Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

“Injectors” RHIC Retreat 2024

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11/15/2024

@BrookhavenLab

Talk that is

- Polarized protons
  - Polarization performance
  - Skew quad resonance correction commissioning
  - Split/merge user commissioning
- Comments about operation in the injectors

Talks that are not

- No dedicated talks for
  - Separated discussion of proton/heavy ion performance
  - OPPIS status/performance
  - Skew quads (a major new system)
  - Substantial reliability “challenges”

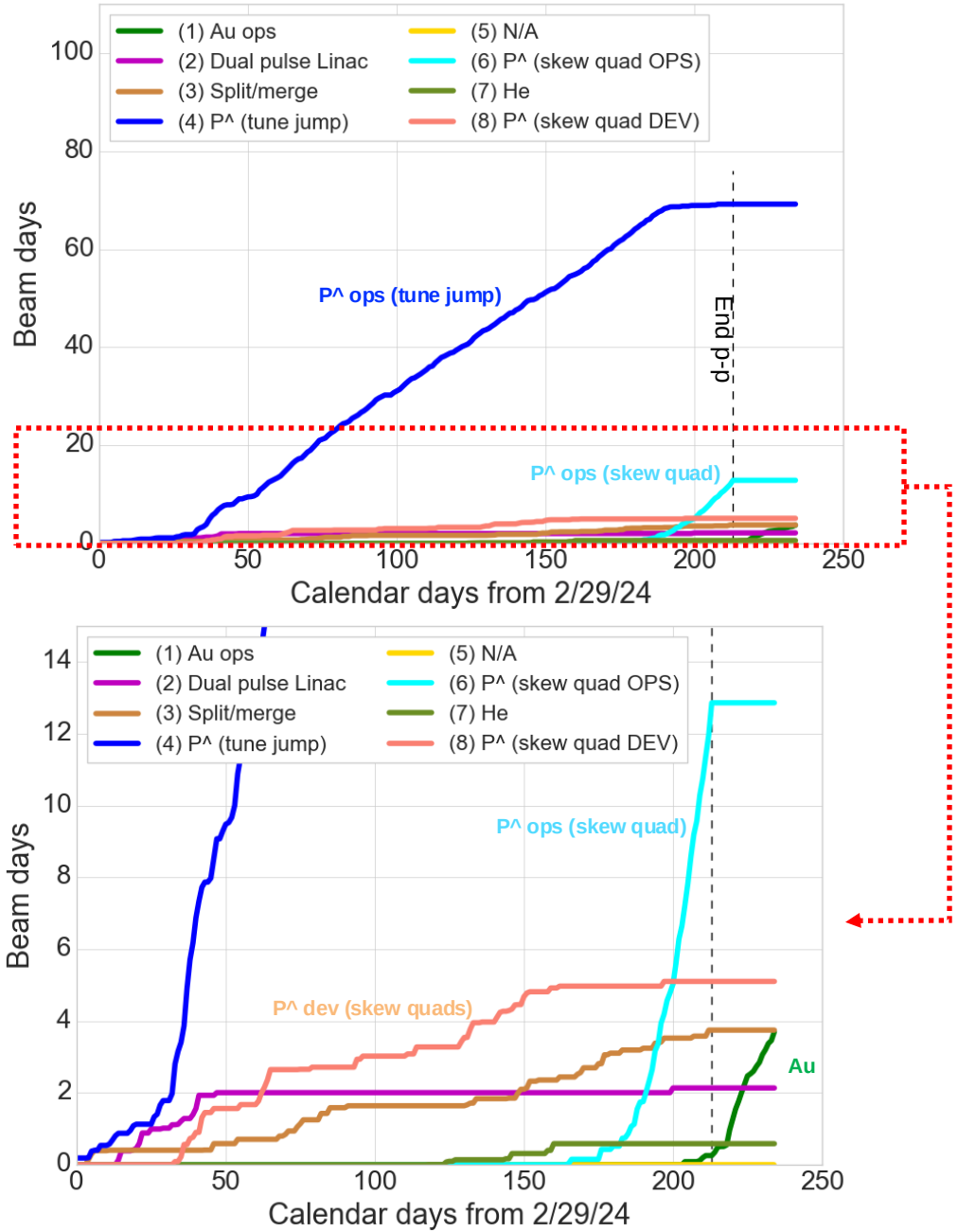
Startup Timeline

- Nominal plan was for 6 weeks AGS startup time prior to RHIC cooldown (normally 3 weeks for p^)
  - Extra time planned to allow for additional skew quad commissioning time
  - Difficulties with OPPIS and cold snake delays polarized operation (and ops with nominal p^ optics) by 3-4 weeks

- March: unpolarized beam commissioning.
  - Split/merge and dual pulse Linac user development
  - Skew quad installation, power supply hookup and beam-based polarity checks
- April: 2 weeks polarized proton setup in AGS (in actuality less than normally planned)

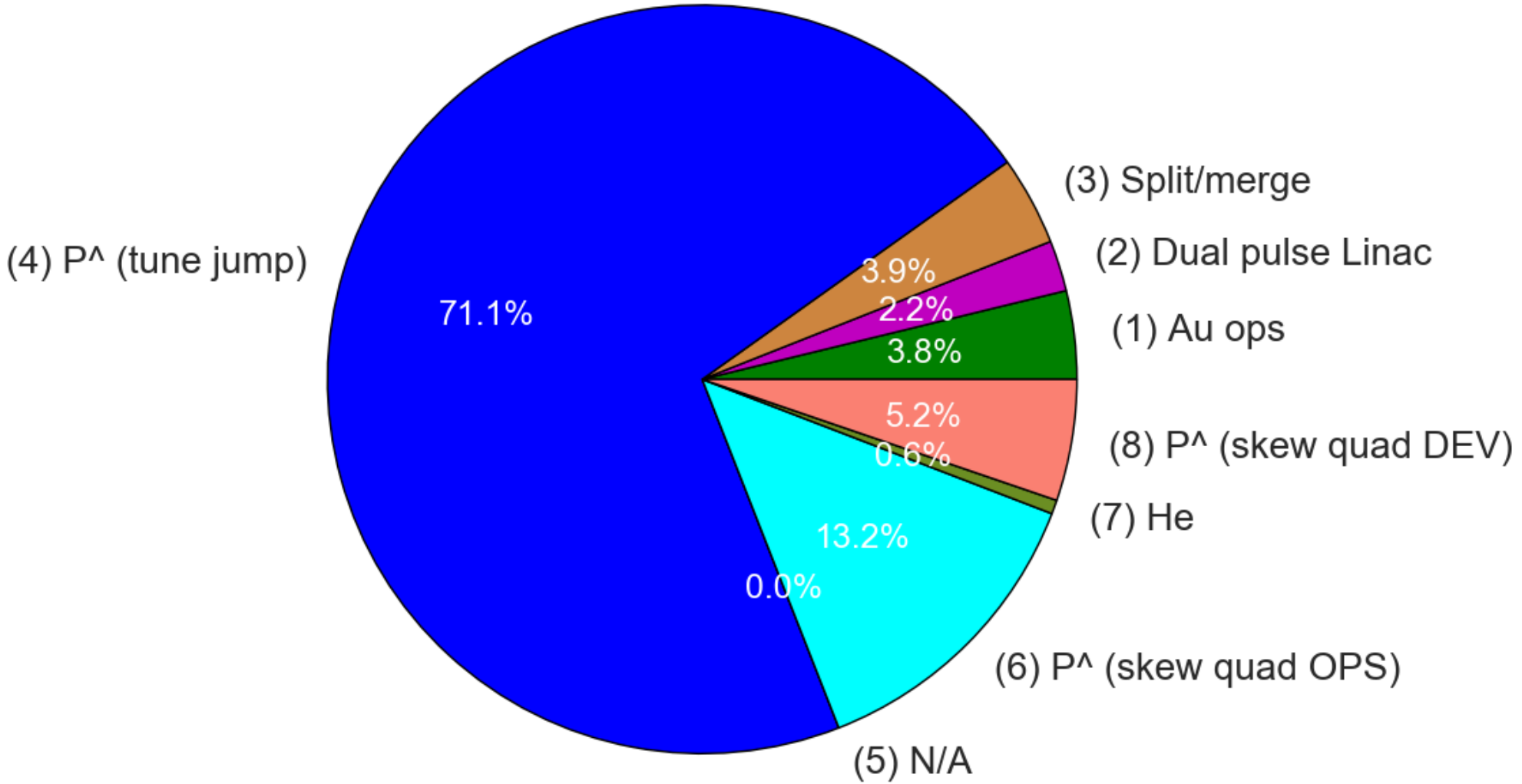
"Beam days" = (# of supercycles with beam in AGS) * (supercycle length in days)

