkay, S. Henderson (TJNAF), R. Hettel, X. Huang, S. Kallakuri, J. Kerby, S. Kim, R. Lindberg, B. Micklich, V. Sajaev, M. Sangroula (MIT), N. Sereno, Y.P. Sun, D. Teytelman (Dimtel), U. Wienands, K. Wootton, A. Xiao, C.Y. Yao, A. Zholents
- Simulation codes
  - Serial and parallel versions of ELEGANT[1,2] and related tools[3]
  - Wakefields: ECHO[4], GdfidL[5]
  - Ions: FIILINAC[6], ELEGANT
  - Beam-material interaction: shower[7], MARS[8]
  - Other: TAPAs[9]
- Computations used ANL's Blues and Bebop clusters, ASD's Weed cluster
- ESRF generously shared an early version of their H7BA lattice

1: M. Borland, LS-287.
2: Y. Wang et al., AIP Conf. Proc 877.
3: M. Borland et al., IPAC2003.
4: I. A. Zogorodnov et al, PRSTAB 8, 042001.
5: W. Bruns.
6: L. Wang et al., PRSTAB 4, 084401.
7: L. Emery, PAC96, 2309.
8: N.V. Mokhov, FNAL Tech. Rep. FN-628, 1995.
9: M. Borland, NAPAC16, 625.