APS-U Commissioning and Lessons Learned

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LER 2025, October 8, 2025

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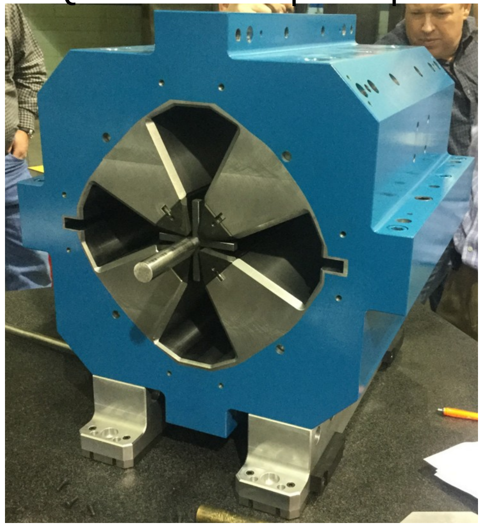
APS-U natural emittance is 42 pm.rad

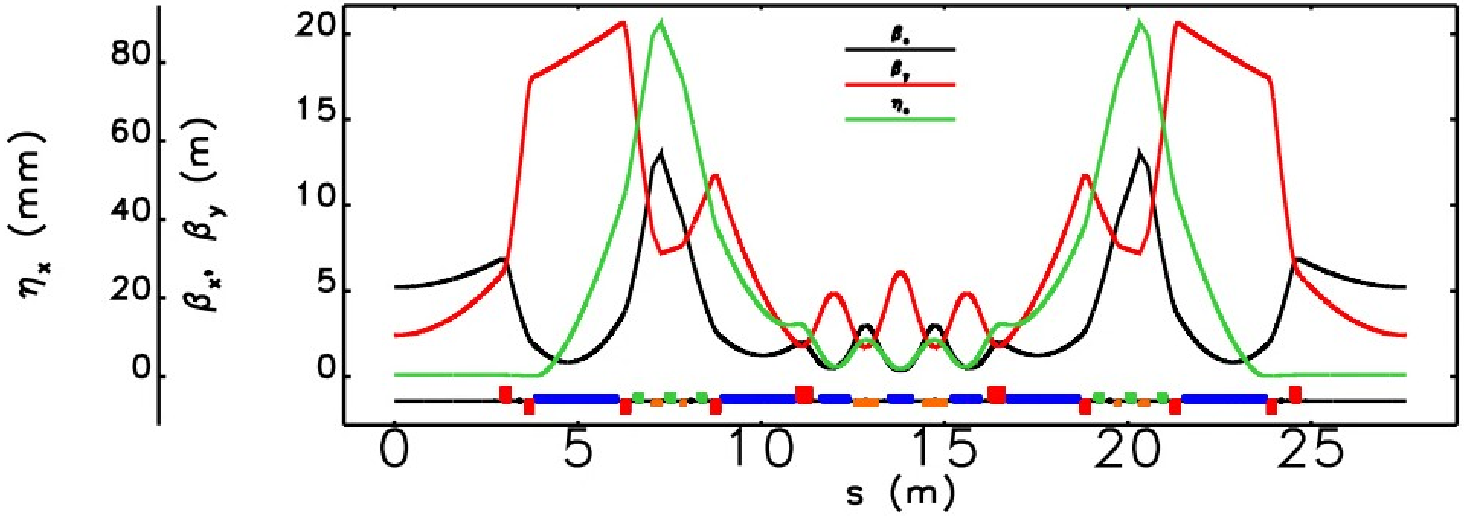
"If you can accumulate, you have not pushed your lattice far enough" – conventional wisdom

- New storage ring utilizes hybrid 7-bend achromat lattice (following ESRF design)
  - Six additional reverse-bend dipoles (for total of 13 dipoles)
  - No permanent magnet-based magnets
  - Vanadium permendur (VP) pole tips to increase strength
- Horizontal injection, single-bunch, on-axis swap-out
  - The same kickers are used to inject and extract stored bunch
  - Injectors are not upgraded
- Superconducting passive bunch-lengthening cavity to improve lifetime

Quad with VP pole tips



Lattice functions for one sector



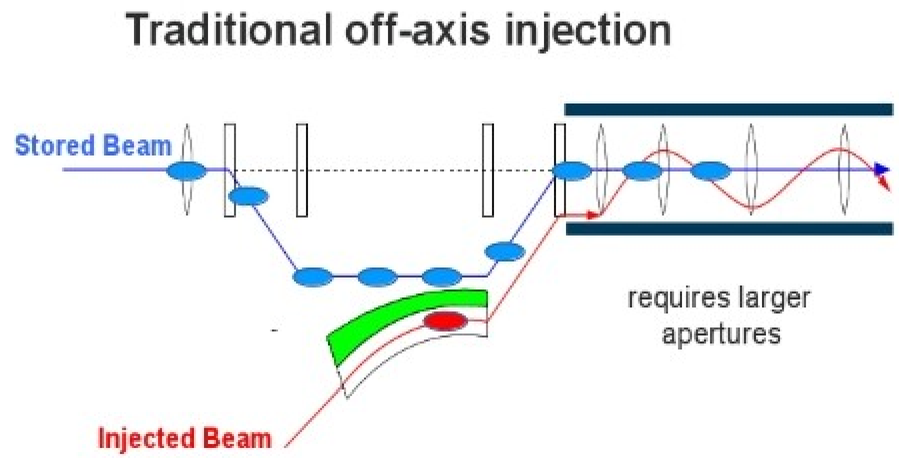
Swap-out injection can accommodate for smaller aperture

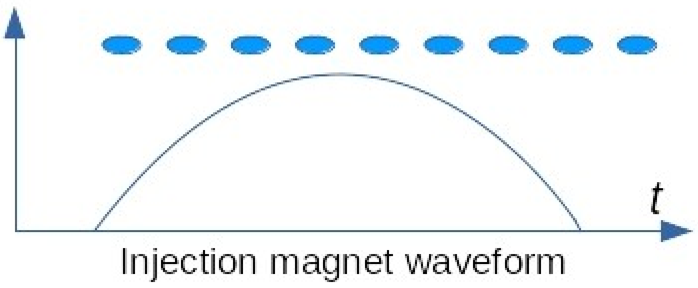
Traditional off-axis injection

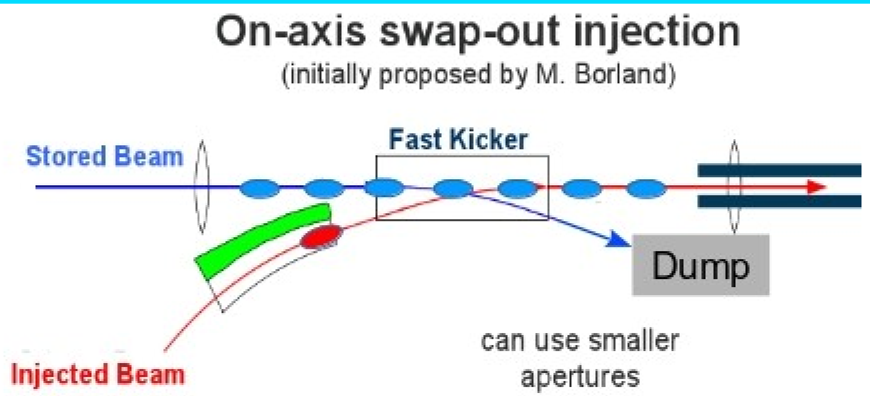
- Allows accumulation: adds injected bunch to stored bunch
- Kicker pulse length comparable to revolution time
- Requires larger area of stable motion to accommodate for injected beam oscillations

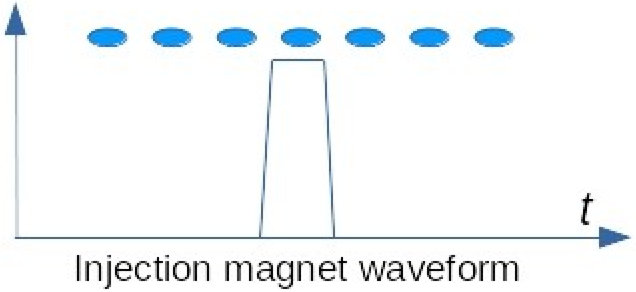
On-axis swap-out injection

- Does not allow accumulation: replaces stored bunch with injected bunch
- Kicker pulse rise/fall time less than distance between bunches
- Stable motion area only needs to accommodate injected beam





