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U.S. DEPARTMENT OF ENERGY

Polarization increase with AGS skew quads in Run 24

V. Schoefer for team

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RHIC Machine Advisory Committee, Dec 16-18th

Overview

- Principle: Horizontal resonances in the AGS and correction with skew quads
- Installation, equipment checkout, early commissioning overview
- Proof of principle experiment
- Commissioning
  - Orbit effects
  - Polarization impact
- Future work

Polarized Protons in AGS

Polarization is preserved in the AGS with two partial helical dipole snakes (10% and 6% rotation)

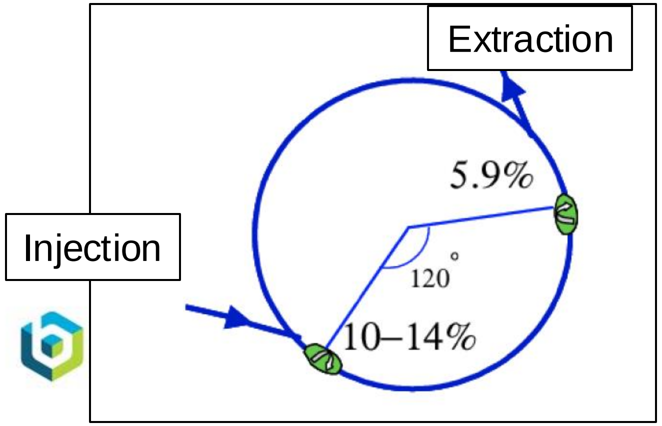
Provides spin tune 'gap' where imperfection and vertical intrinsic resonance condition are never met

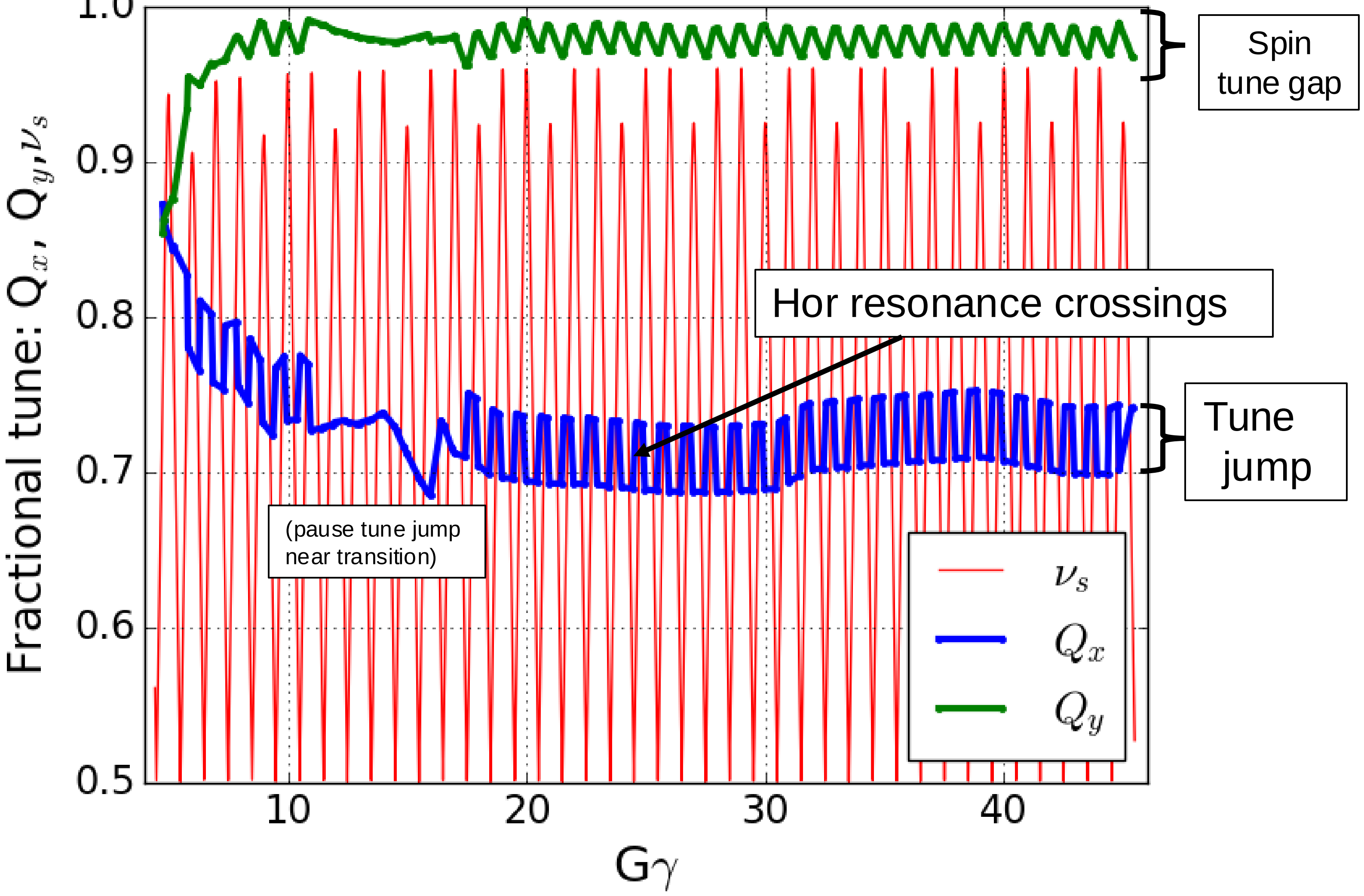
- $\nu_s \neq N$ (full spin flips)
- $\nu_s \neq N +/- Q_y$