Cumulative time with beam at AGS extraction for each user

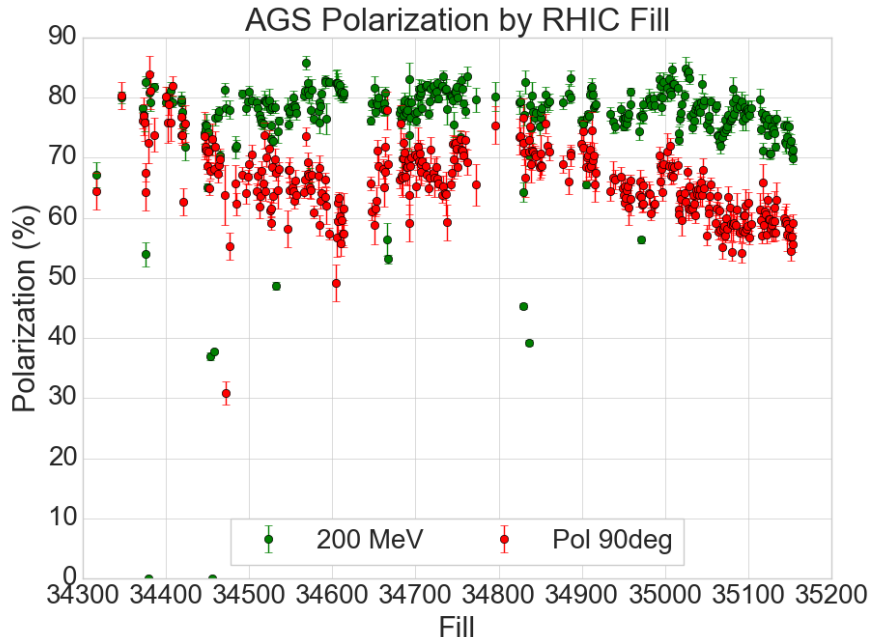


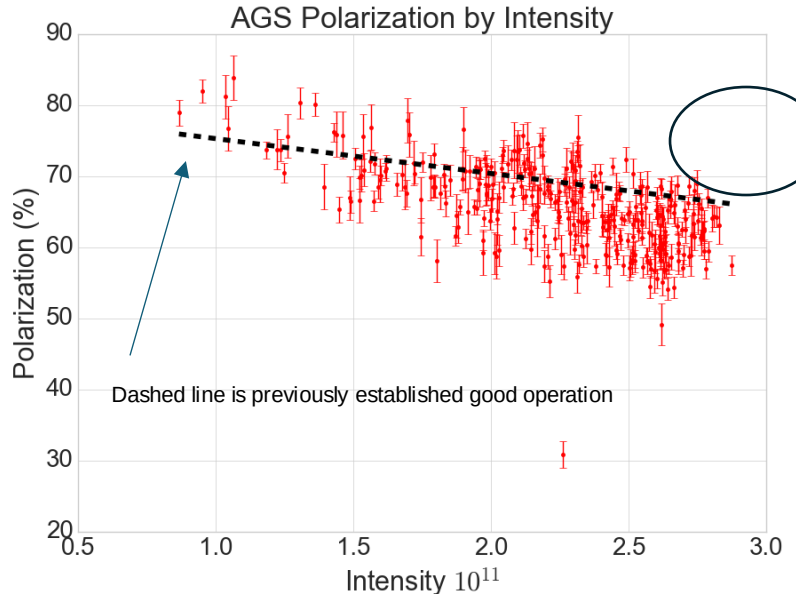
Beam time breakdown

(user number) in parenthesis

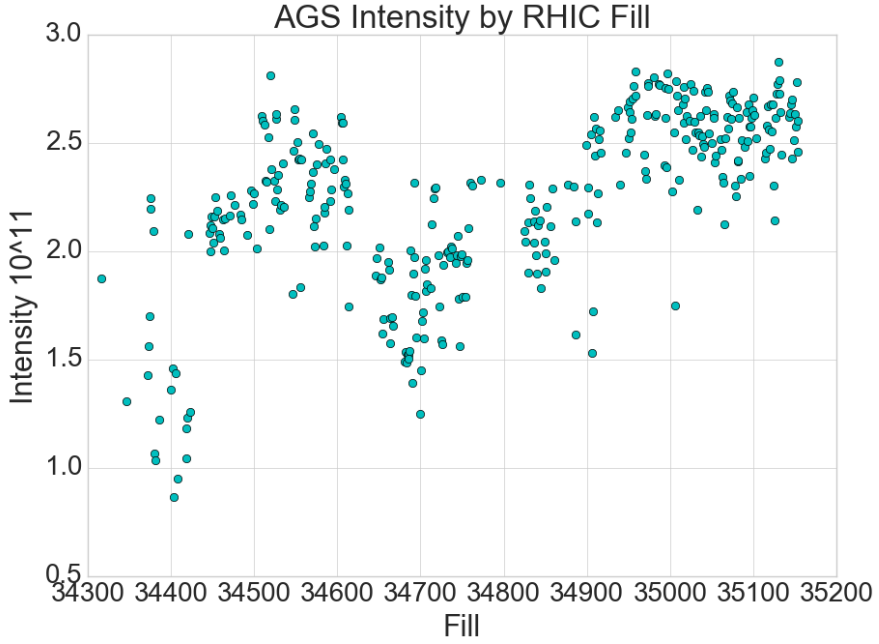


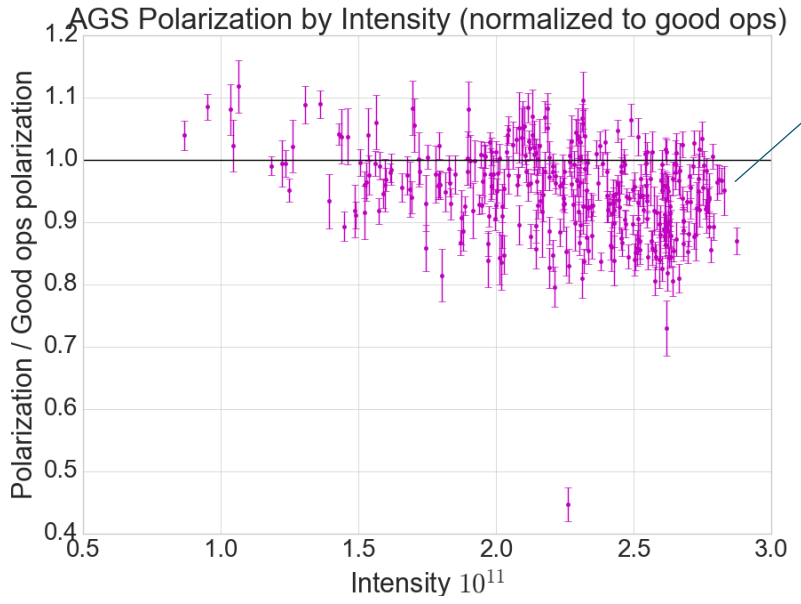
Run 24 Polarization Performance

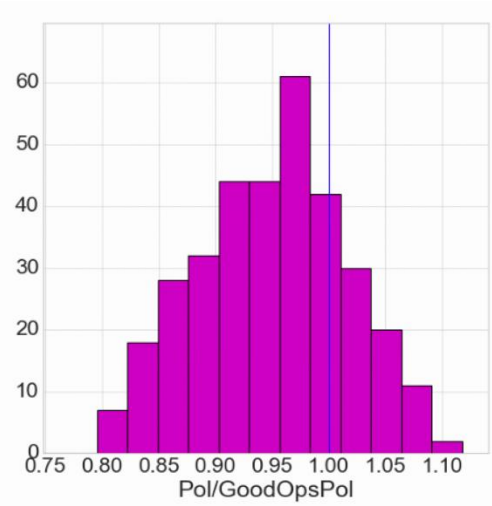




EIC target region







Mean polarization performance Run 24: 95% of established optimum, with a sigma of +/-7%

Source performance/stability

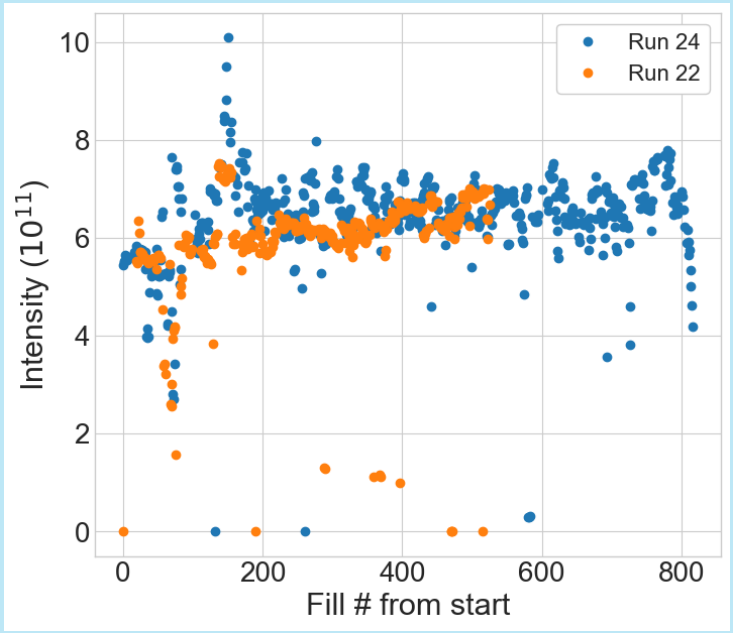
Source intensity comparable to Run 22.

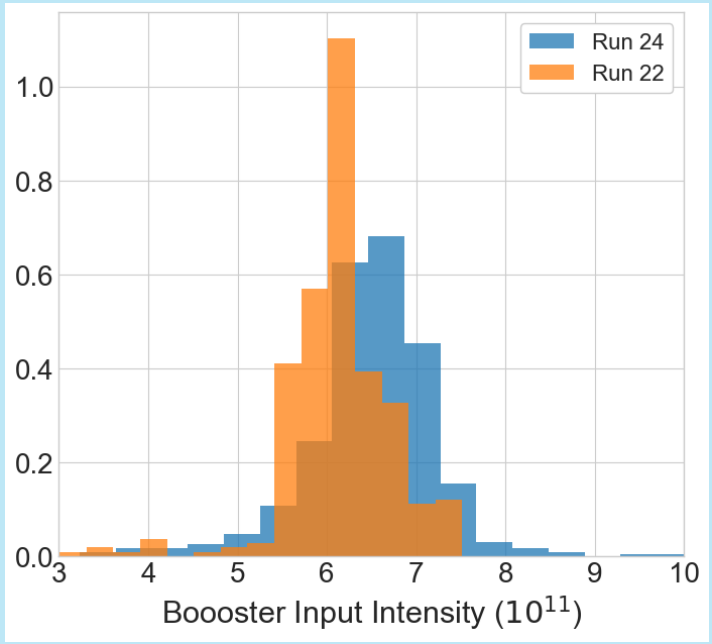
Periodic ~1 wk variation due to Rb fills in Run 24, not in Run 22

Polarization both lower in average (~5% rel) and larger in variation in Run 24, relative to 22

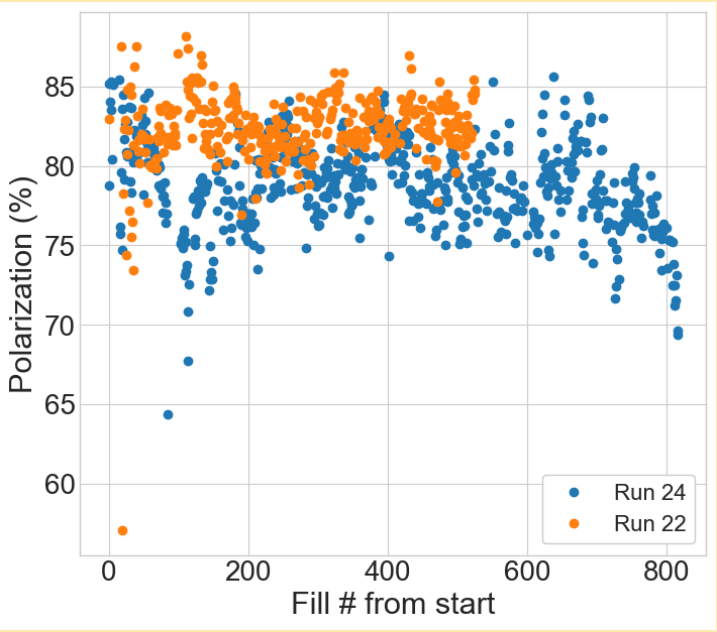
	Run 22	Run 24
Pol (mean)	82.4	78.7
Pol (σ)	2.3	2.8