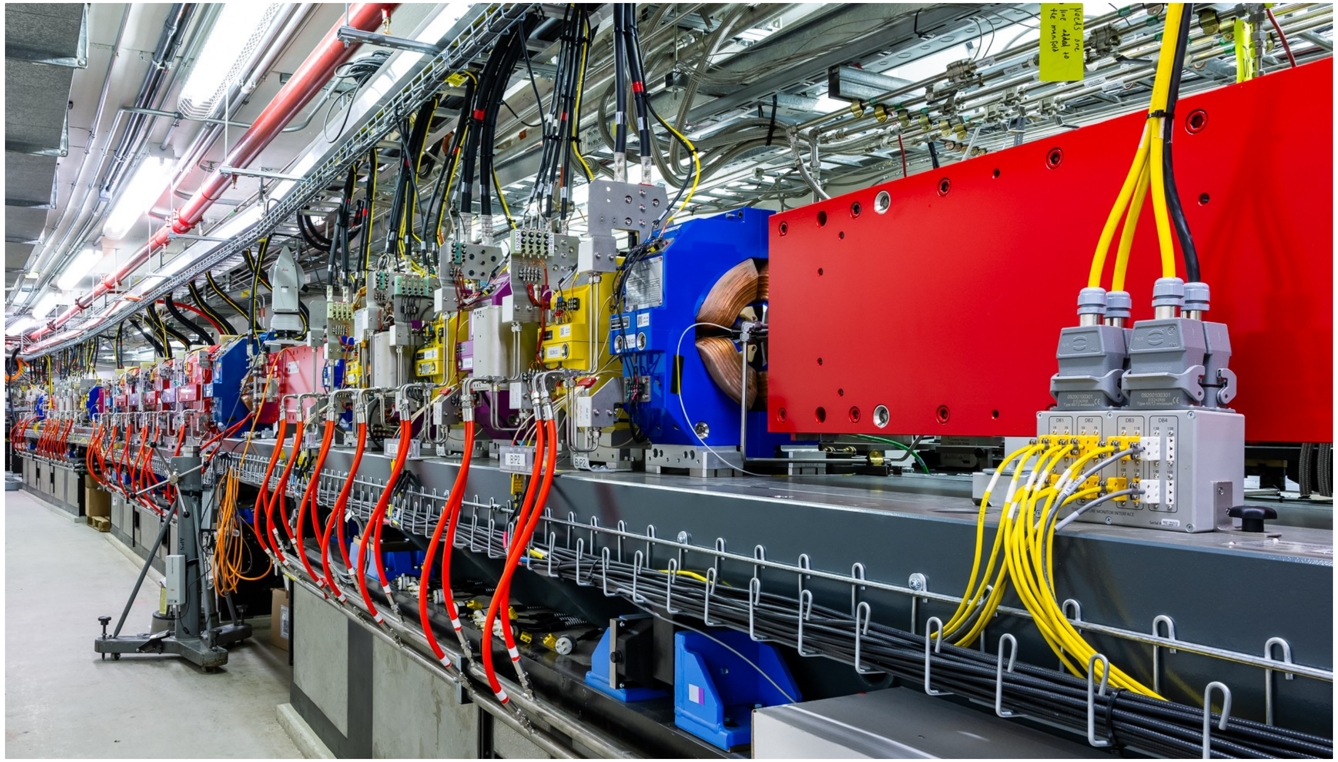




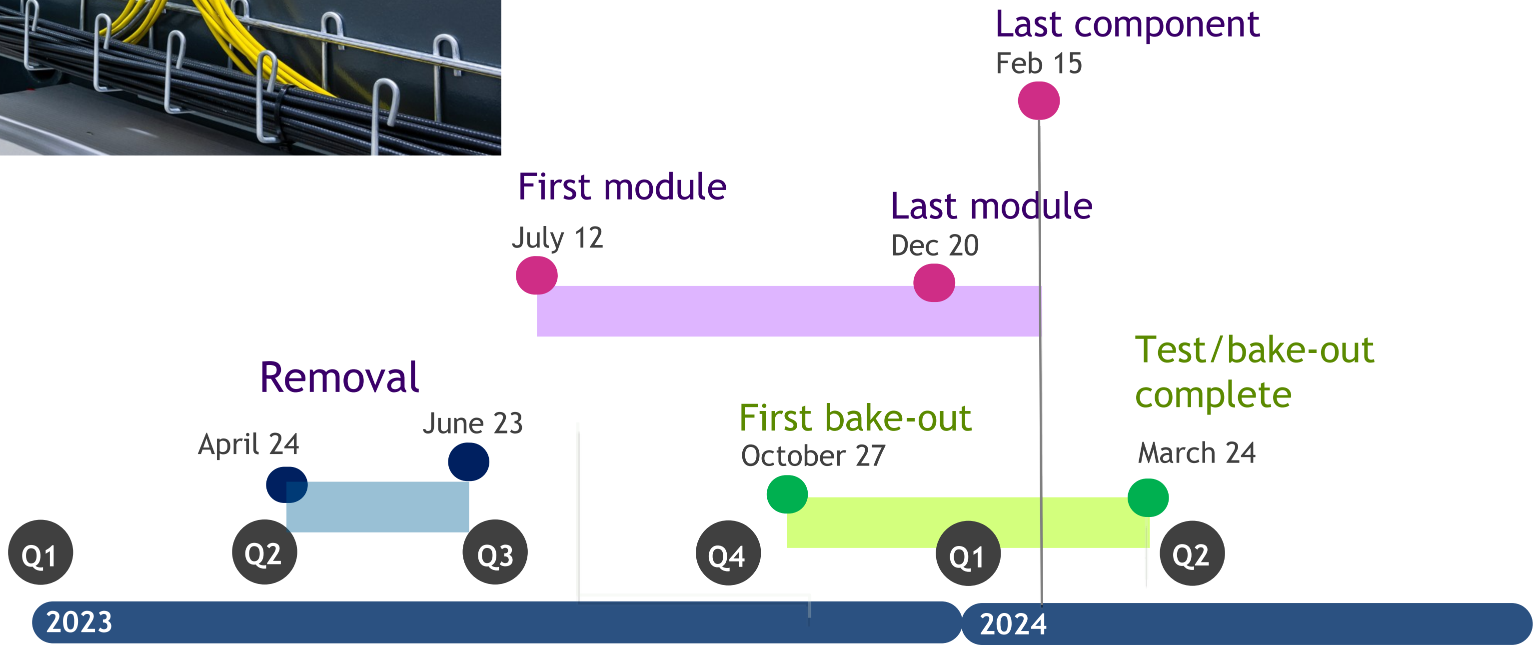
Diagrams provided in part by C. Steier

Argo NAT

APS stopped its operation on April 24, 2023



- Removal and installation in line with expectations with the exceptions of a few vacuum components, BPMs arriving late
- End of March 2024 dedicated to Accelerator Readiness Review
- Permission from DOE to start commissioning came April 10, 2024

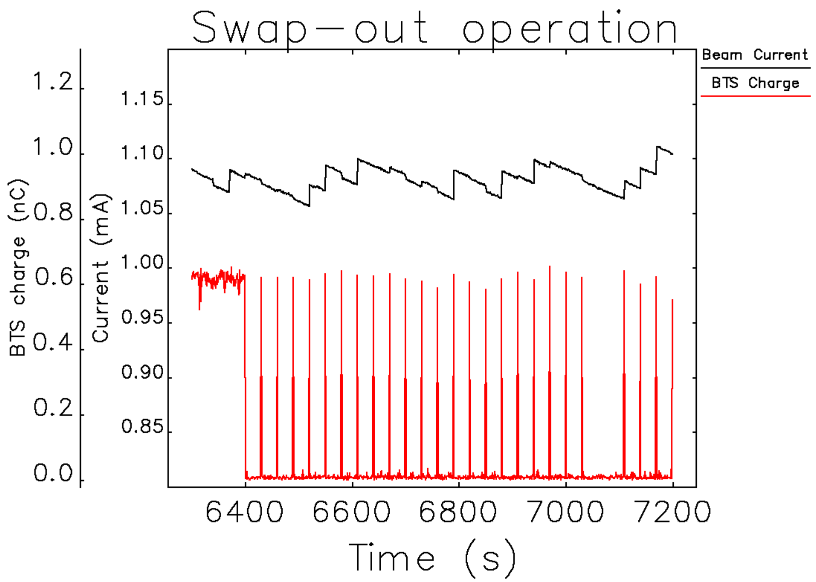


Multi-bunch swap-out was first demonstrated on April 29

- Accumulation in the injector and short-pulse kickers enable swap-out:
  - Injectors can presently generate 12 nC single bunch
  - Short-pulse injection kickers allow swapping out single bunches
- To protect swap-out dump, decoherence kicker blows up to-be-extracted bunch
- Fan-out kicker protects full-beam dumps

APS-U kickers:

Injection kickers	Fired at injection H plane 3 mrad; 11 ns pulse	Place injected bunch on axis, extract stored bunch to dump
Decoherence kicker	Fired 200 turns prior to injection V plane 0.2 mrad; 11 ns pulse	Blows up beam size of extracted bunch
Fan-out kicker	Fired at fast beam abort V plane 0.1 mrad; 5 µs pulse	Spreads out stored bunches over beam dump surface

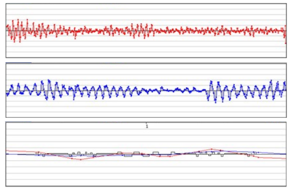


12-bunch 30-second swap-out

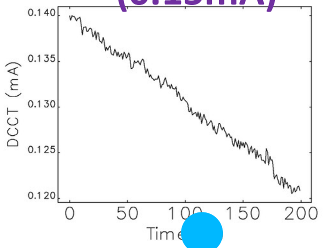
M. Borland and J. Calvey run first swap-out

Commissioning timeline

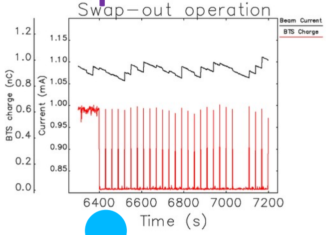
First turns



Stored beam (0.15mA)



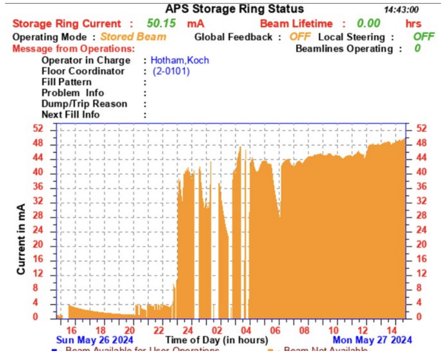
Swap-out operation



10 mA

25 mA

50 mA



First light at user beamline @ 50 mA

April 10	Machine studies
April 13	Radiation studies
April 18 / April 20 / April 29	Machine studies
May 2	Septum failure
May 12 / May 17 / May 17 / May 25 / May 27	Machine studies
June 2	Septum failure
June 15 / June 17	Machine studies
June 19	Beamline commiss / Machine studies

April 10 – DOE authorizes start of commissioning

April 13 – First turns

April 20 – Stored beam (0.15mA)

April 29 – Swap-out operation

May 12 – 10 mA

May 17 – 25 mA

May 17 – Vacuum conditioning started

May 25 – Diagnostics beamline shutter opened with swap-out

May 27 – 50 mA

June 17 – First light at user beamline @ 50 mA

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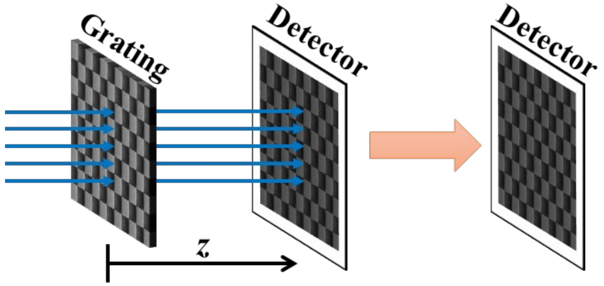
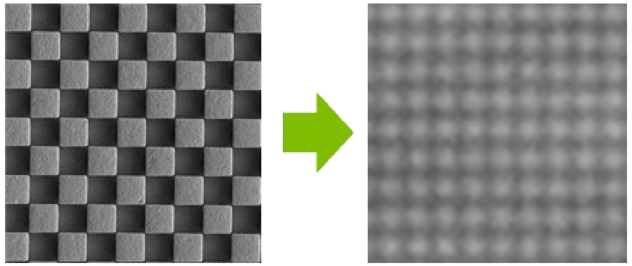
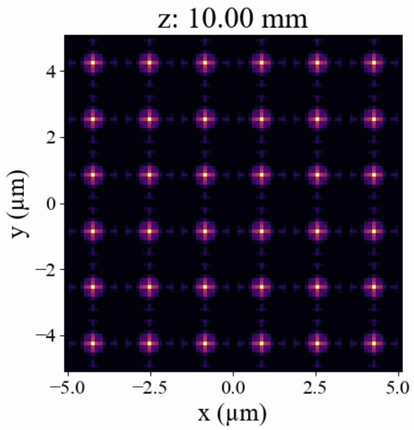
Emittance measurement at 3-ID-B, August 2024