Horizontal resonance condition still met

- $\nu_s = N +/- Q_x$
- Horizontal resonance are weak, but many (82 crossings)
- Currently handled with fast tune jump

  $\Delta Q_x = 0.04$, 100 μs





Partial snakes drive horizontal resonances

Simple case (one partial snake)

Spin motion consists of

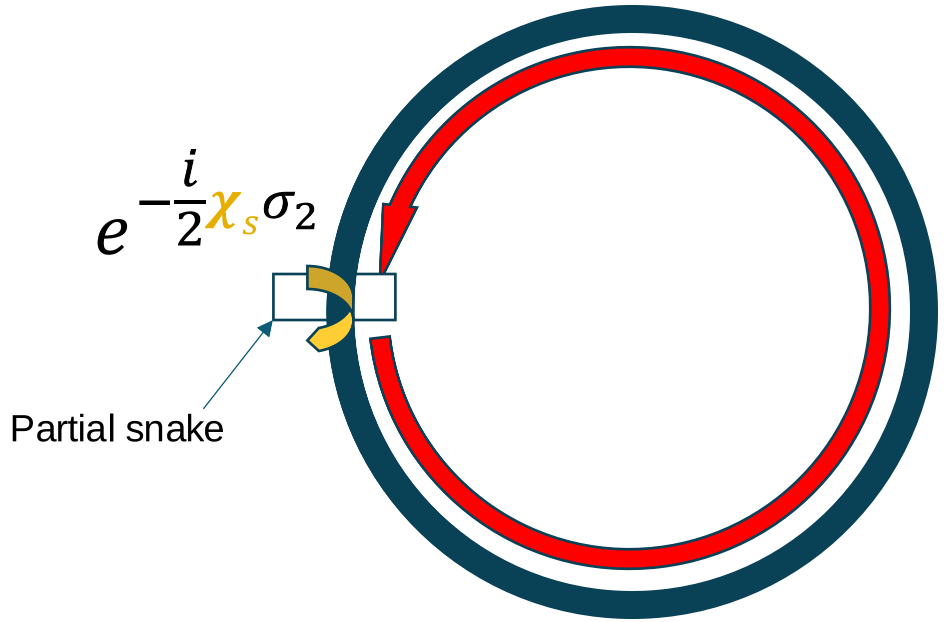
1. Spin rotation about longitudinal by angle χ_s
2. Design particle spin precesses about vertical by $2\pi G\gamma$ from main bend
3. From horizontal betatron motion, extra precession angle $(1+G\gamma)\Delta x'$

The horizontal betatron motion modulates the spin precession phase at every snake transit at Q_x producing sideband resonances at

$$\nu_s \cong G\gamma = N +/- Q_x$$

"Toy AGS ring"

$$e^{-\frac{i}{2}\chi_s\sigma_2}$$



$$e^{-\frac{i}{2}\left(2\pi G\gamma-(1+G\gamma)\Delta x'\right)\sigma_3}$$

$\Delta x'$ = the one-turn change in betatron angle

Same as resonance condition from betatron coupling
Can introduce coupling to exact cancel snake term

Motivation

- Tune jump increases polarization 8-10% (relative to uncorrected)
  - Simulation indicates this is about half the polarization lost to horizontal resonances
  - Tune jump is 100 µs long: requires precise timing, subject to drift

- Skew quad correction
  - Full cancellation of snake resonance drive with coupling resonance drive 15-20% (relative to uncorrected)
  - Correction active for ~1 ms, more tolerant to timing (energy) error

MAC-20 (Dec 2023) Recommendation R6

1) After applying the overall scaling of the correction, polarization measurements should be performed at several intermediate energy steps where the largest polarization losses are expected. In addition, horizontal spin resonance driving terms should be measured at these intermediate energies.