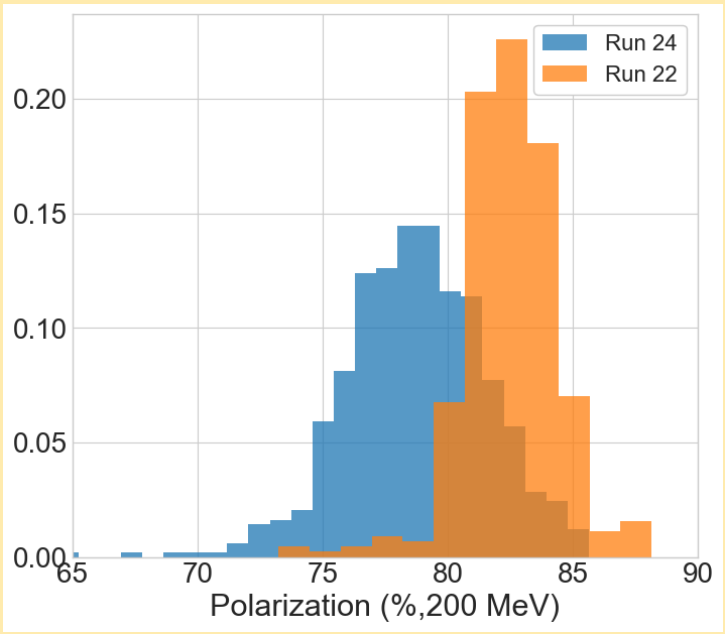
Intensity





Polarization



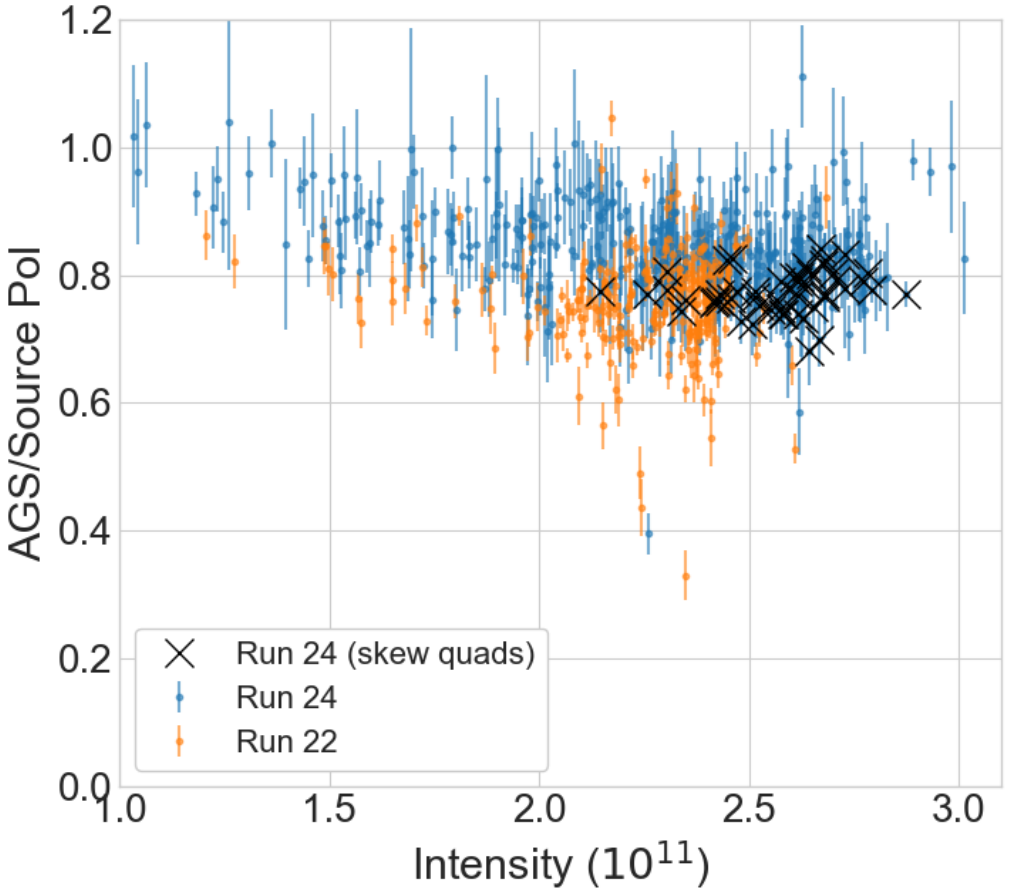


AGS Polarization efficiency
AGS Extraction/Source

Polarization transmission through AGS slightly better than Run 22 over most intensities

Skew quad fills not obviously different from tune jump at the highest intensities

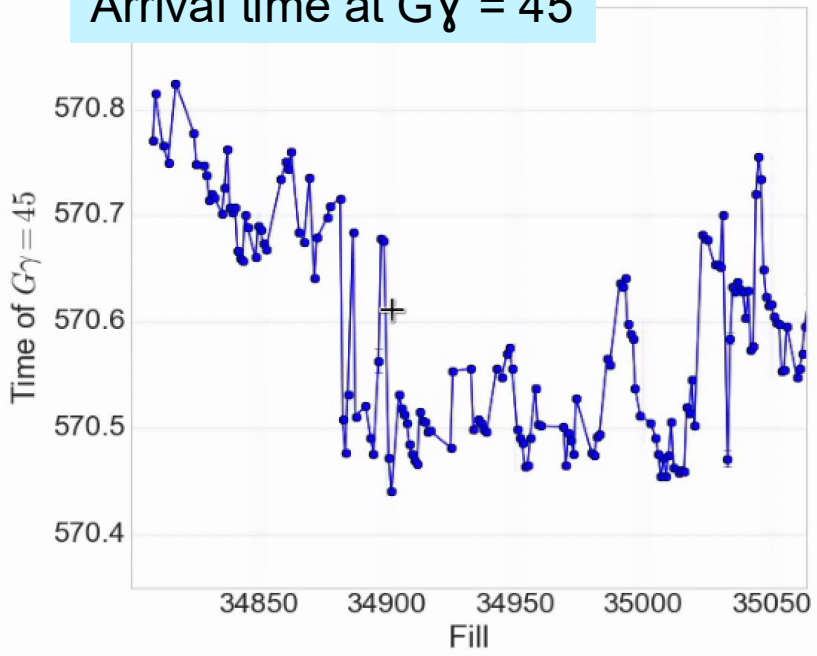
AGS Polarization/Pol(200 MeV) by Fill



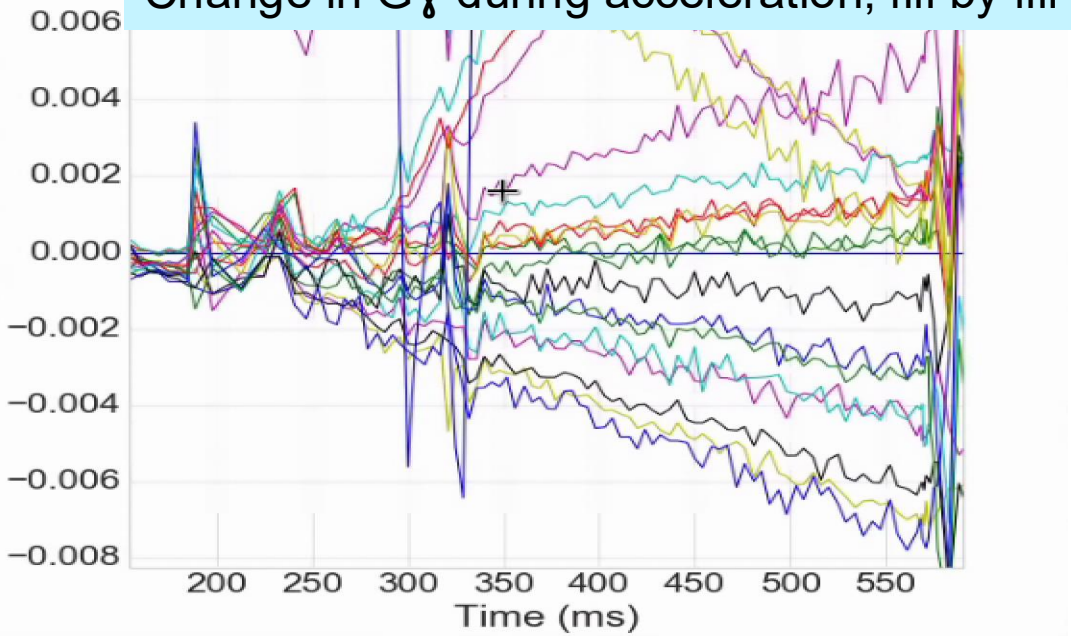
Energy stability

- Slow drift of the energy as a function of time during the ramp
  - For tune jump 100 us is significant, 200 us is bad
  - Tolerance is better with skew quads, but would still prefer stability
  - Injection matching
- Change during a fill is small (drift is ~hours)
- Deviation is often linearly increasing during ramp
- ML project to improve calibration precision, make online continuous calibration and quantify uncertainty
- Conventional analysis of the MM field contribution to this drift
  - We have a slow software feedback for RHIC energy matching
  - Consider developing a system for the whole cycle

Arrival time at Gγ = 45



Change in Gγ during acceleration, fill by fill



Skew quad commissioning

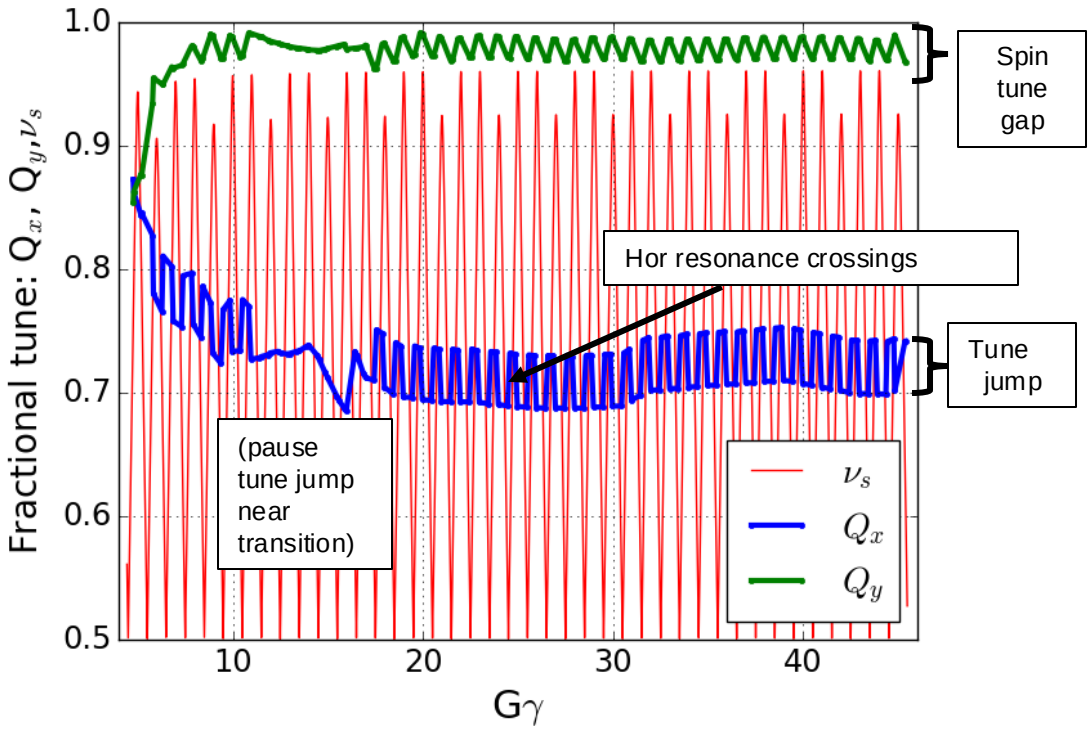
- 15 skew quads in AGS
- Designed to replace and improve upon the tune jump for correction of horizontal depolarizing resonances