- Dedicated diagnostics beamline for beam size measurement is not ready yet
- Source size was measured using grating interferometry

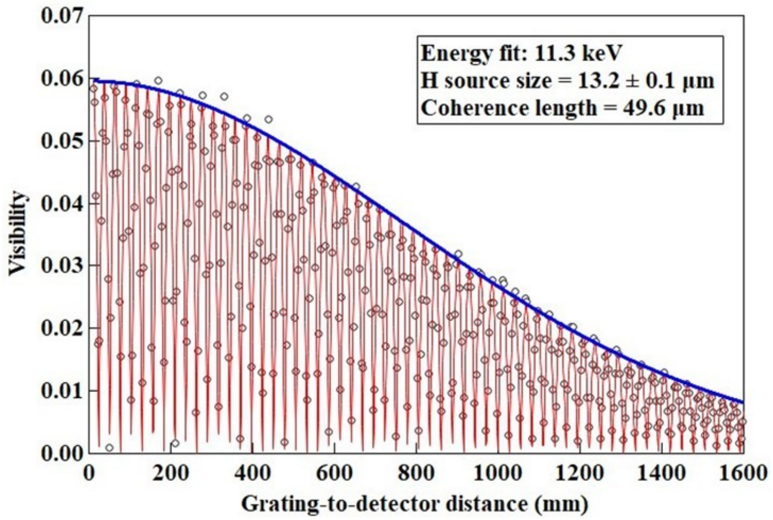




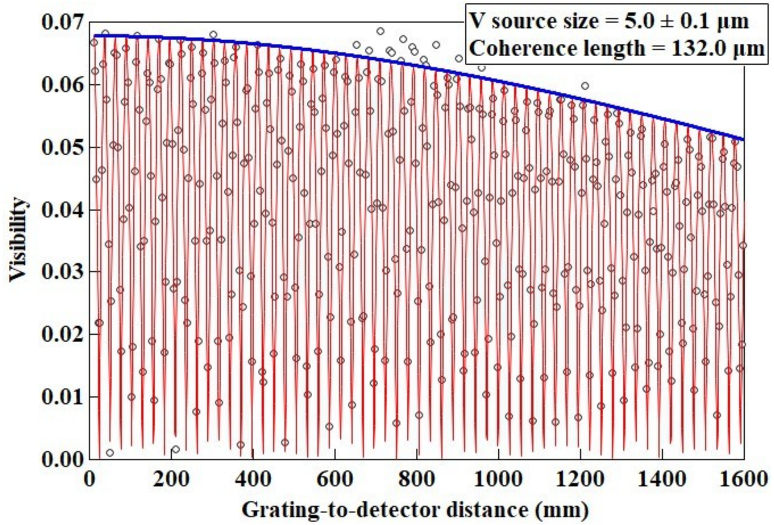
Fabricated at Center for Nanoscale Materials (ANL)



Horizontal scan, full coupling



Vertical scan, low coupling



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X. Shi, et.al., Journal of Synch Rad

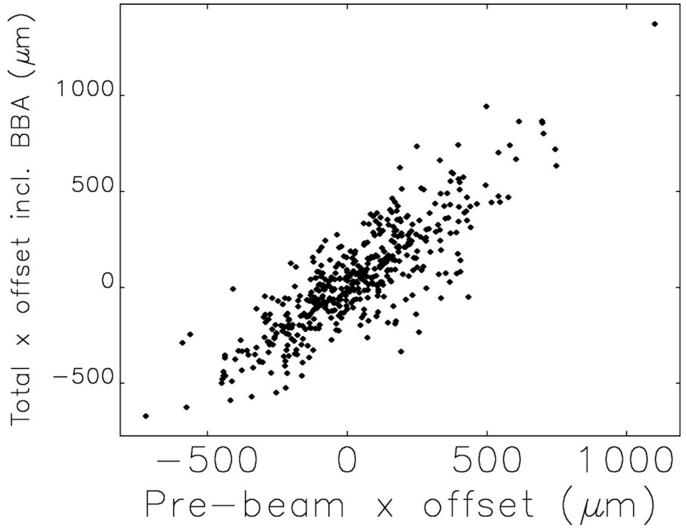
Emittance measurement at 3-ID-B

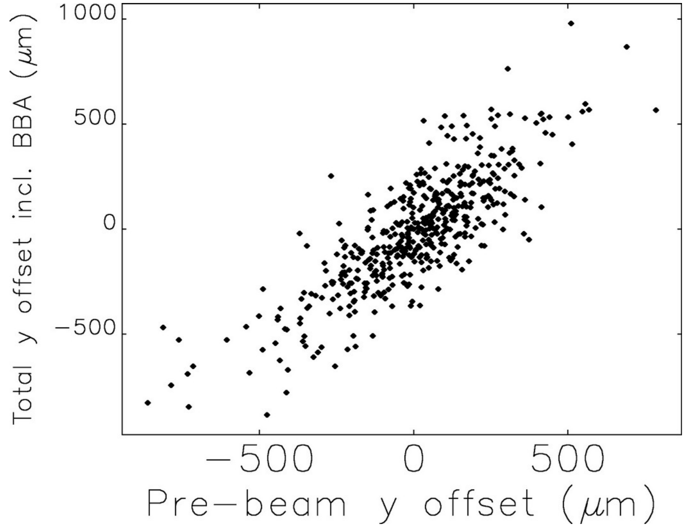
		Full coupling		Low coupling	
		H	V	H	V
Grating interferometry →	Total Σ (μm)	13.2	9.8	16.3	5.0
Simulated →	Photon σ_{ph} (μm)	4.0	4.0	4.0	4.0
$\sqrt{\Sigma^2 - \sigma_{ph}^2}$ →	Electron σ_e (μm)	12.5	8.9	15.8	2.9
Beam size at D →	Total Σ' (μrad)	4.9	5.6	5.2	4.5
Simulated →	Photon σ'_{ph} (μrad)	4.4	4.4	4.4	4.4
$\sqrt{(\Sigma')^2 - (\sigma'_{ph})^2}$ →	Electron σ'_e (μrad)	2.2	3.5	2.8	1.2
$\sigma_e \sigma'_e$ →	**Emittance ε (pm·rad)**	**28**	**31**	**45**	**3.4**
Energy spread subtracted	Betatron emittance	27	30	44	2.0
Beam moments calculations	Model-based Betatron emittance	29	32	44	1.7

(Sort of) Lessons and Other Issues and Other Details

Extensive pre-beam checkouts helped ensure success

- Extended time due to vacuum bake-out delays was used effectively for system checkout
  - Network issues addressed
  - No polarity or cross-wiring issues found in SR magnets or diagnostics
  - BPM mechanical and electron offsets measured and preset in control system
- Application software “dress rehearsal” found several issues, mostly related to PV name changes between simulator and real machine
- Swap-out permissive testing was performed
  - Required system for enforcing limits on magnet settings
  - Tests allowed resolving two issues:
    - Misunderstanding about required current readback rate
    - Several malfunctioning current readbacks





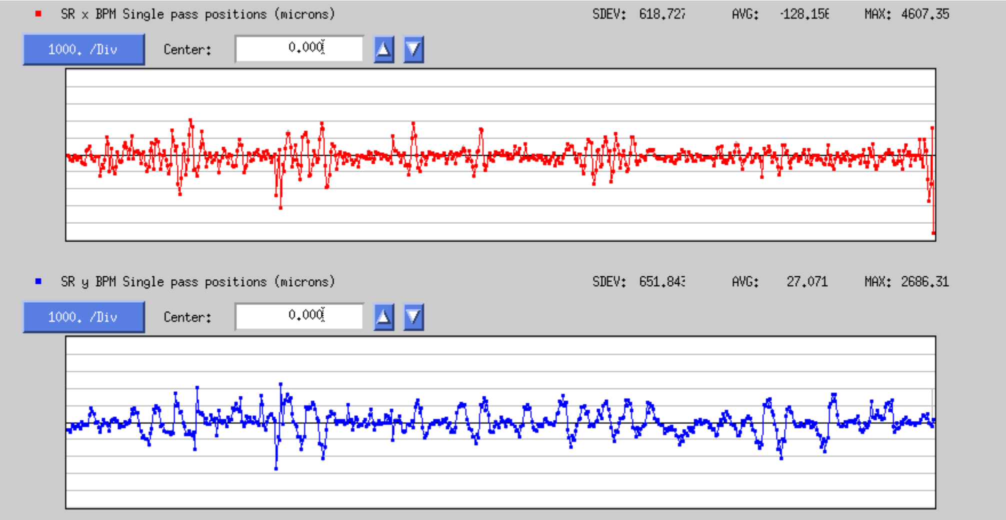
≥64% of the offset value is accounted for already by the pre-set offset values.