Single resonance crossing at one intermediate energy accomplished (see later slides). One other energy attempted ($G\gamma = 35.26$) – setup had very low baseline polarization. Not enough time to repeat. Useful effort, to be revisited.

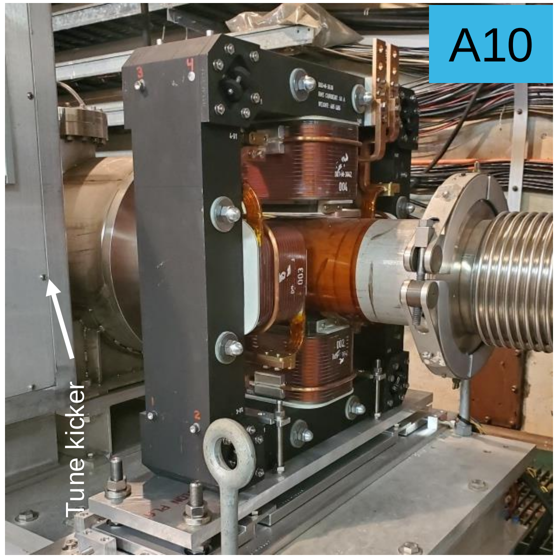
2) Study remaining sources of depolarization by weaker higher order snake resonances or weak hybrid resonances.

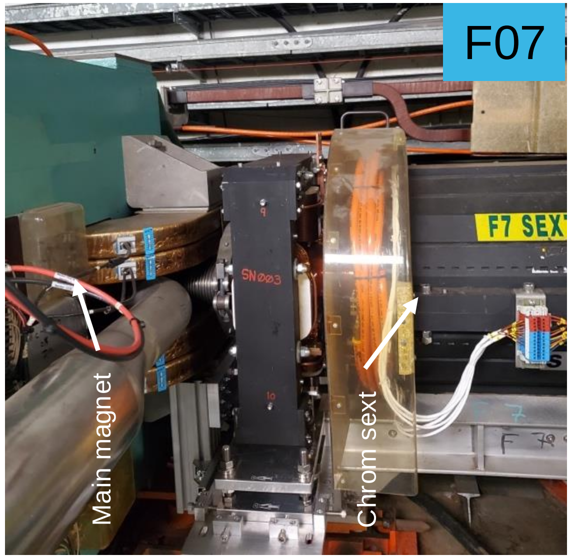
Mostly preliminary progress in setting up a Bmad model with full snake field maps, working toward including realistic errors. Not discussed heavily here.

Magnets and locations

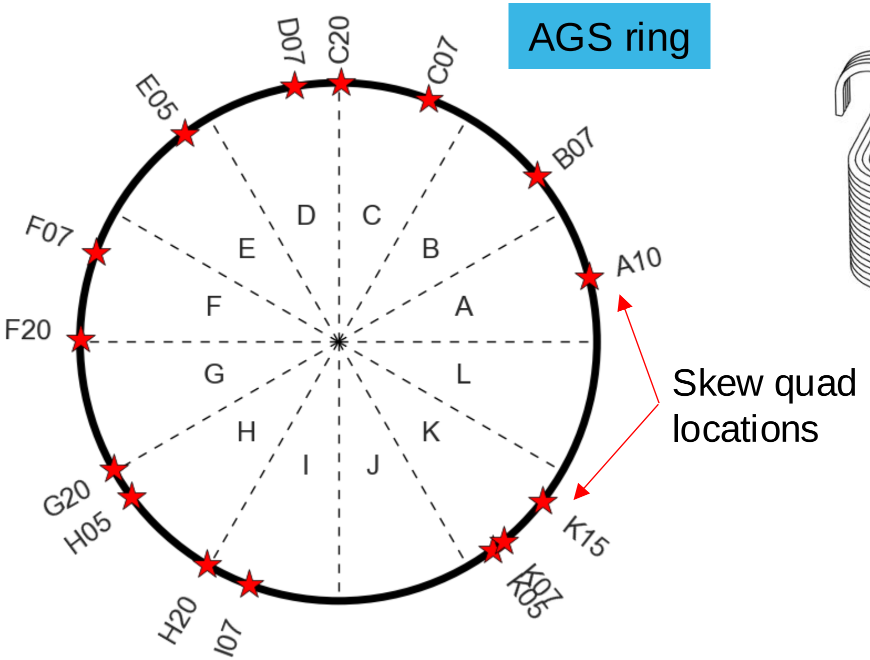
- A set of 15 skew quadrupoles with integrated skew quadrupole gradient at least 0.2 T meets the physics requirements
  - 9 placed at narrow locations in the AGS adjacent to sextupoles
  - 6 locations in longer (mostly empty) straight sections
  - Locations determined largely by brute force optimization from the available ~30 locations