- Nov 2023: Magnets #13,14 installed. Final magnet held at power supply vendor for testing

- Nov-Apr 8th: Power supplies delivered and connected in phases
  - Significant ”after market” modifications to each one, mostly to improve p.s. heating
- Mar 5th : First 6 magnets powered, ready for testing

- Mar-Apr: Beam based polarity checks (zero polarity errors), orbit correction

- May 4th: Proof of principle test!
- May-Jun: beam-based tests, interleaved with *a lot* of RHIC setup
- July 29th: First demonstration of ramp effect
- Sep 9th: RHIC operations with skew quad user



~About 20 shifts of commissioning time over many calendar weeks

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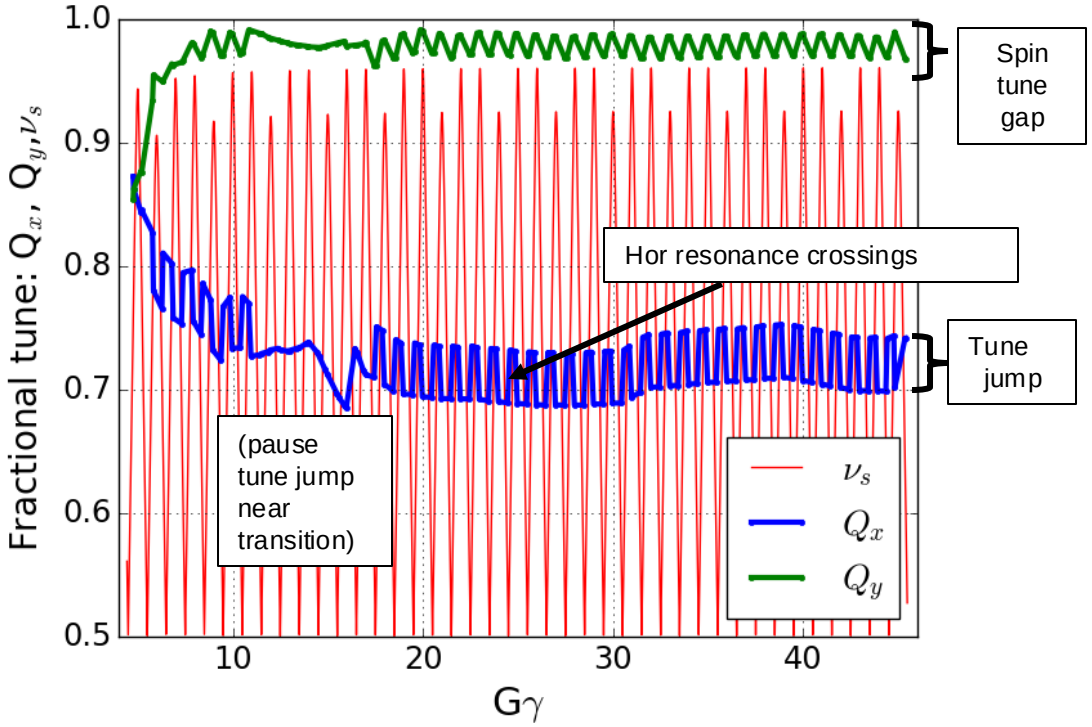


Many thanks to Ioannis, Ed, Chirag and others
Fast development and implementation of changes to the p.s. switching.
ZERO problems operating even in August.

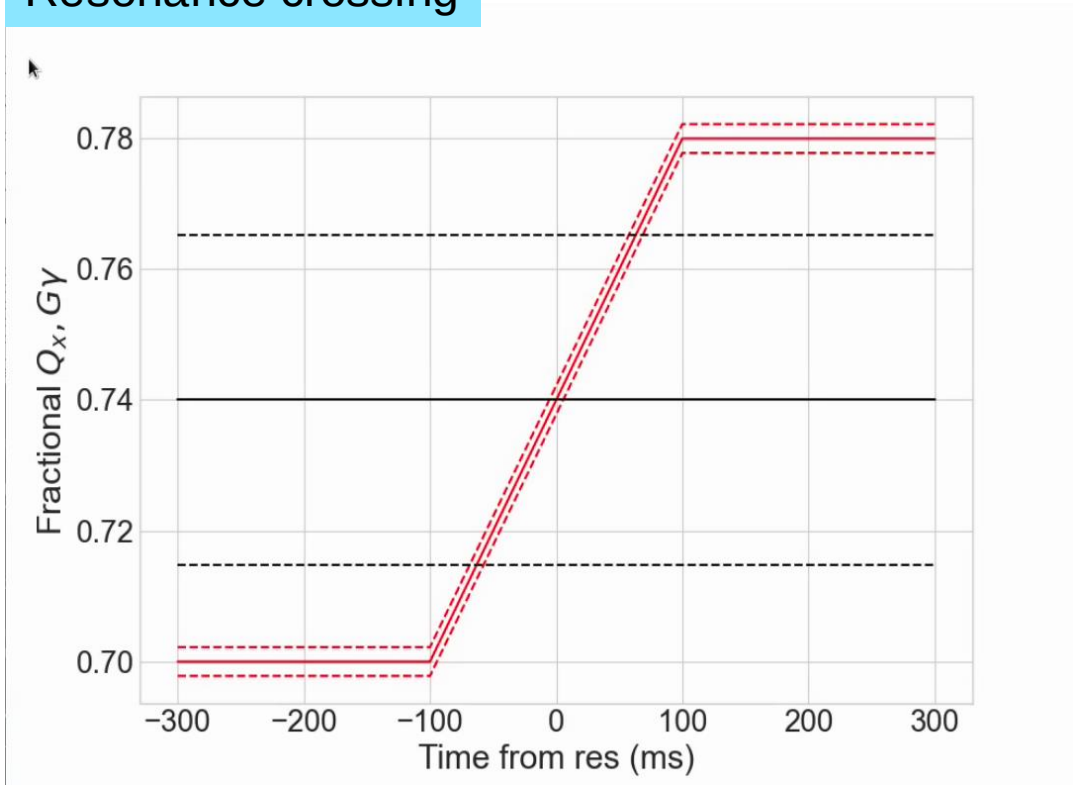
Commissioning: Proof of principle single resonance crossing

- At nominal acceleration rate ($dG\gamma/d\theta = 4.7 \times 10^{-5}$), max polarization loss from a single resonance is 0.1-0.5%
  - too small to to measure individually
- Configure a crossing at fixed energy: just above nominal extraction, with ramped horizontal tune and *very slow ramp rate* (>100x longer)

Parameter	Value
$G\gamma$	45.74
dp/p (full base)	1×10^{-3}
Chrom ξ_x	4
ΔQx	0.08
Tune ramp length [ms]	200
Crossing rate (α)	1.7×10^{-7}

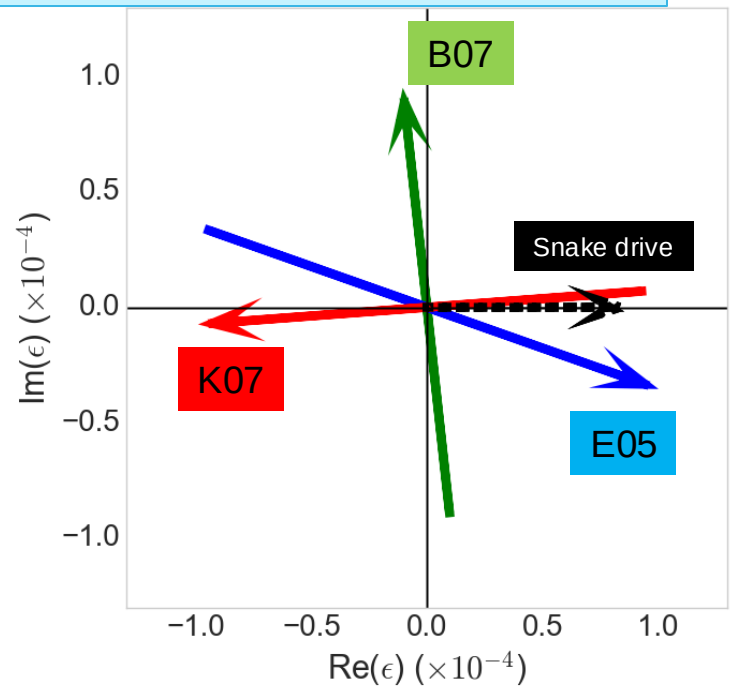
Slow crossing gives measurable 20-25% relative polarization loss