Graphs courtesy M. Borland

Well aligned machine resulted in quick first turn, but optimizer was needed to work around unexpected aperture limitation

- Planned for physics-based commissioning but also prepared optimizers
- First-turn threading corrected trajectory well but could not result in second turn (simulations predict 5-10 turns)
  - The beam was clearly lost around septum
- Bayesian optimization found a 2-mm orbit bump needed to store beam
  - This was later attributed to septum vacuum chamber manufacturing error

Good first-turn trajectory but no multiple turns

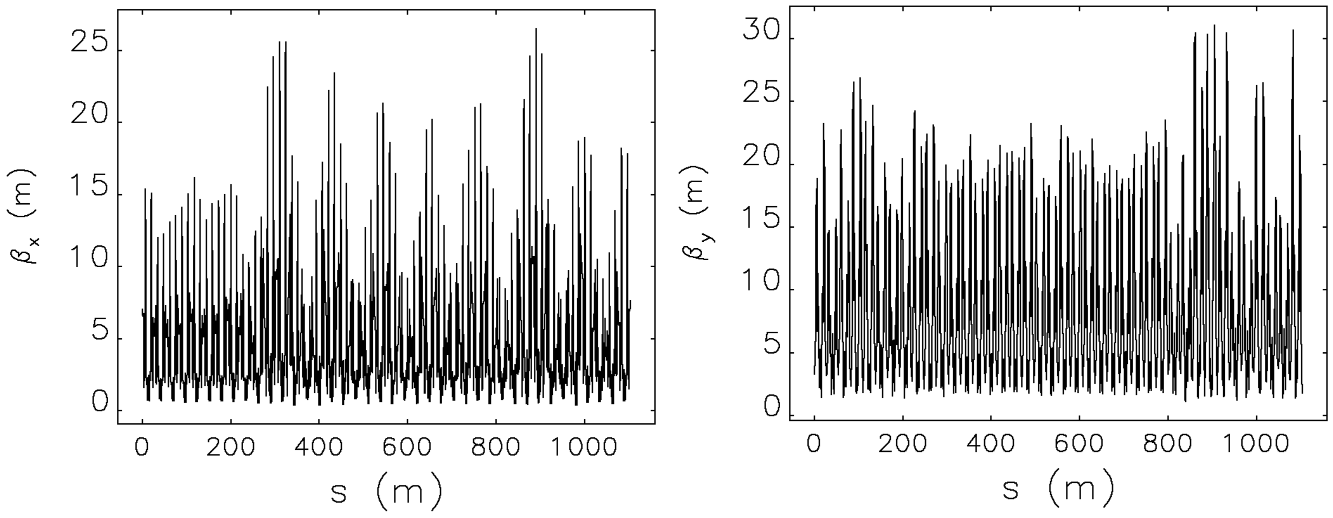


A few iterations of lattice correction resulted in a well corrected lattice

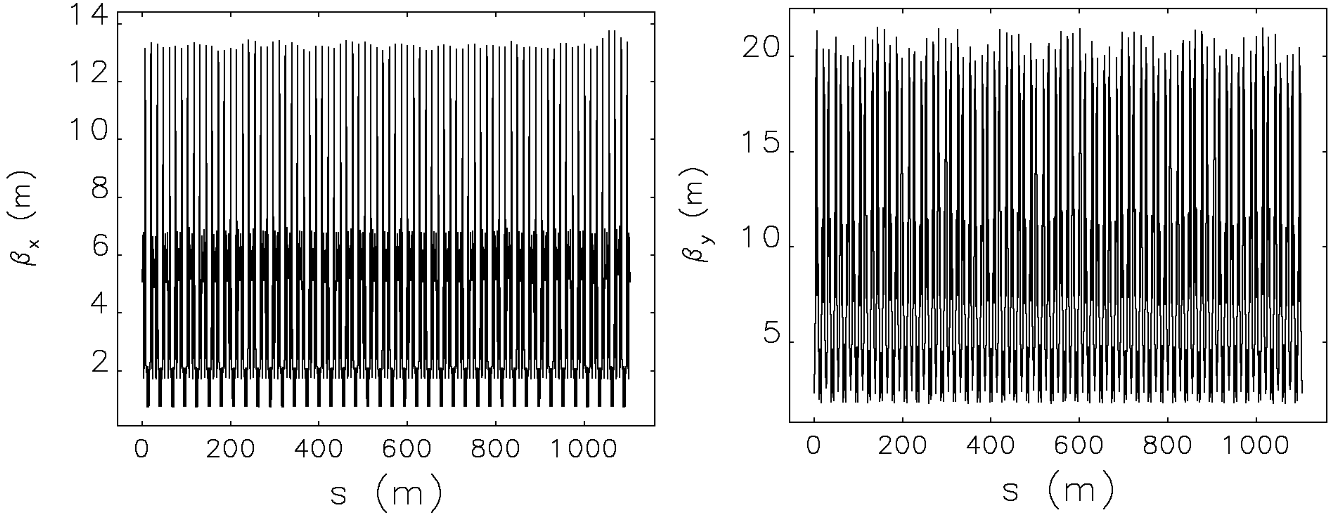
- Lattice correction is based on response matrix fit
  - 20 correctors per plane (out of hundreds) are used to speed up measurement
- Coupling correction is also response matrix-based – we have no online beam size monitor yet

- Residual error of the RM fit significantly exceeds the measurement noise
  - Does not prevent from determining lattice with reasonable accuracy and performing correction

Immediately after storing first beam at 0.3 mA:



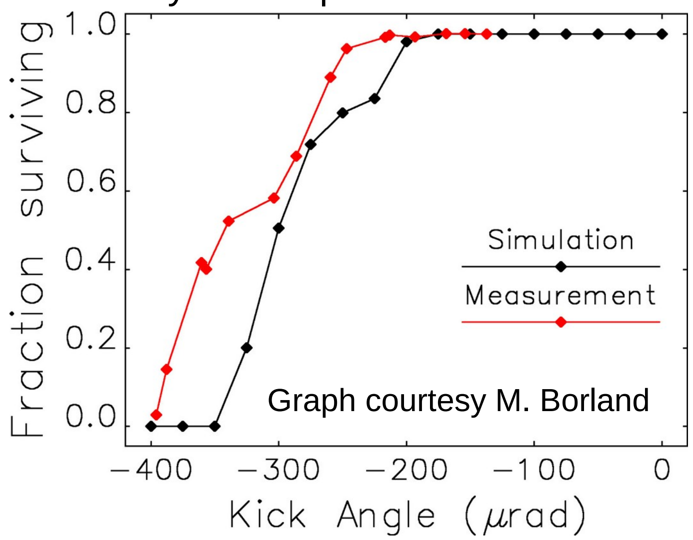
After a few correction iterations at 10 mA:



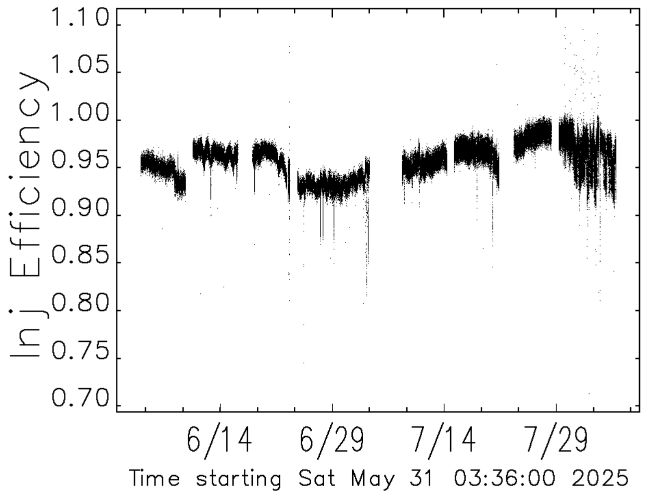
Small DA does not prevent from good injection efficiency

- Horizontal measured dynamic aperture reasonably agrees with simulations
  - Model is based on response matrix fit
  - Physical aperture is based on our best knowledge (septum limit is in)
  - Corresponds to ±1.5 mm at injection
- Despite aperture limitation in septum, injection efficiency is still very good
  - Variation if below 1% rms

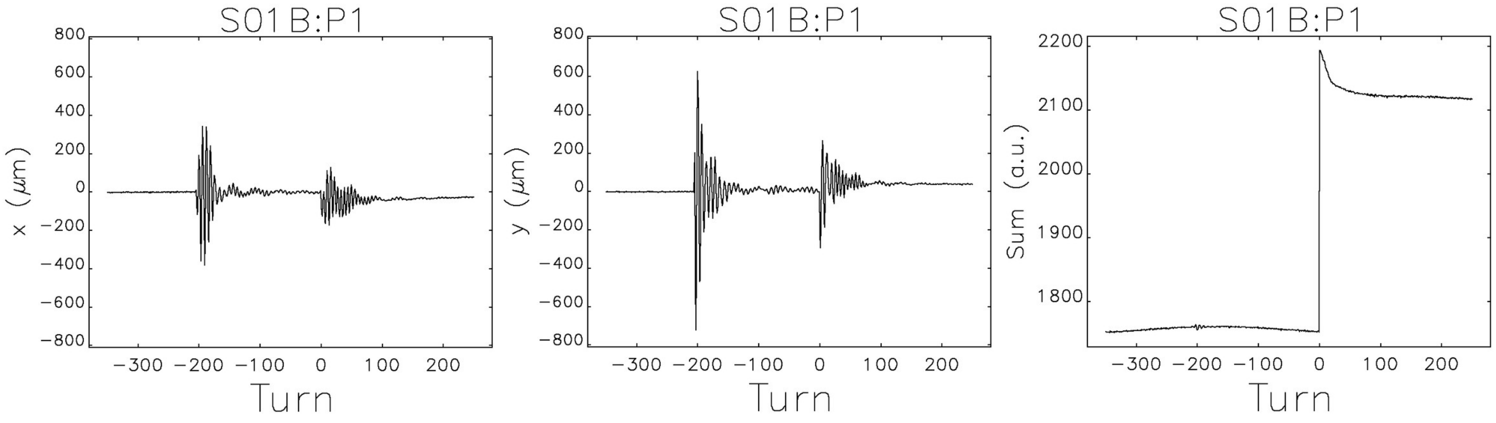
Dynamic Aperture measurement



Injection efficiency during user operation over 2 months

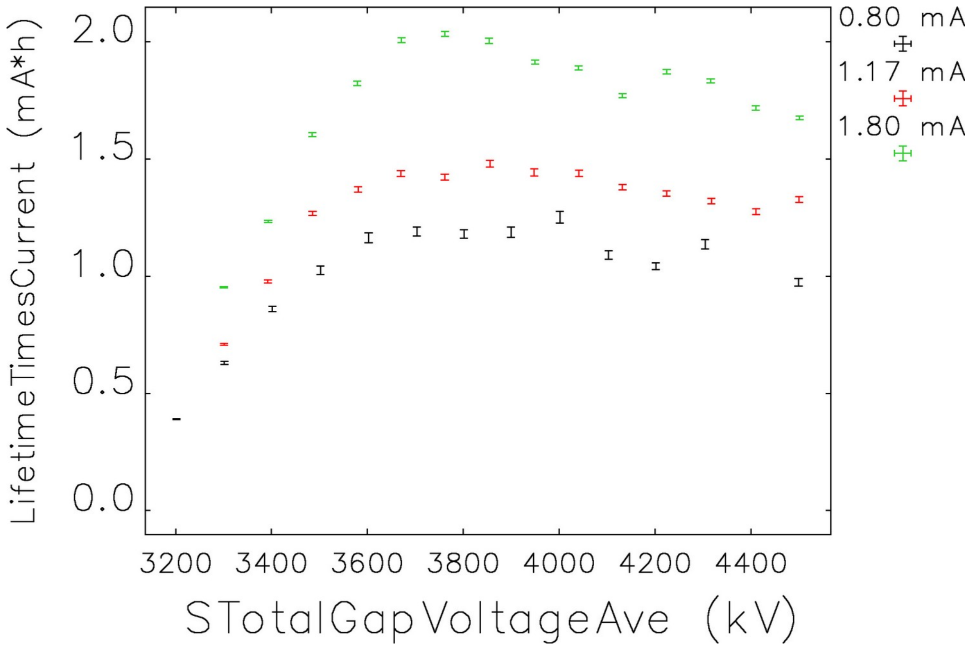


Typical injection motion (decoherence kick + swap-out)