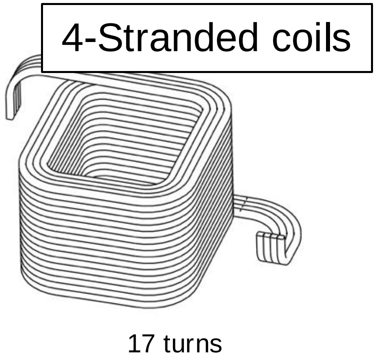
  Note: At top energy one AGS main magnet causes ~70° of spin precession
    - Geographically close != close in phase





Magnet Param		unit
Length (mech.)	0.17	m
Bore diameter	0.16	m
Pole tip field (max)	0.15	T
Int grad (max)	0.32	T
Current (max)	275	A
Current (rms,max)	60	A
Lamination thick.	0.635	mm



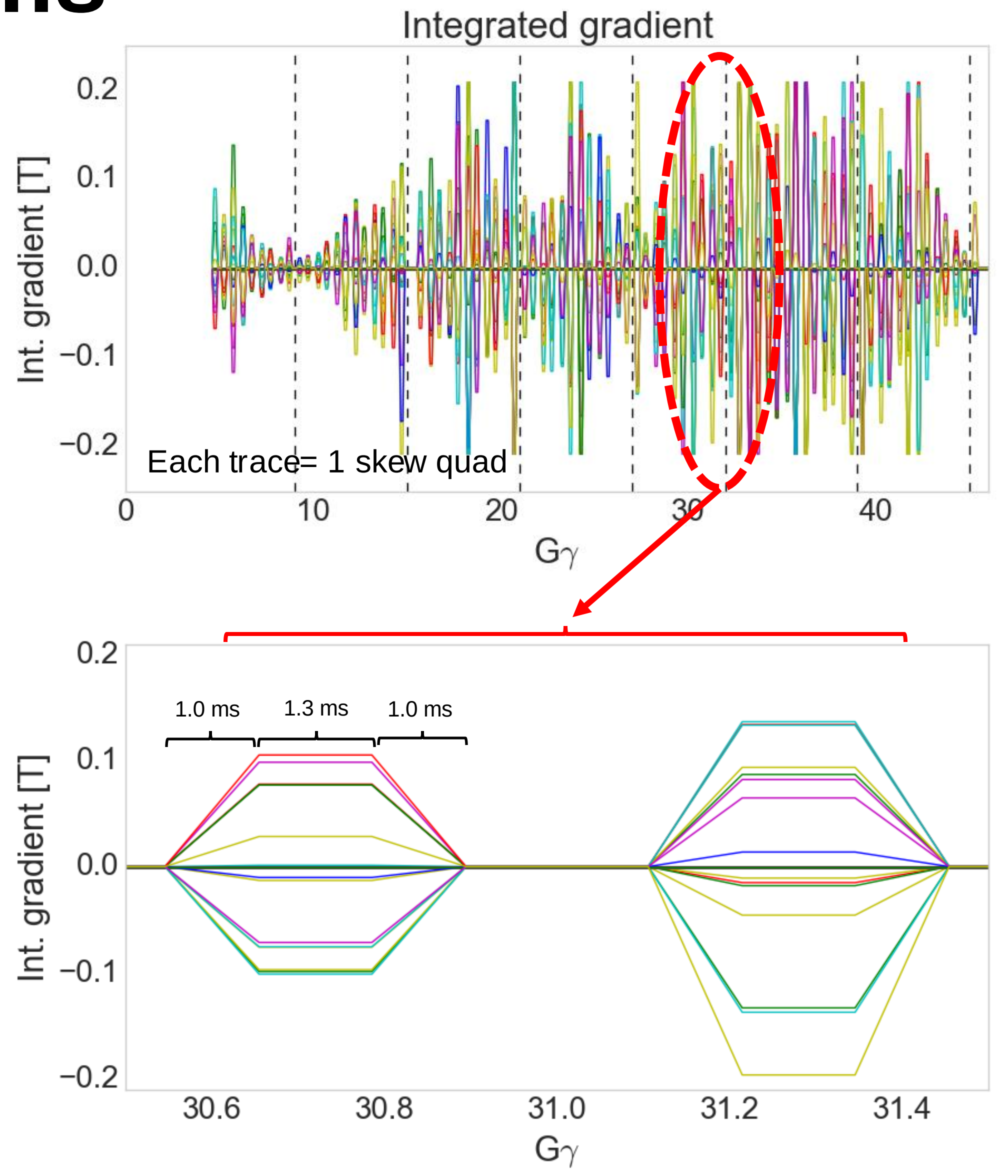


Calculated correction waveforms

- Pulsing the skew quads with 1 ms rise, 1.3 ms flattop and 1 ms fall allows changing currents quickly to accommodate new correction vectors every resonance

  Also avoids having skew fields during strong vertical intrinsics (tracking showed small polarization losses at these with skew quads powered)

- Calculated resonance strength reducible to zero at almost every resonance
  - Tune shift from coupling < 0.005