Resonance crossing



Commissioning: Proof of principle single resonance crossing

Resonance ‘portrait’ at Gγ = 45.74

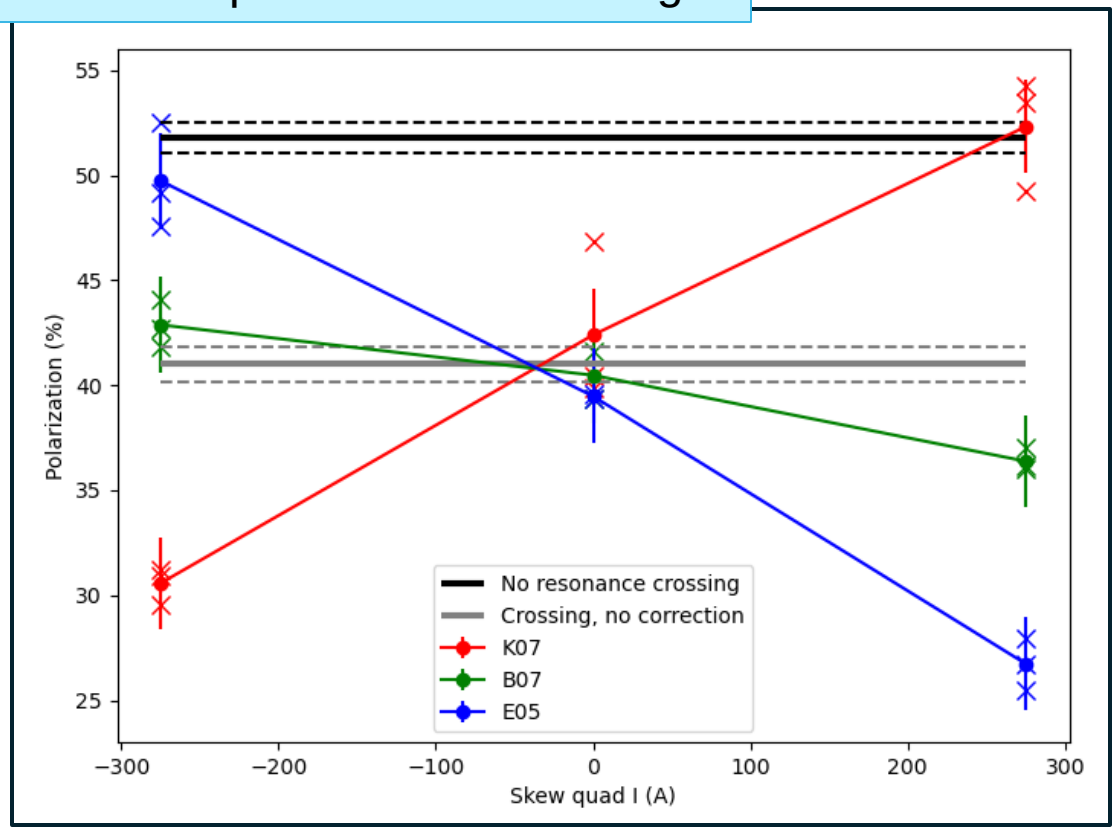


Select three skew quads with good relative phasing

- K07 in phase with snakes
- E05 180º from K07
- B07 orthogonal to snake drives

Skew quad arrow length is full current range of supply (arrow head is positive)

Polarization response to skew strength

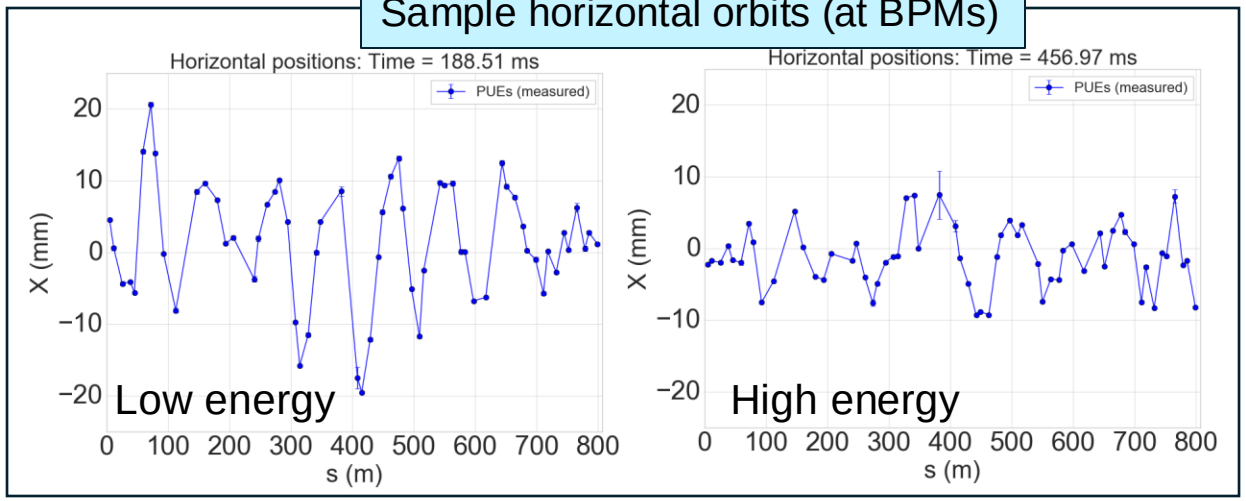


- Phasing of skew quads is as expected
- Demonstration of total correction
- In anti-correcting phase, expect *more* loss from simple Froissart-Stora estimate
  - May be multiple crossings from synchtron motion during long crossing
  - To be investigated in simulation

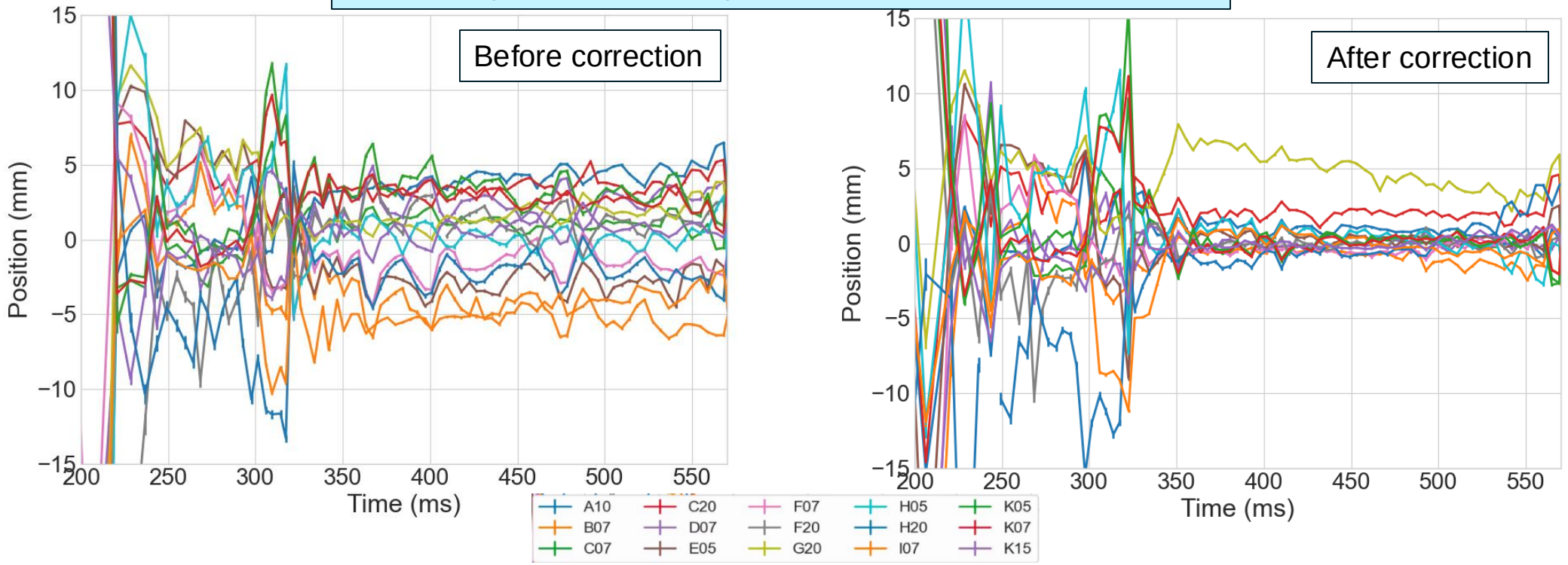
Skew quad during acceleration: Orbit effects

- Large horizontal orbit excursions in AGS
- High vertical tune (8.985 – 8.991)
- Horizontal off-centering in skew quads leads to large vertical orbit changes and beam loss.
- Beam-based orbit offsets measured and corrected
  - Skew quads pulsed, infer offset from vertical orbit change + model
  - Correction limited by weak steering dipoles

Sample horizontal orbits (at BPMs)



Horizontal position at skew quads, inferred from orbit differences



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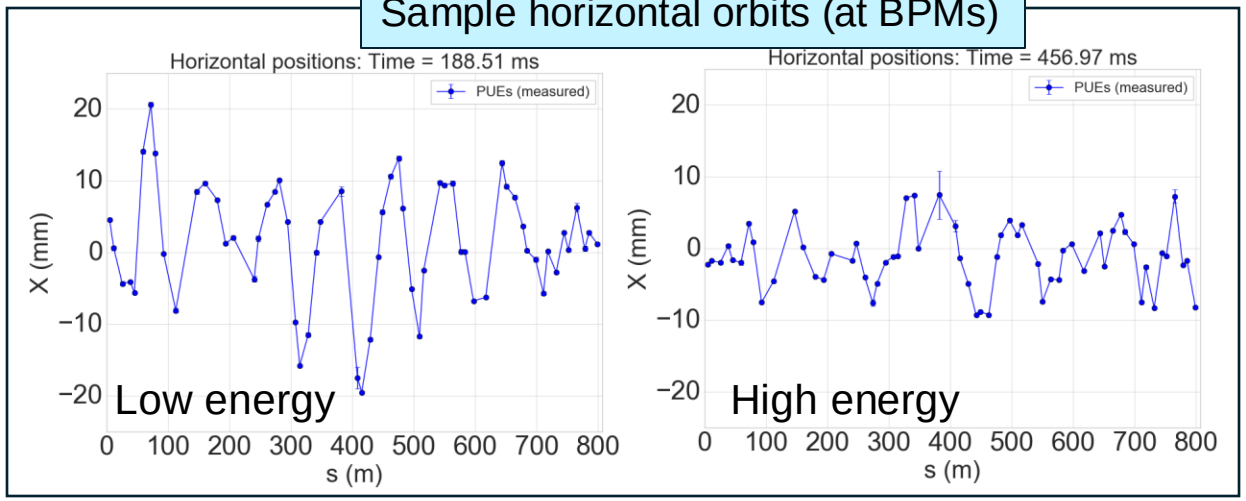