Momentum acceptance lower than expected

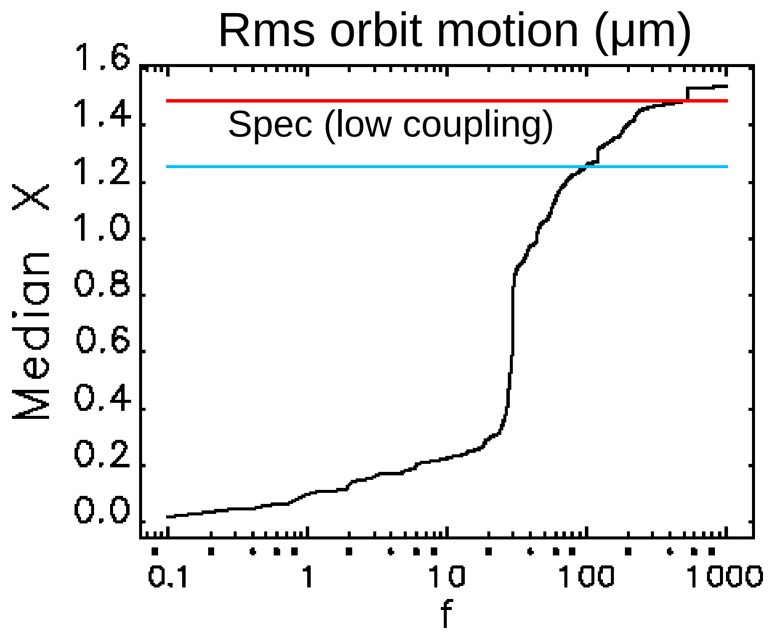
- Measurement of single-bunch lifetime vs rf voltage scan shows a knee at ~3.7 MV
- For design lattice with good correction (1% rms), this is expected to be at ~4.4 MV
- Possible causes and issues include
  - Collimators are at ~3mm from orbit instead of expected ~4.5 mm
    - Insertion of collimators emphasizes ID protection, ignores lifetime.
  - Bowed septum chamber and uncertainty about other apertures in septum region.
  - Have not measured offsets of sextupoles, which might help lattice correction
- The situation is workable operationally

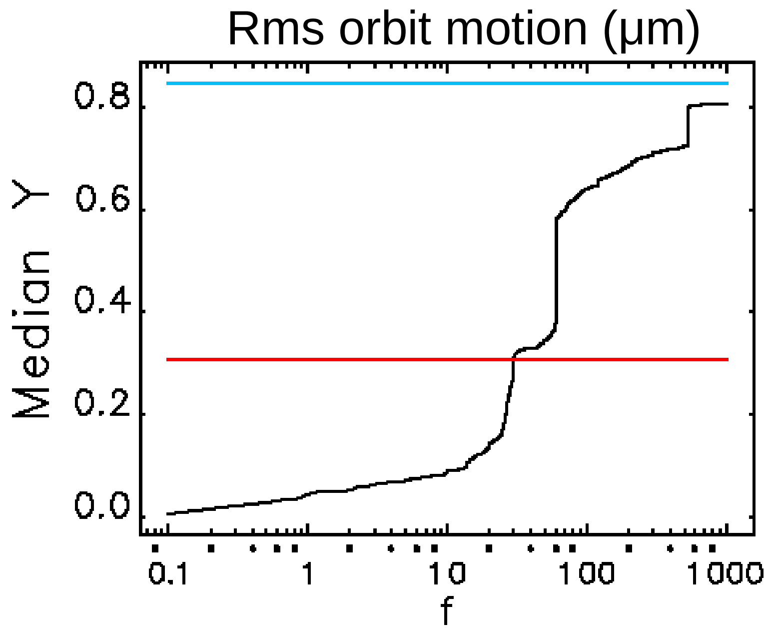


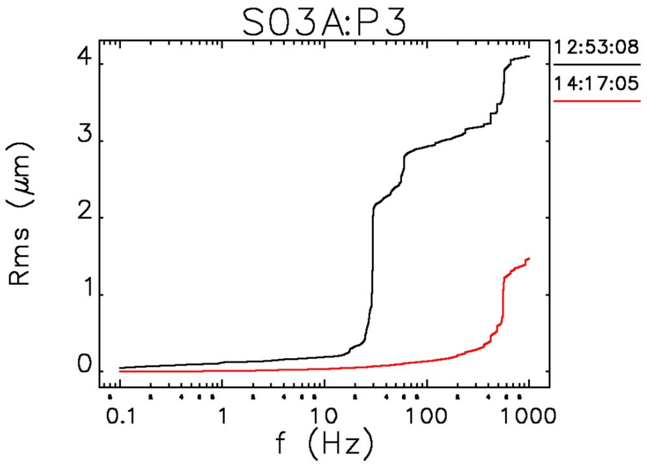
Graph courtesy M. Borland

Orbit stability close to expected

- Simulations predicted orbit stability without orbit correction close to requirement (10% of the beam size)
  - Fast orbit correction was descoped from the project
  - Measured rms orbit motion is close to APS-U requirements
- A few beamlines suffer performance reduction due to this orbit motion
  - Orbit stability specification is not good enough for some beamlines
- We are working on completing fast orbit feedback
  - 22 kHz update rate, 1 kHz target bandwidth
  - The team has recently completed first simple test: one corrector and one BPM



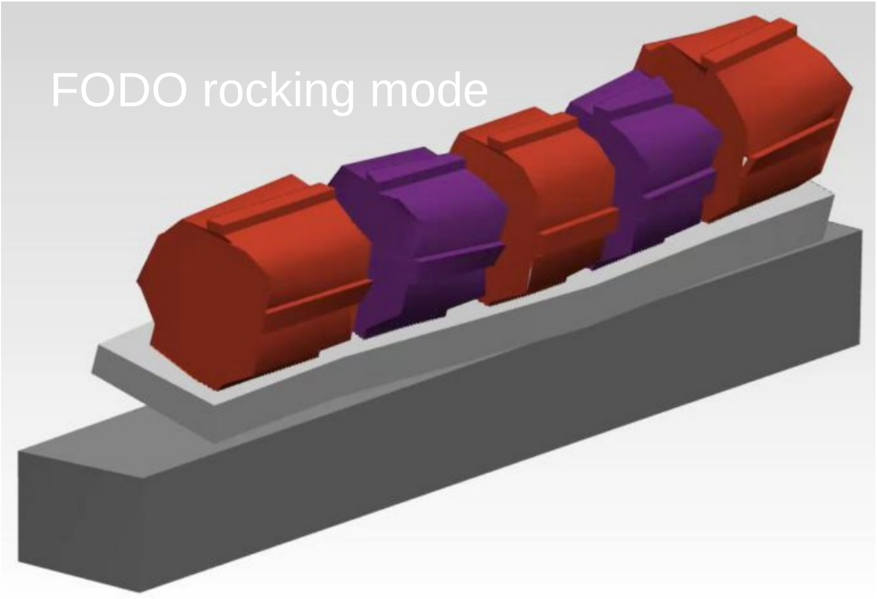




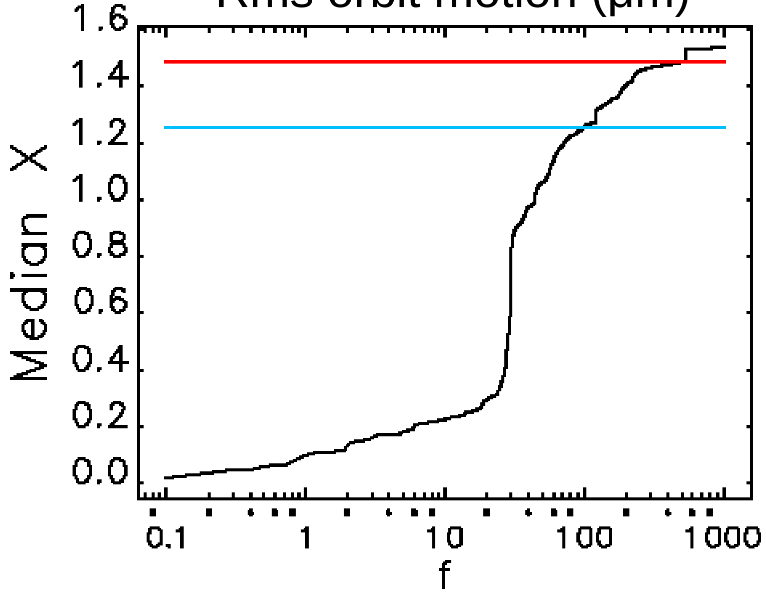
Orbit stability close to expected, but vibration simulations are quite off

- Preliminary measurements show 30-Hz line comes from FODO module rocking motion
  - Simulations predicted this mode at 40 Hz
  - Ground motion has a small peak at 30 Hz that is amplified now
  - FODO rocking orbit amplification factor is 15, existing ground measurements do not show strong enough 30-Hz motion
- Working on passive damping for this mode