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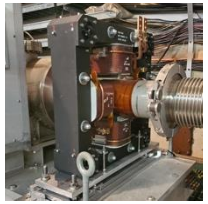
Commissioning Timeline

Dec ’23	Jan ’24	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct



Unpolarized beam in AGS

RHIC Operation (using AGS tune jump)

Au ops

14 of 15 mags delivered
1 held at p.s. vendor

Delivery of supplies

Polarity checks, orbit tests

May 4th
Proof-of-principle experiment

Development of skew quad setup interleaved with RHIC ops

RHIC ops
(w/ AGS skew quads)

Integrated development time between February start and use for RHIC operations ~20 shifts

Magnet Measurements (follow up from previous MAC)

Latch plates: IN

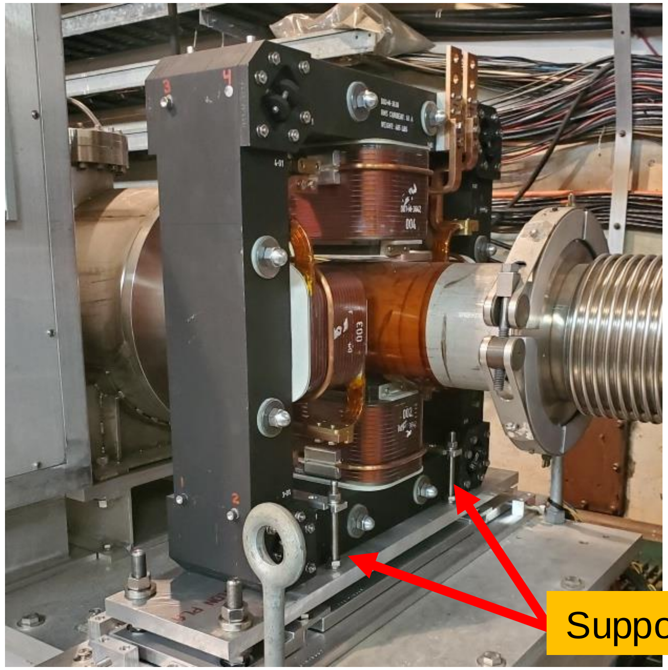
Latch plates: REMOVED

Multipoles measured on magnet #16 with and without the aluminum 'latch plate' inserted over the top of the lower magnet yoke (see below).