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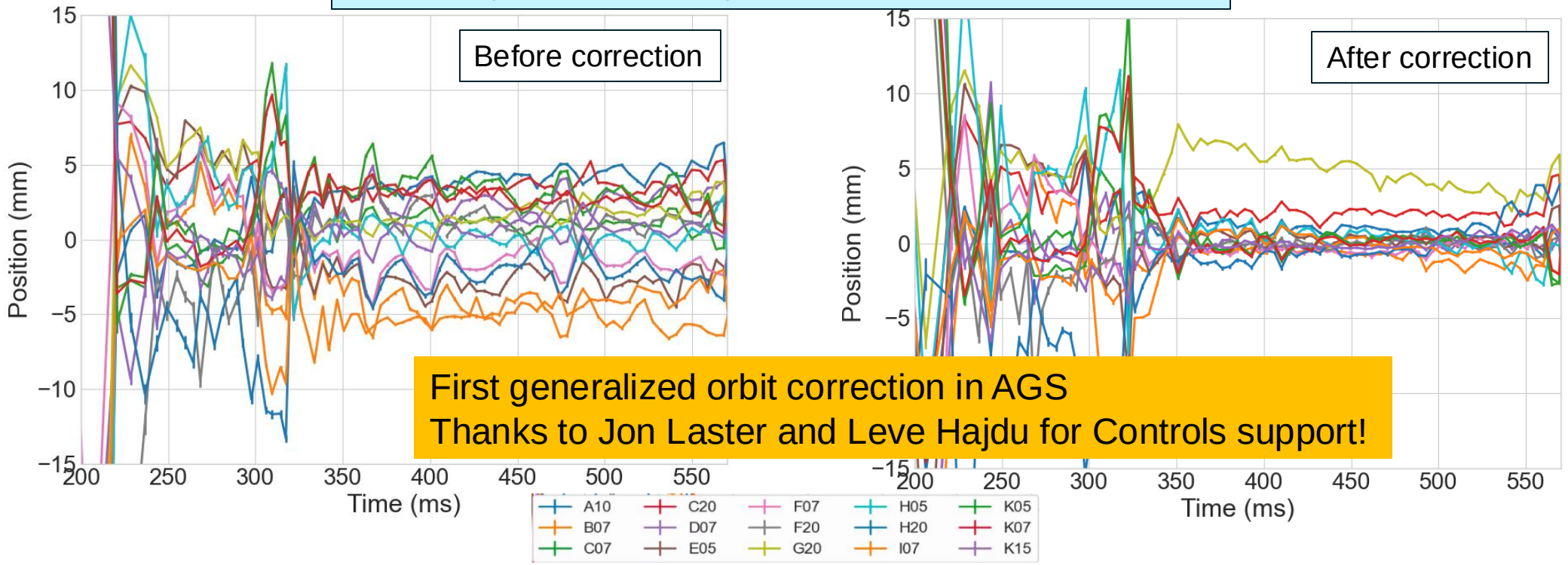


First generalized orbit correction in AGS
Thanks to Jon Laster and Leve Hajdu for Controls support!

Orbit corrector currents

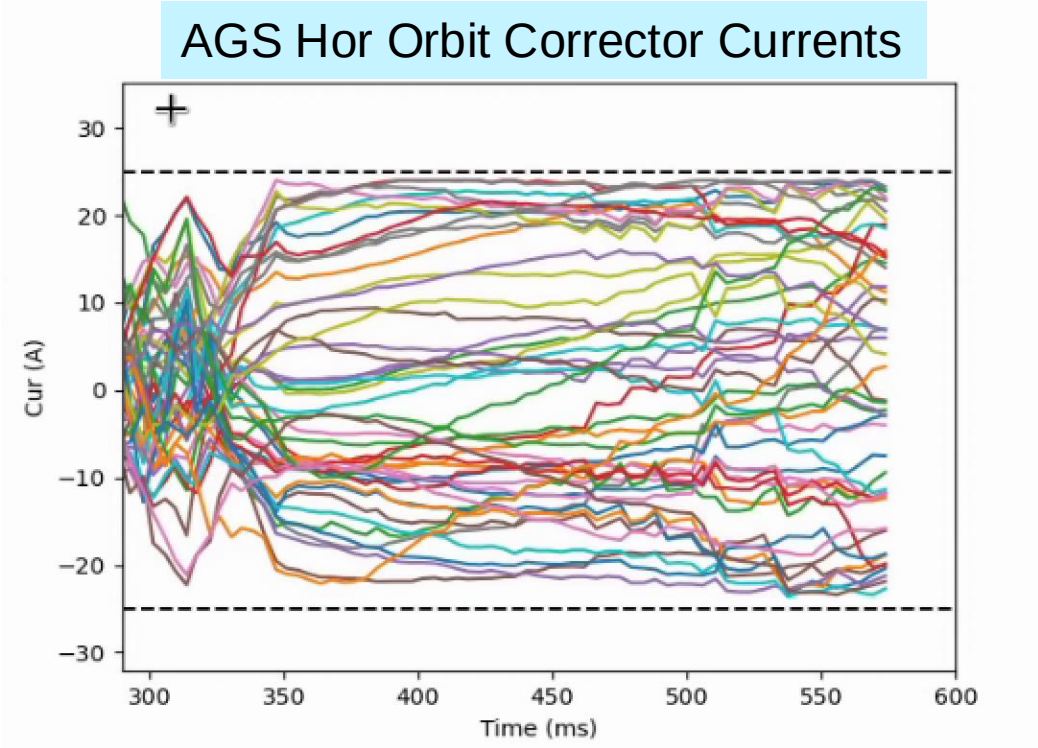
Centering in skew quads requires maxing out some orbit correctors and nearly maxing others

Global correction would require more than factor of 2 higher currents

High currents make each corrector less reliable, more likely to be single point failure.

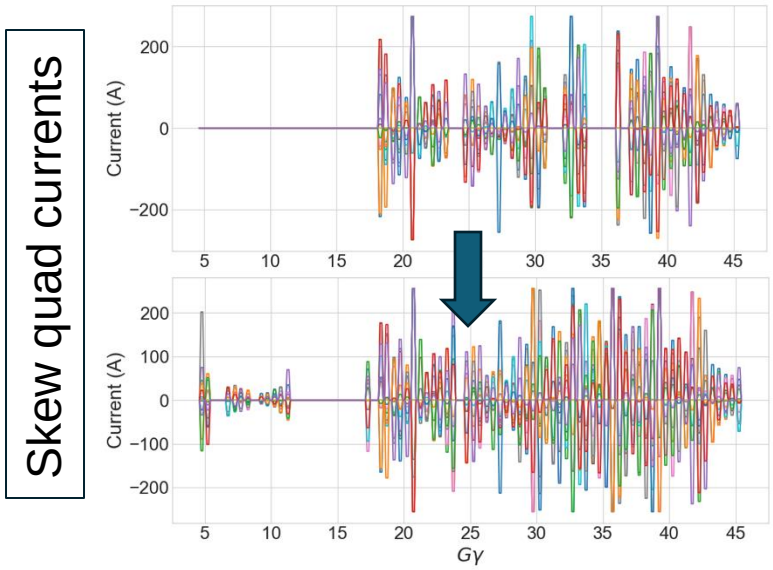
Motivates:

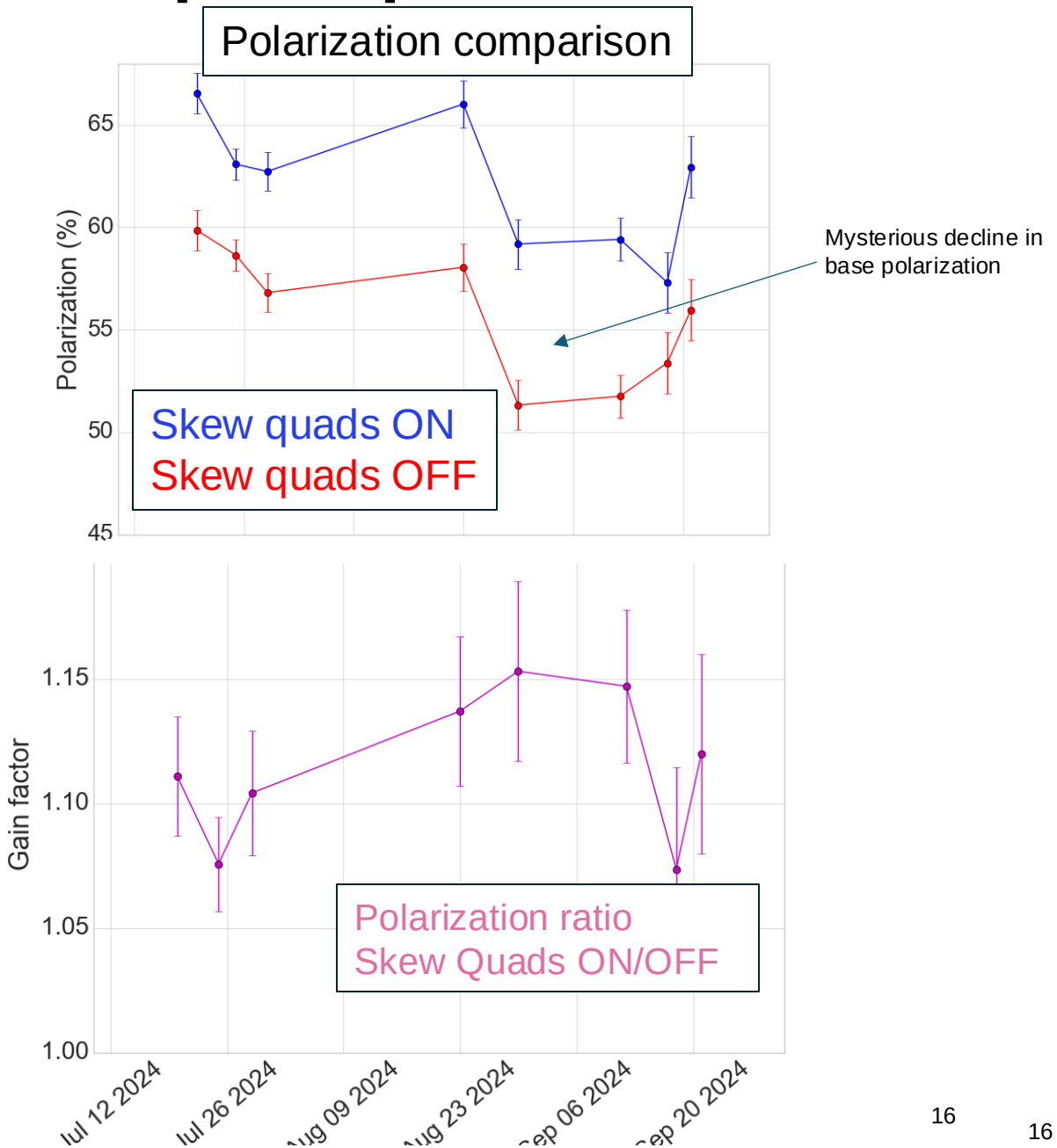
- Survey realignment
- Investigating possibility of upgrades:
  - Stronger correctors
  - Additional correctors (possibly 50% more if adding on at each remaining PUE location is possible)
  - Model/controls work toward global orbit correction



Skew quadrupole commissioning: ramp and polarization

- Enabling more pulses via
  - Incremental orbit improvements
  - Fixing bug in resonance calculation for low energy resonances when Qy not in spin tune gap
  - Included model-predicted orbit response of the skew quads in the optimization to minimize resulting vertical rms
    - Resonance strength, $|\varepsilon| = 0$
    - Tune shift from coupling, $\Delta Q_y < 0.005$
    - Vertical $|M_{orm}*(k_{skew}*x_{skew})|_{max} < 1$ mm