- Orbit motion simulations are estimations, so do not rely on the exact numbers



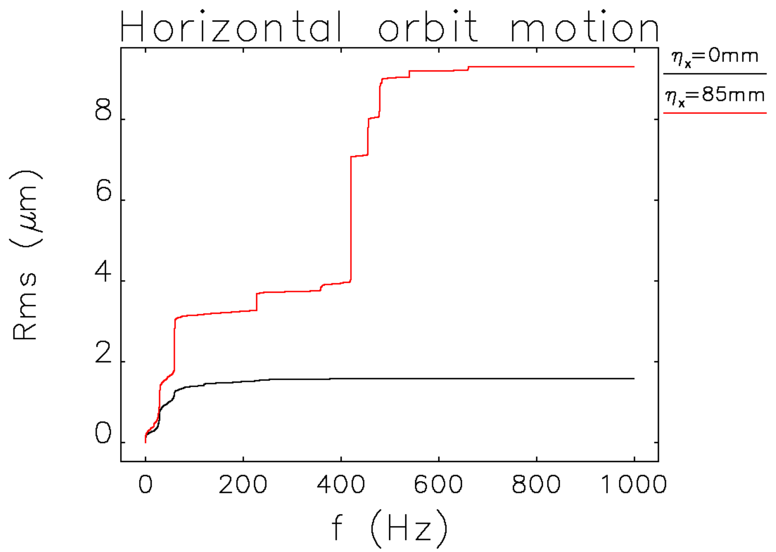
Rms orbit motion (μm)

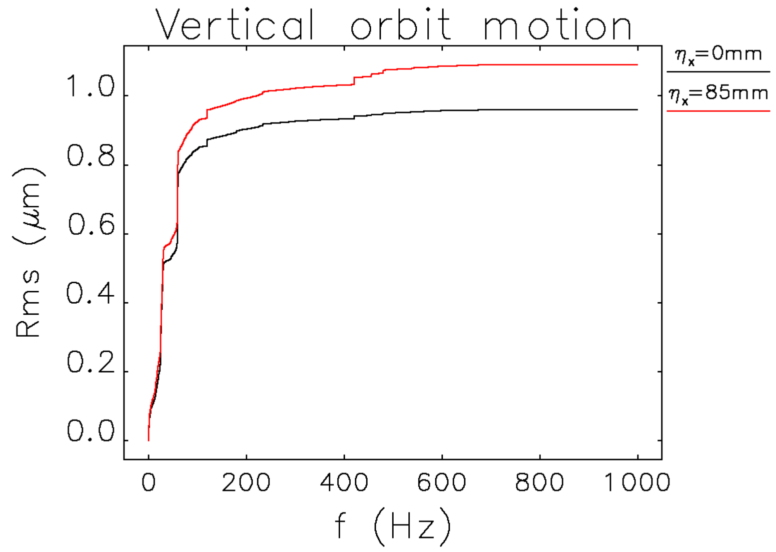


Low synchrotron tune significantly amplifies RF noise

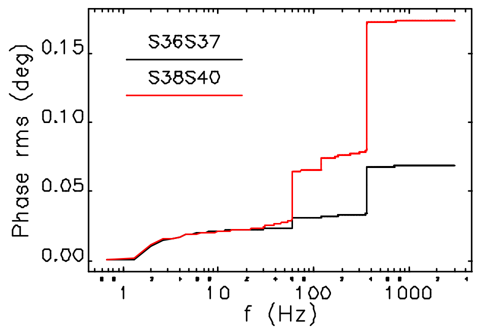
- APS runs on two 1-MW klystrons which are known to be rather noisy at harmonics of 60 Hz
  - APS-U synchrotron tune is 300 – 600 Hz (depending on BLS)
  - Expected to amplify beam energy noise due to RF noise
- Feedback-like noise suppression system was implemented as part of APS-U
  - Noise is reduced but not eliminated
- Presently $\Delta E/E$ rms noise of $1\text{x}10^{-4}$
  - Results in large orbit motion on dispersive BPMs
- Plan to improve RF noise suppression system soon
  - Long-term solution is solid-state-based RF

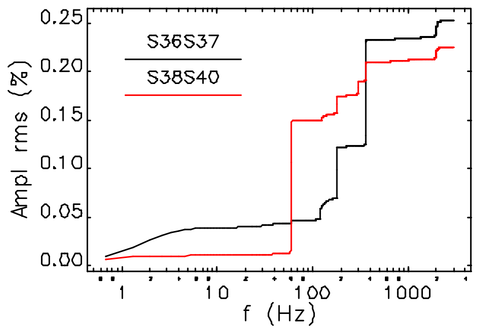
Orbit motion on different BPMs





Pre-APSU RF phase and amplitude noise

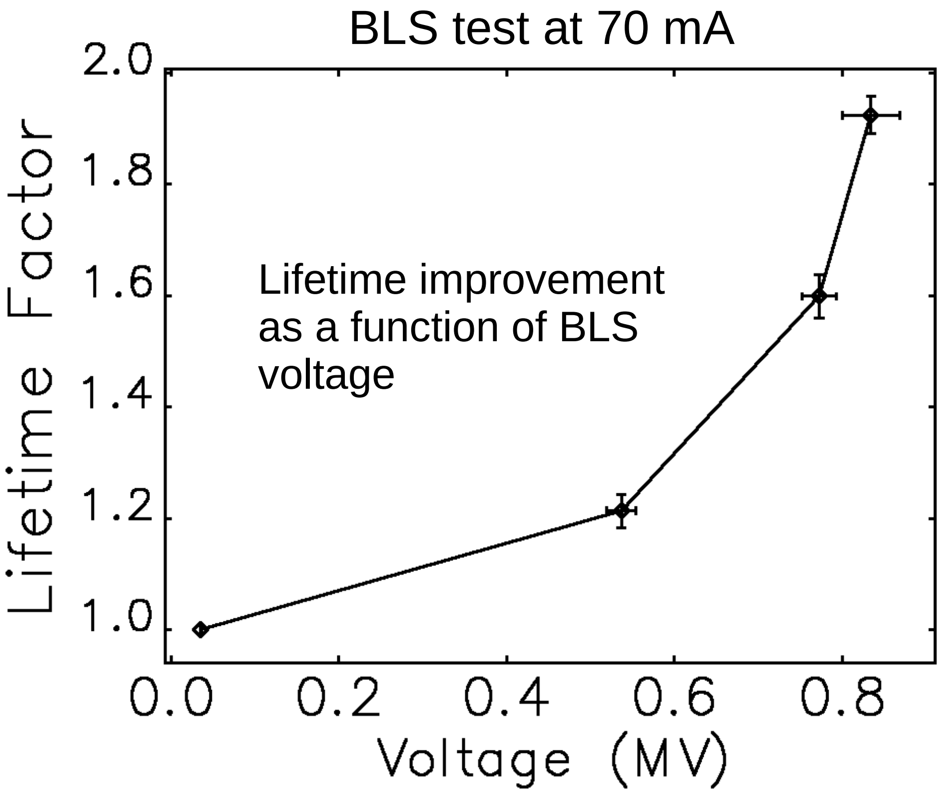


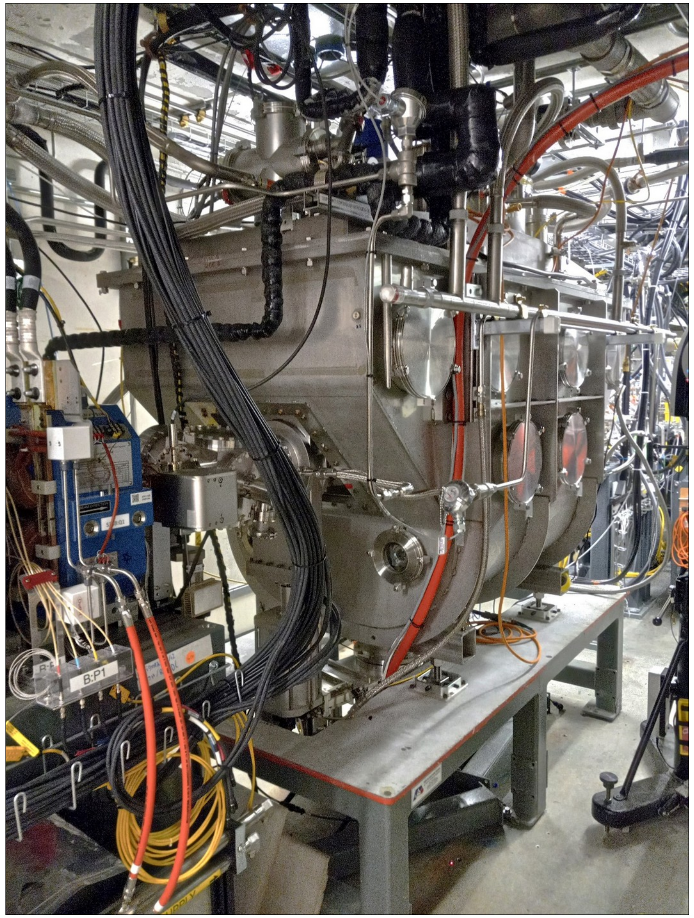


Bunch Lengthening Cavity (BLS) increases lifetime by a factor of 2

- Single-cell, passive, 1408 MHz cavity operating at 2.1 K
- Use of BLS in user operation was delayed due to issues with quench interlocks
  - First operation with user beam started Oct 8 at 0.5 MV
- Presently, BLS operates at 1.1 MV with 200 mA

We expected lifetime to increase by a factor of 4





BLS Cryomodule in the tunnel

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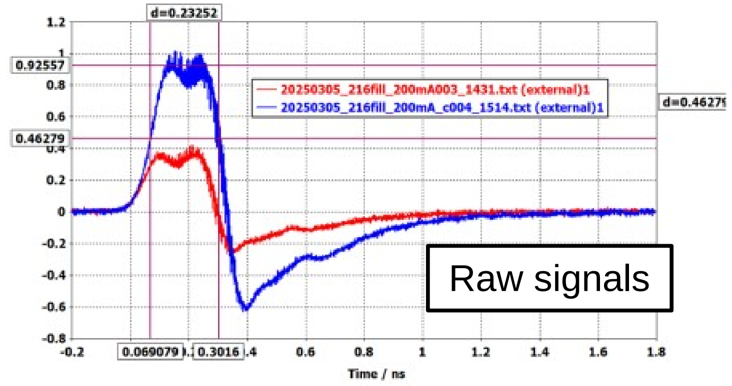
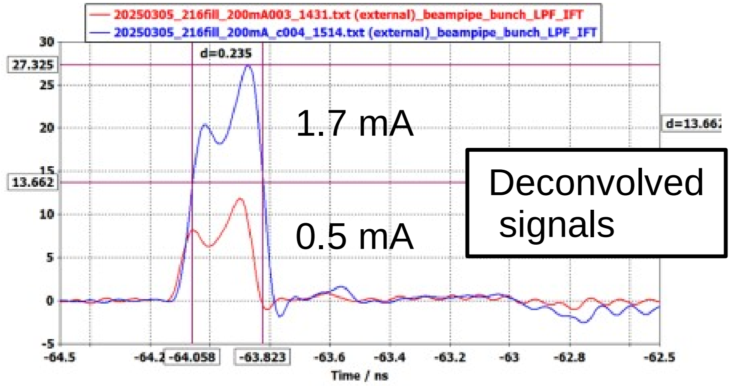
Measured bunch profile shows expected double peaks