Support bracket insufficiently well insulated

Normal dB/dt dependent sextupole component vanishes without latch plates. Consistent with removing eddy current effects in lower yoke from the two conducting loops formed by the support

All aluminum latch plates swapped out for G-10 plates



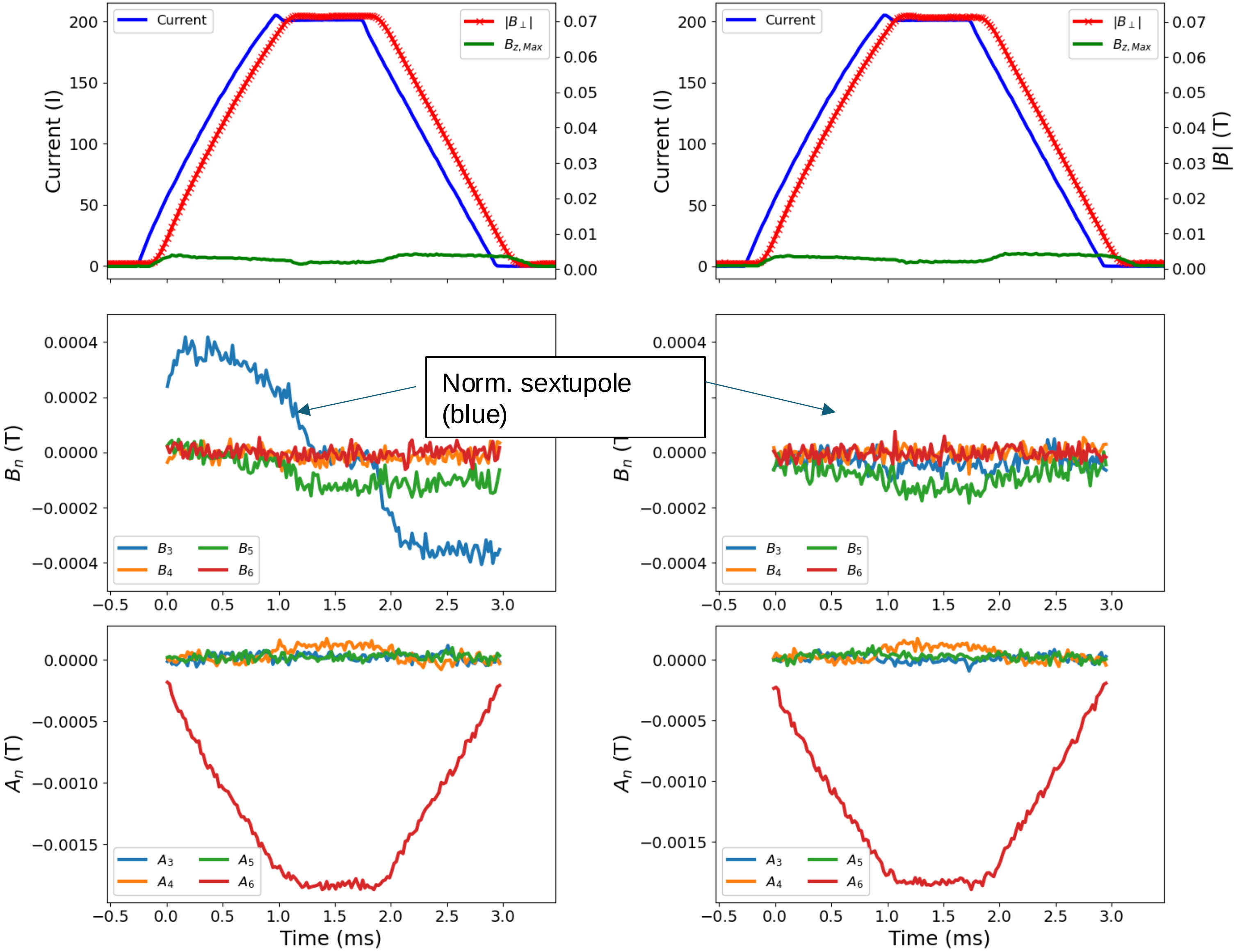
Support brackets

Current, Field magnitudes

Absolute Multipole

Normal

Skew



Preliminary commissioning tasks

- Polarity checks
- Beam-based time response checks
- Proof-of-principle resonance crossing experiment
- Orbit centering in skew quads