16

Correction scaling measurements

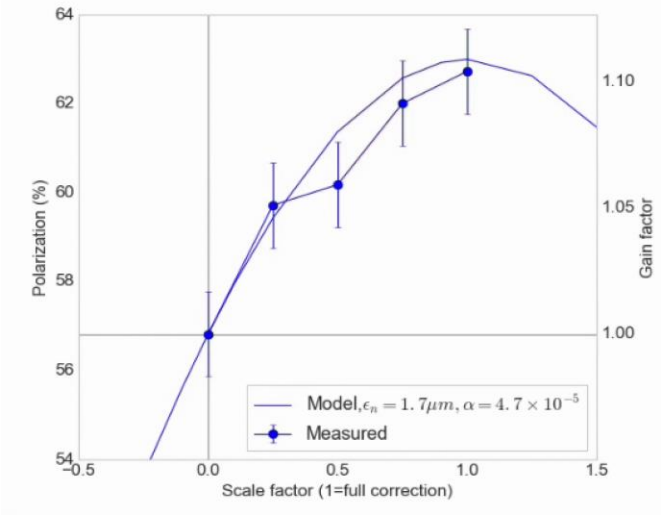
Overall scaling of the correction currents from zero to full correction

Agreement with the model is *better* if only the higher energy (after transition) resonances are corrected

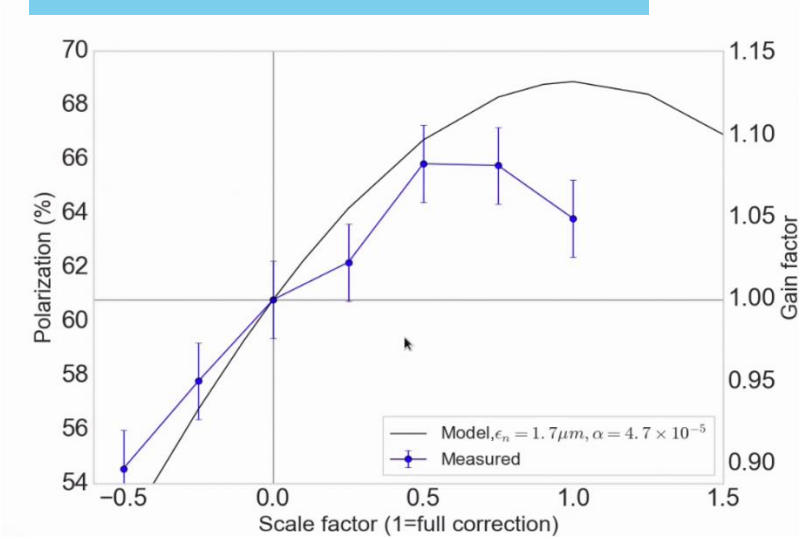
Implies errors in resonance calculation at low energy are still significant

Near 0+ easier to do more harm than good

Correcting only resonance above transition



Correcting only resonance above and below transition



Skew quad status

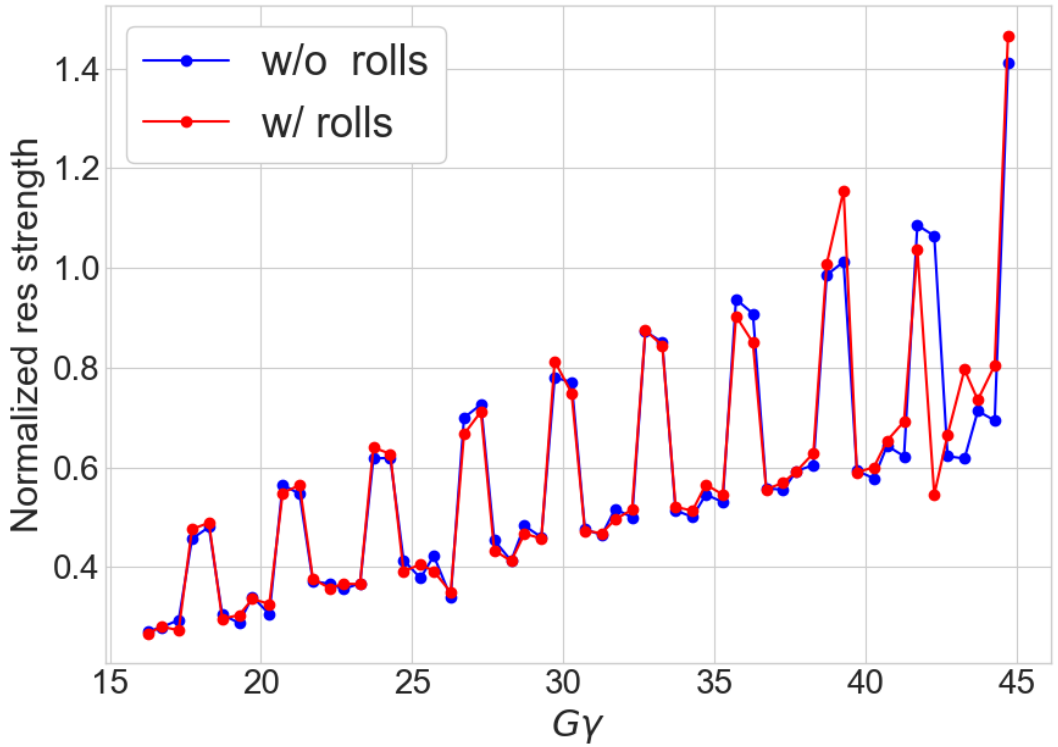
- Commissioning tasks all successful
- Successful demonstration of principle and practical implementation on ramp

- Polarization gain over base is 12-15%.
  - To be compared to 8-10% from the tune jump

- Operation is robust enough to replace the tune jump as the default system

- Where is the rest of the polarization from the skew quads (goal gain factor is 15-20% over base)
  - 1% in the transition ‘gap’
  - Beta beat likely a small contribution
  - Next likely culprit is residual coupling
    - Survey, realignment of AGS magnets planned for next two shutdowns (no alignment before Run 25)
    - Main magnet roll and vertical sextupole offsets of principal concern

Resonance calculations with 2010 main magnet rolls



Small impact at high energy
Working on the low energy model

Split/merge setup

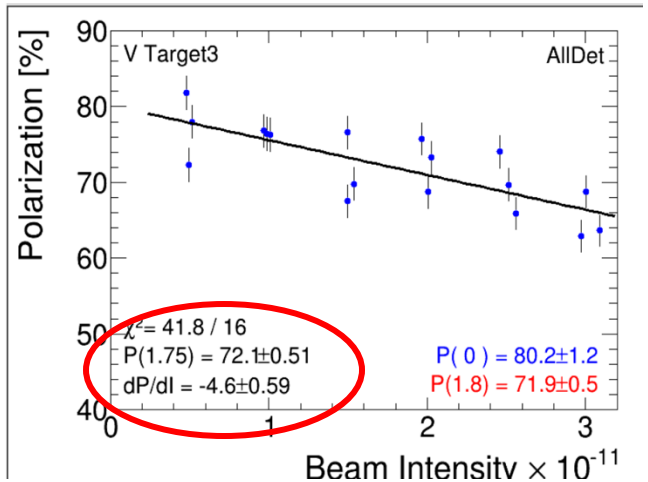
Aimed at reducing space charge at AGS injection

Value @ $3x10^{11}$	Single bunch	Split/ merge
Pol (%)	66.4	67.3
Emit hor	3.1	2.6
Emit vert	3.2	2.7

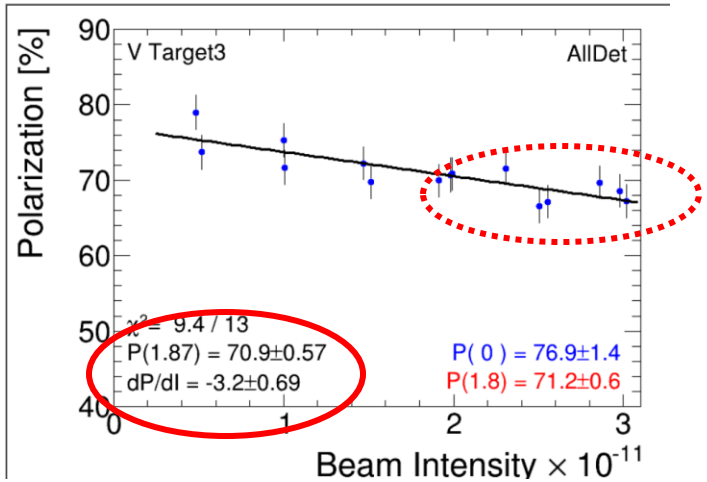
(emit is rms, norm, urad)

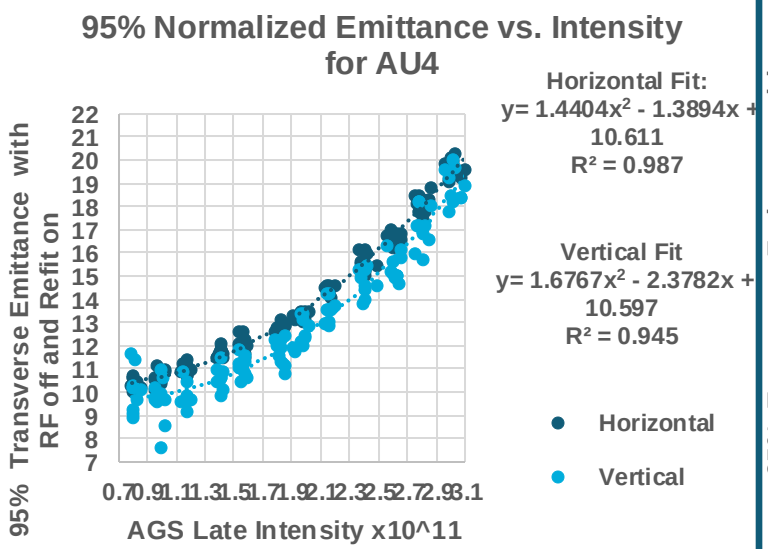
- Slope dP/dI is less
- Emittance is 15% smaller
- Polarization is only slightly changed (?!)
- Seem associated with the P(0) offset: normally associated with Booster or source
  - *Not so sure this interpretation holds up*
- Long emit is ~1.2 eVs (+20% from nominal)

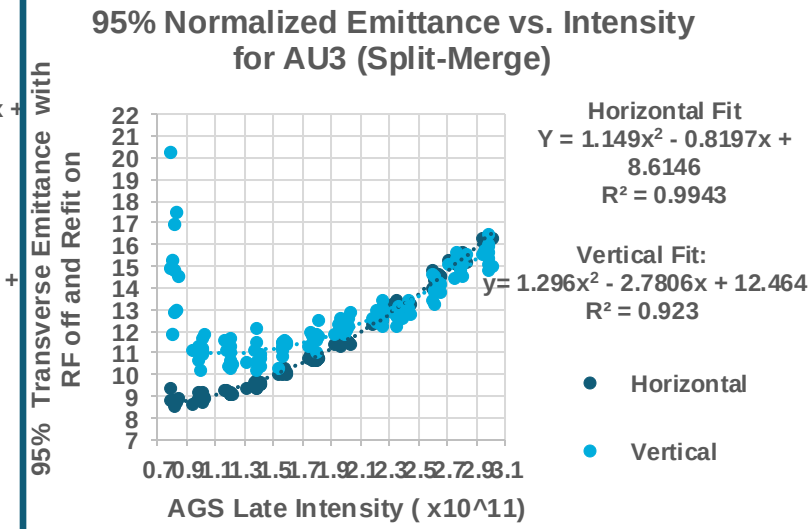
Nominal user (single bunch)