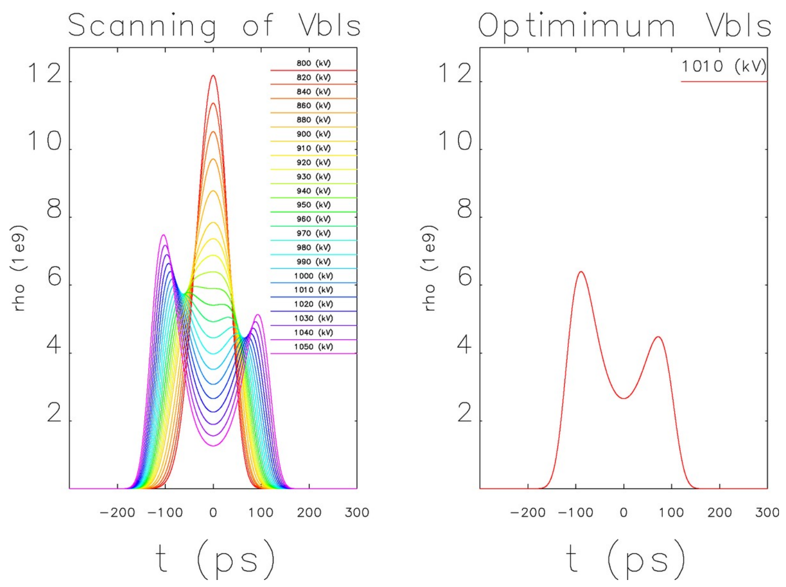
- Measurement is done by inverting response of cables of a rf bpms signal (W. Cheng)
- Corresponds well with density profile calculation
- Preliminary light optical imaging of many bunches confirmed (Wootton)



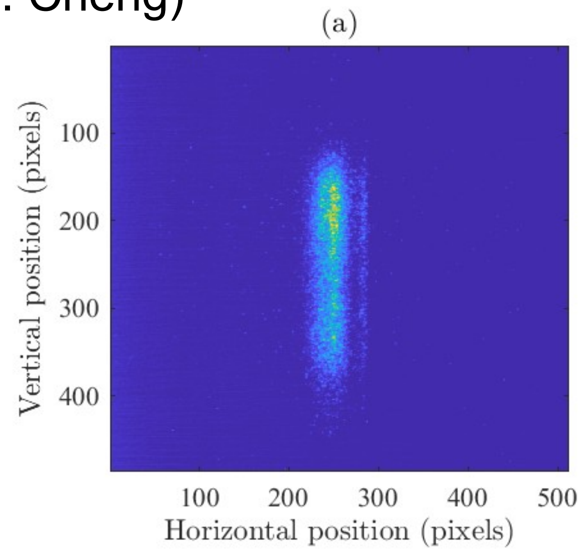


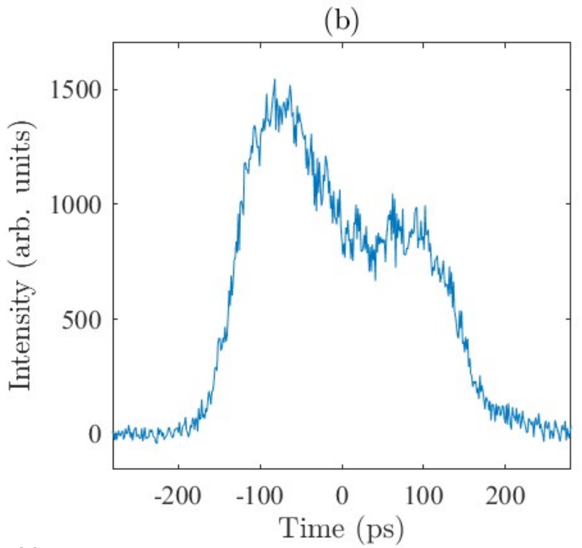
Double peak has a ratio of 1.6:1 roughly the same as model with no wake fields

Haissinksi equation results



The peaks appear reversed from scope trace because of coordinate change





Graphs courtesy W. Cheng, L. Emery, K. Wootton

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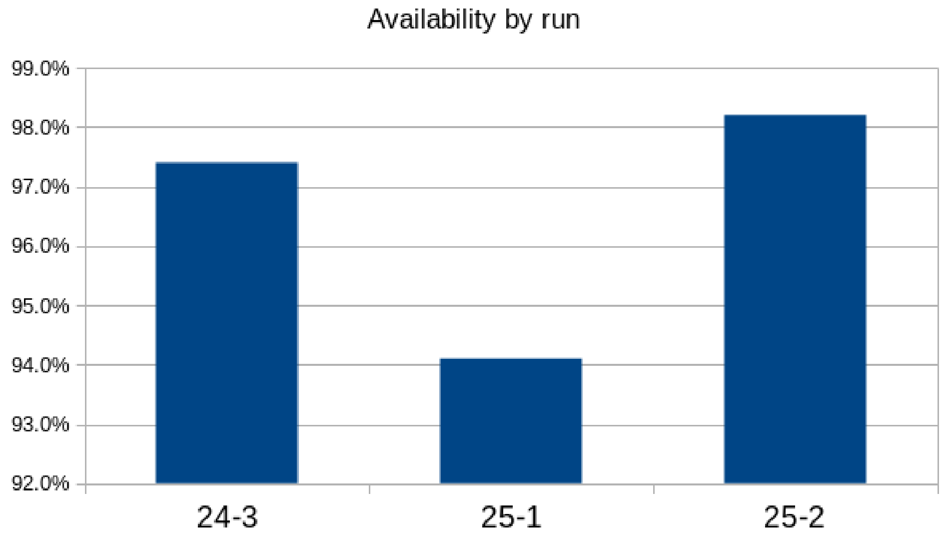
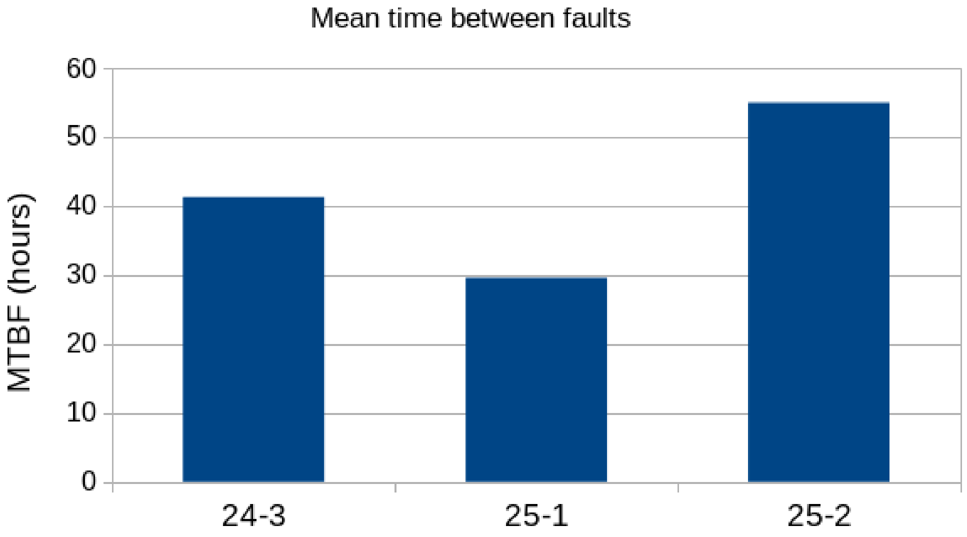
Quick transition to operations left no time to study machine

- Regular user operation started September 2024
  - 5000 user hours per year
  - Machine reliability is good
- Present SR conditions
  - Multi-bunch mode at 200 mA (216 bunches)
  - Timing mode at 140 mA (48 bunches)
  - Full coupling
  - Lifetime 2 – 4 hours
  - Bunch lengthening cavity voltage: 0.9 – 1.1 MV
  - Beam emittance, typical ID gaps: 25 pm.rad (model)

- 5000-hour schedule does not allow enough time to study the new machine
  - Better machine understanding will be crucial to provide the best possible conditions





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Machine works well enough but issues remain

- APS-U commissioning was very successful
  - User operation restarted quickly with emittance below 30 pm
  - Swap-out works well even with aperture limitation
    - Septum vacuum chamber was just replaced to eliminate aperture limit
- First year of user operation delivered 5000 user hours with 96.5% availability
  - 50 beamlines are producing science, 21 beamlines are in various stages of commissioning
- Machine characterization is advancing slow due to operational schedule
- Among major issues still to resolve:
  - Fast orbit feedback commissioning
  - Lifetime is shorter than expected
  - Higher charge needed from injectors for timing mode