Polarity checks

Vertical orbit response from horizontal orbit shift

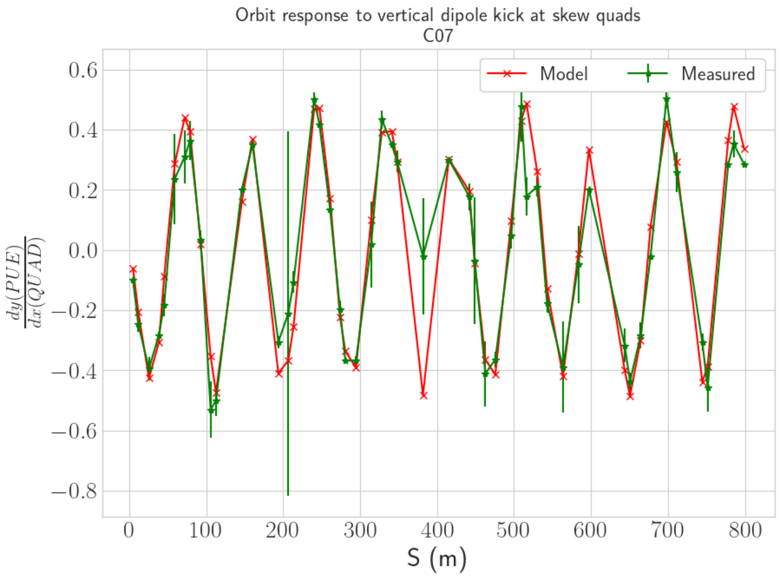
Polarity is determined via orbit response

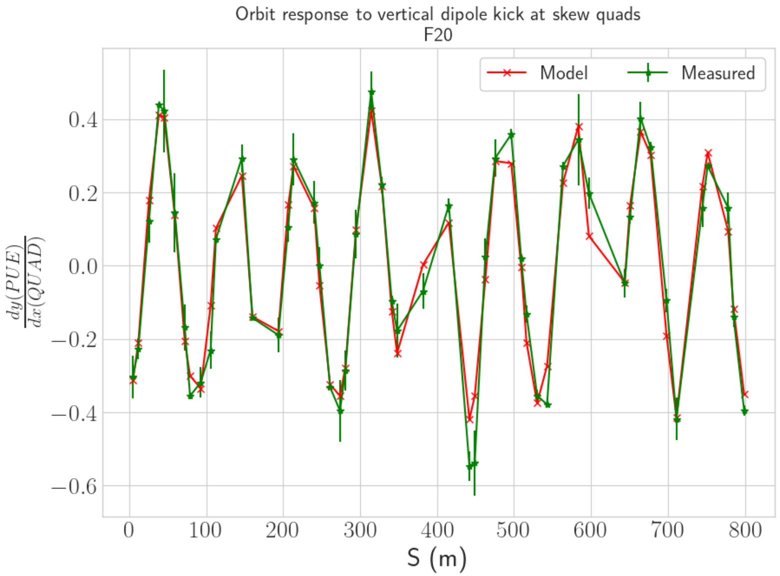
Radial shift introduced : dp/p

- Horizontal motion from dispersion at all skew quads of unambiguous sign, horizontal shift predicted using model dispersion
- Each skew quad pulsed independently
- Vertical orbit response is measured at two values of dp/p, compared to model

Can be done at top energy where model is generally simple

All 15 pass on first check. Easy to reproduce (to verify after p.s. work, long shutdowns, etc).