Split/merge



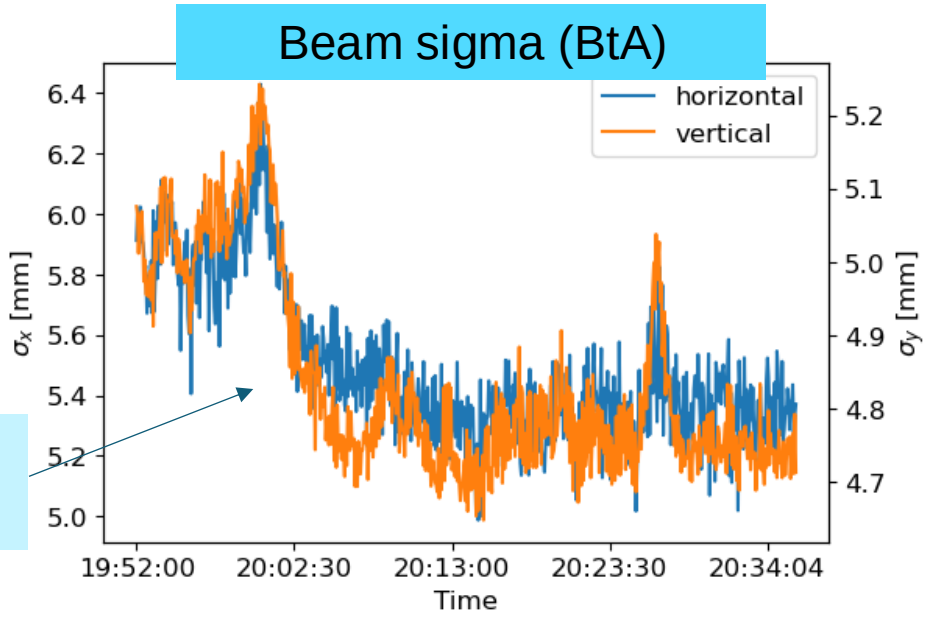




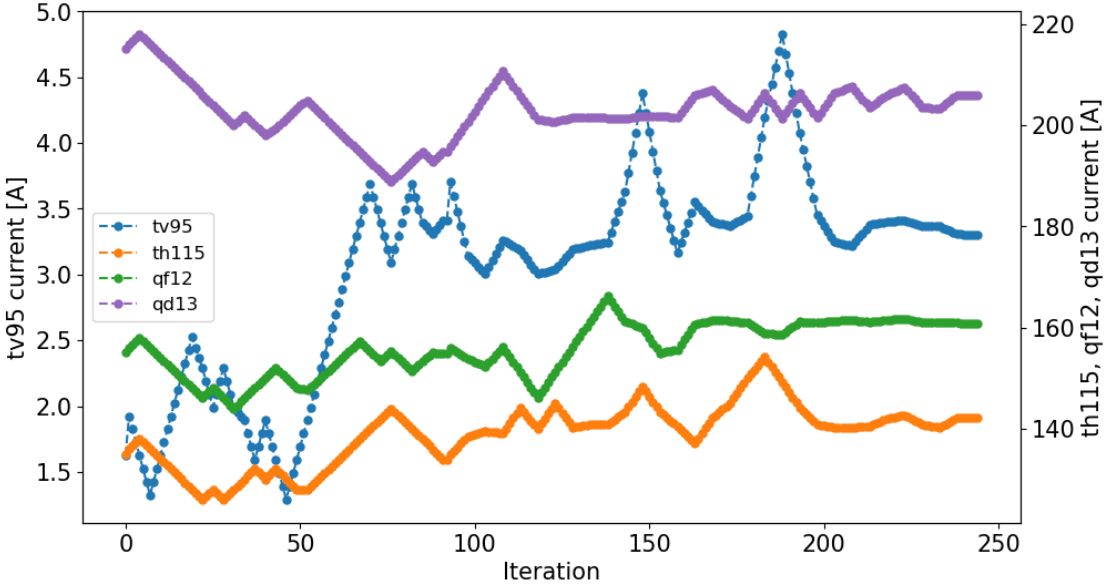
LtB Injection Optimization with ML (Lucy Lin)

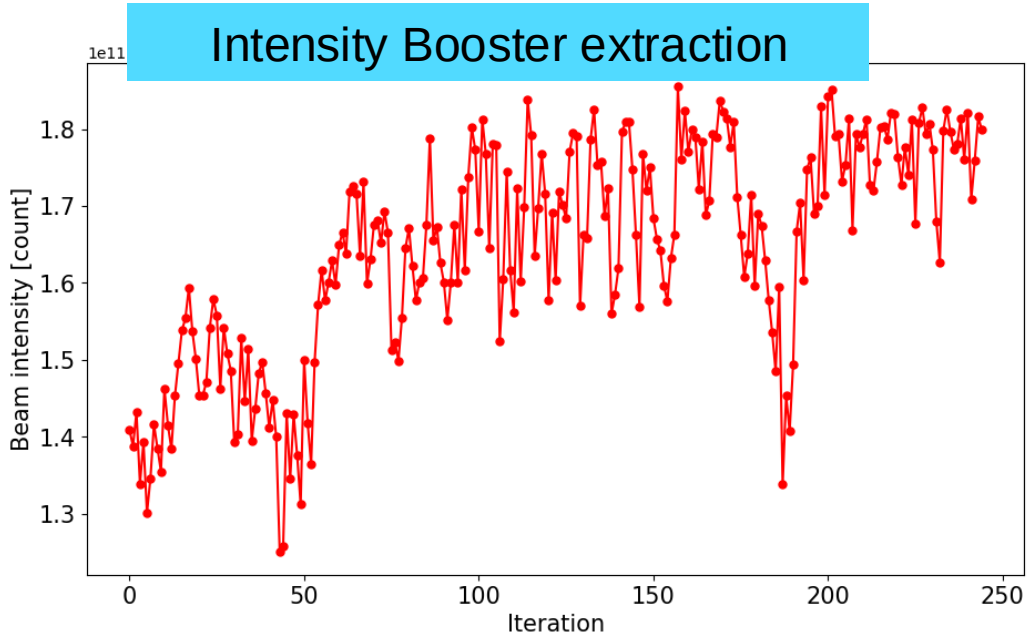
- Demo on intentionally detuned LtB
- Bayesian Optimization algorithm automatically maximizes Booster beam intensity using LtB optics
- Higher intensity after fixed scrapers → smaller beam size → higher luminosity $\mathcal{L}$
- Beam size decrease observed in both planes in the BtA line corresponds to intensity increase
- Similar algorithm under development for AGS injection
- Minimal model inputs
- Likely to help better maintain previously achieved optimum

Not an explicit objective, consequence of improving scrape efficiency



$$\mathcal{L} \sim \frac{N^2}{\beta^* \varepsilon} \sim \frac{N^2}{beam\ size}$$





Injector physics and operations

The number of people who can work independently with beam in the injectors is small

- Run 11/12: Commissioning of the tune jump (last major commissioning effort)
  - Leif (Gg-meter), Woody (power supplies), Yann (physics/simulation), Haixin (polarimeter analysis/data)
  - Nick T, Kip, Mei, Steve T, Francois, Thomas Roser, Vahid, Vincent, Keith Z
  - 13 people (11 shifters, Keith and Thomas)

- Run 24:
  - Vincent (skew quad commissioning)
  - Keith (*entire* split/merge and dual pulse configurations, little/no physics involvement)
  - Kiel (Run coordinator), Haixin (polarimeter scans/data)
  - 4 people

- Limited expertise has consequences:
  - Beam time in injectors is ‘opportunistic’, with a broad field *someone* can use it when it arrives (not true if half the injector group is the run coordinator)
  - Limited attention: Every small “fire” stalls the main efforts
  - Have not raised levels of automation/robustness commensurately with decrease in personnel (many systems that ran on continuous attention and good will now don’t) (e.g. I did not commission the two new AtR cameras) “The inheritance problem”
  - The Run 24 operation+development effort really strained our abilities to keep up
    - Is the current level of support really sufficient to commission an entirely new polarized species? (3He, ~5-6 beam months of 24/7 work identified).

Reliabilities and Capabilities

- OPPIS
  - Periods with unpolarized beam tolerable this year because so sPHENIX priorities
  - Need to re-establish lines of communication
    - Used to have agreements with ops about Intensity/Rb temp control to smooth out intensity

- AGS Cold snake
  - Similar: periods with unpolarized beam not counted as ‘failure’ because of unique operating concerns
  - Example of Injector group comfortably accepting reduced capability
    - Ramp down now significantly longer: impacts p-Au operation and development efforts (we fill Au first at least….)

- AGS Extraction bumps
  - Workaround for one failed supply
  - These supplies specifically identified several years ago by operations as a weak point for diagnosis of problems

- AGS Tune Meter
  - 1 week failure
  - On the short list for RHIC->EIC “Middle Ages” overhaul
  - Example of getting a capability back after >10 years (independent plane control of kick strength)

- Multiple multi-hour repair accesses one weekends
  - Not counted as failure, so largely unnoticed
  - Not indicative of general reliability

Bottom lines and outlook

- Injectors delivered physics for RHIC operation together with two commissioning efforts
- Skew quadrupole resonance correction
  - mature enough to replace the tune jump in future operation
  - Better gain factor relative to tune jump
  - Improvements
    - understanding residual coupling in AGS important
    - Model of realistic AGS (with errors) , especially low energy
    - Correcting near transition energy
    - Survey and alignment of AGS (not for Run 25)
- Split/merge
  - Demonstrated -15% transverse emittances at $3x10^{11}$
  - Small improvement in polarization (might be offset from other sources)
  - We still don't understand the emittance evolution in the injectors
    - Space charge/emittance evolution needs a fairly sustained campaign of physics simulations/measurements
    - Including everything one would do for a new machine: magnet errors, impedance models etc.

- Future operation could start day 1 with a split/merge + skew quad correction setup

- Gold is fine. See EBIS talk.

Skew Quad Special Thanks!

Engineering,Design and Installation Team
George Mahler, Ioannis Marneris, Nicholaos Tsoupas, Richard Lynch, Viorel Badea, Dan Lehn, Jimmy Meier

Equipment all worked 100% as expected!

"**Making it Happen**" Award

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