Extra slides

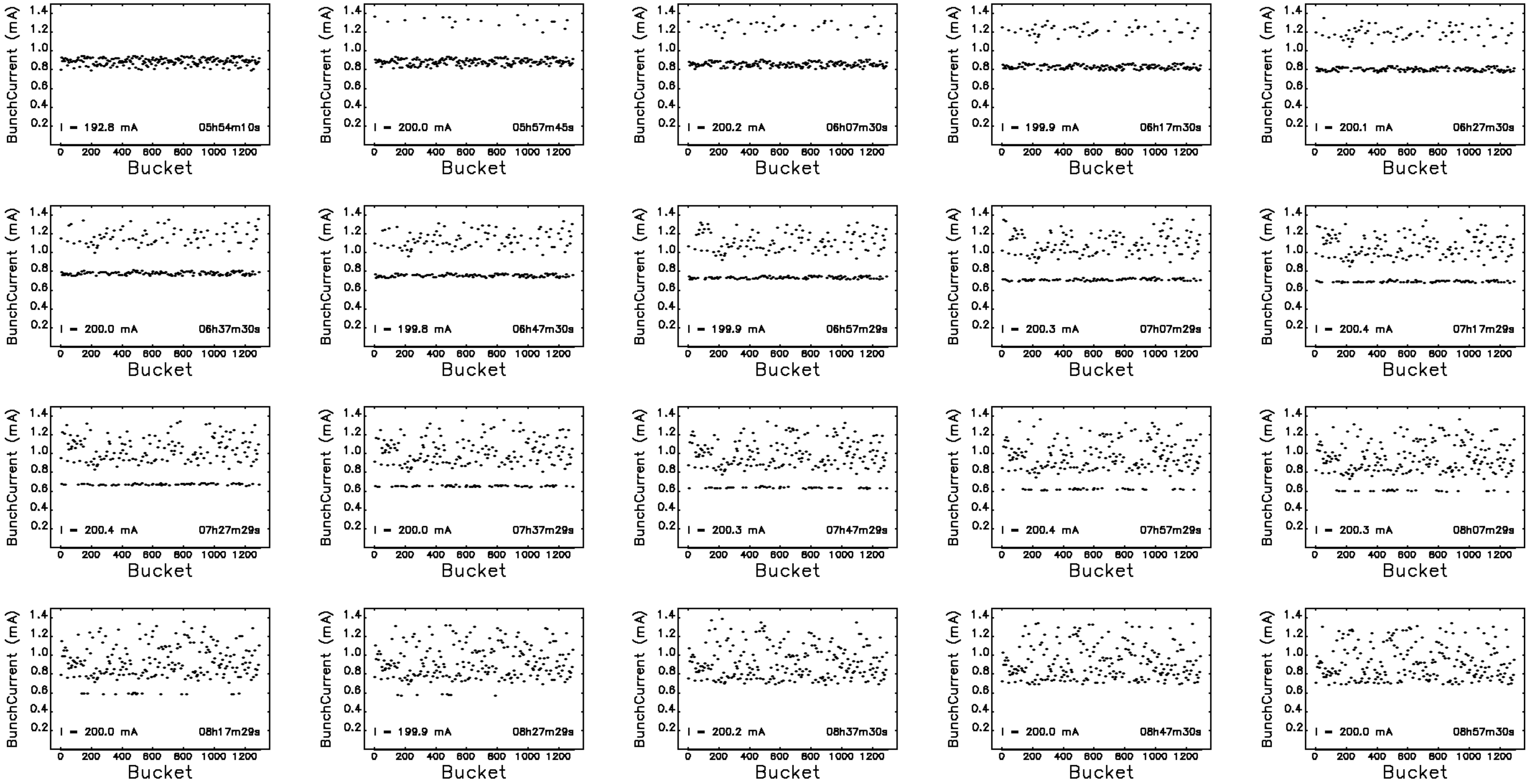
Swap-out injection details

- Initial fill is performed with injected charge slightly above $I_{total}/N_{bunches}$ – 3.4 nC
- After that, injectors need to provide a significant fraction more to compensate for decay of all bunches during swap-out interval
  - Bunch pattern non-uniformity is unavoidable
- Spread in charge is defined by how much the swap-out charge exceeds the minimum
  - Keeping swap-out interval close to 20 seconds
- Injector charge stability is good: ~3% rms

Drop before replacement (%)	BTS charge (nC)	Swap-out Interval (s)
60	7.1	30
50	6.1	23
40	5.4	17
30	4.8	11
20	4.3	7
10	4.1	3
5	4.1	1

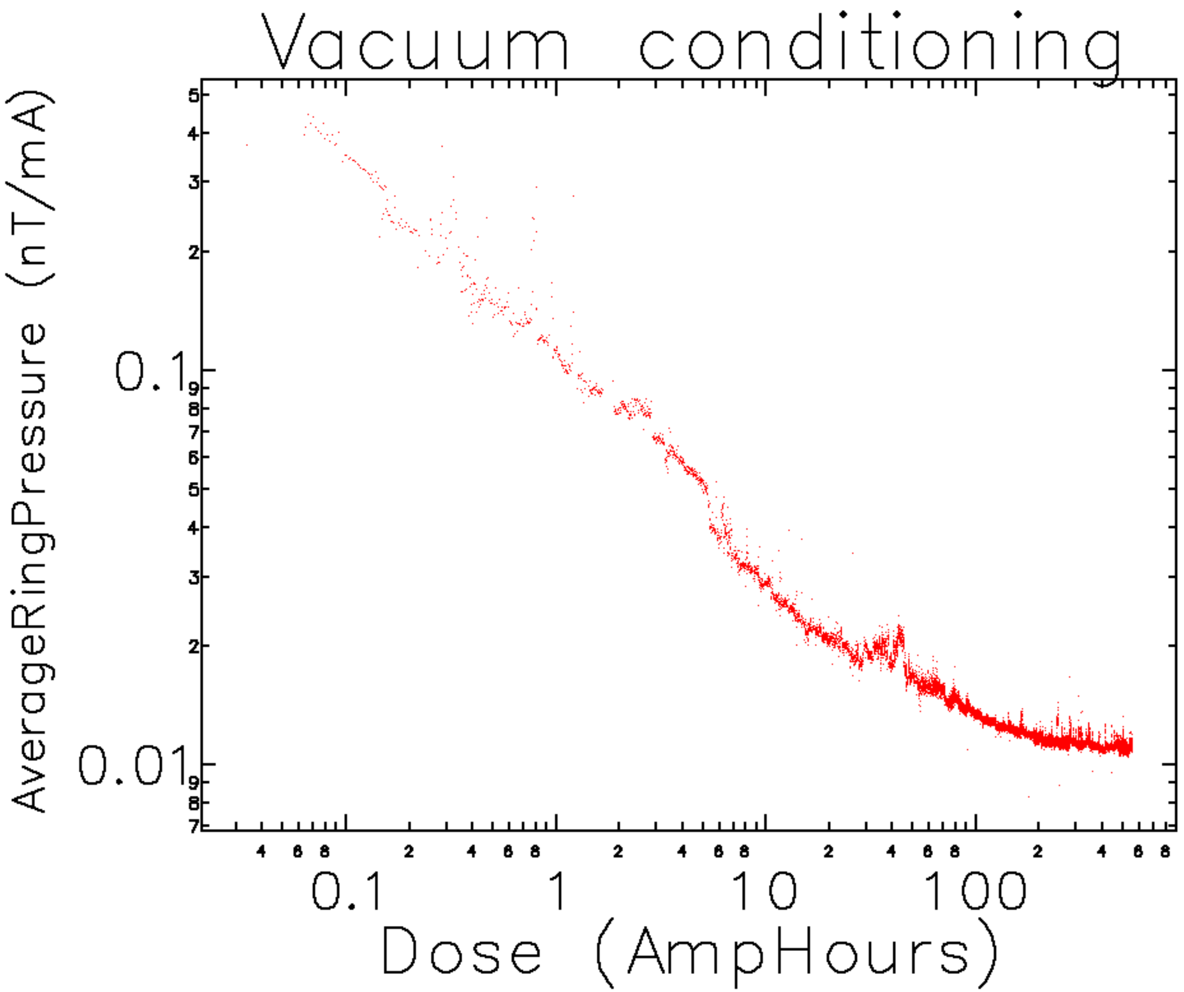
Sample swap-out parameters for 200 mA and 216 bunches

Bunch pattern evolution over 3 hours after fill from zero



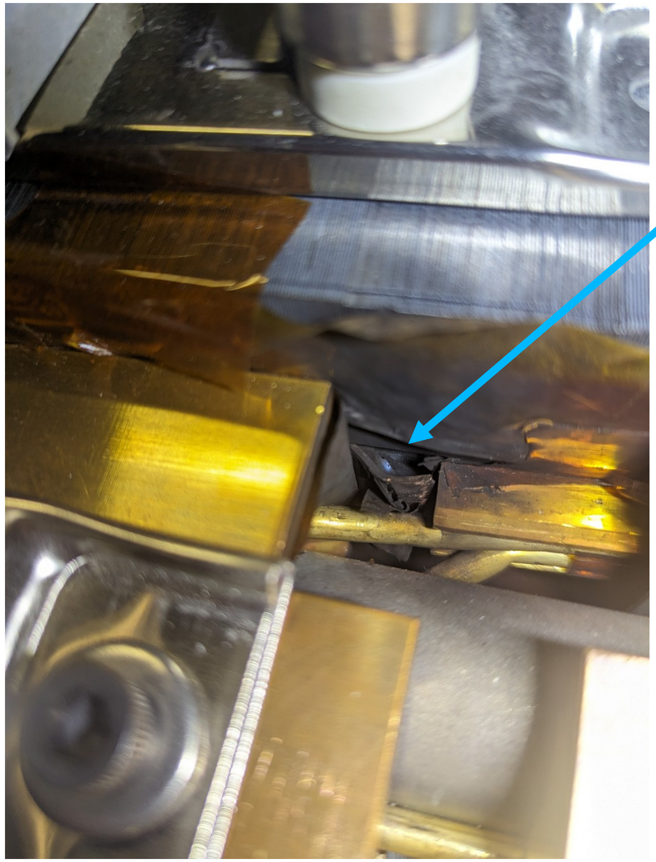
Vacuum conditioning went faster than predicted

- Dedicated vacuum conditioning was performed during commissioning at nights by operators
  - Conditioning shifts started at 10 mA
- Design target is 10^{-11} nT/mA at 1000 A.h dose
  - Reached at ~300 A.h
- Had been operating with several known leaks due to lack of resources
  - Completing of vacuum work at beamlines had higher priority than fixing leaks



SR septum magnet failed twice

- APS-U uses single pulsed septum
  - 1.4 T field, 18 kA current
- A 1-mm thin copper bus is firmly supported along the entire length of the 1.5-m long magnet with the exception of a small 16 mm gap
- On May 2, after ~1M pulses, the copper bus ruptured at the location of that gap
- A spare septum magnet #2 was modified to eliminate the gap in the support and installed; beam was back on May 12
- The septum vacuum chamber sprang a leak on June 2 due to manufacturing defect
- After unsuccessful attempts to fix the leak, the septum magnet #1 was installed back
  - Commissioning continued on June 15
- Magnet #1 is still in operation



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Explanation for large orbit bump around septum was found while installing septum #1 back

- Survey showed that the stored beam tube bowed outward such that its inner surface was touching the design beam orbit ~0.7m upstream of the septum exit (instead of being 3 mm away from the orbit)
- Could not be fixed in place
  - Septum was pivoted 1.5 mrad around its exit to provide more clearance
- A new design for the septum magnet has been developed and the magnet is being built

Horizontal cross-section of the septum magnet