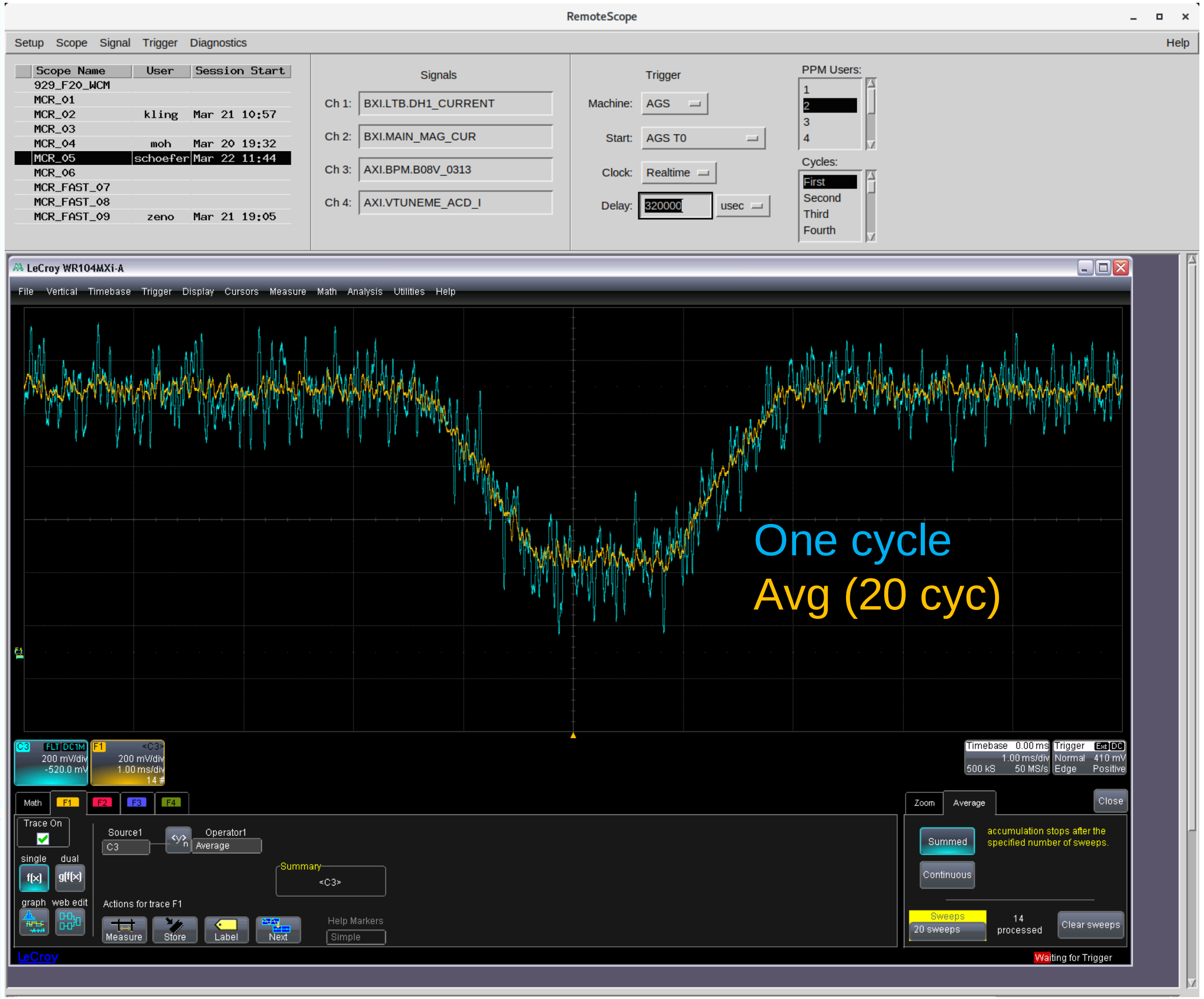


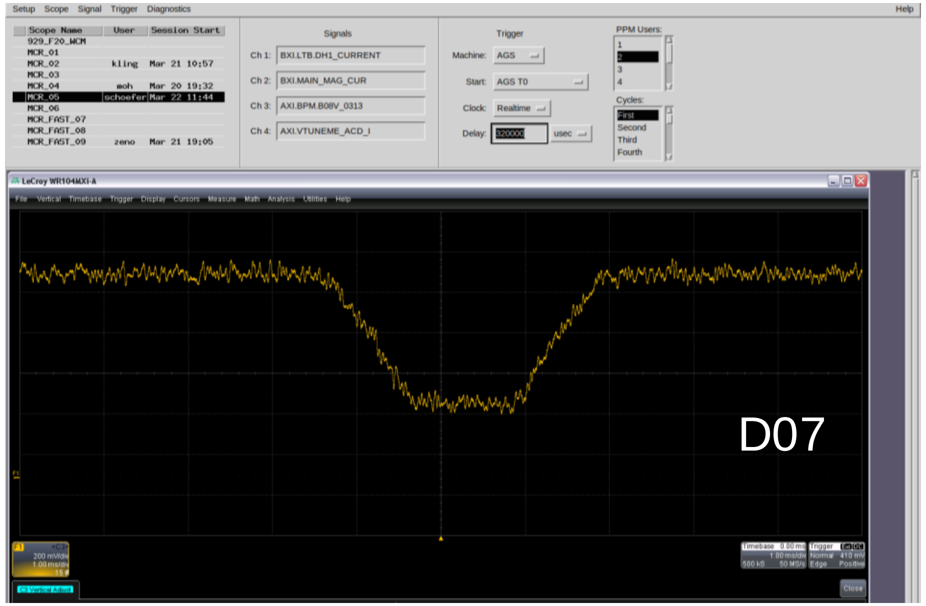


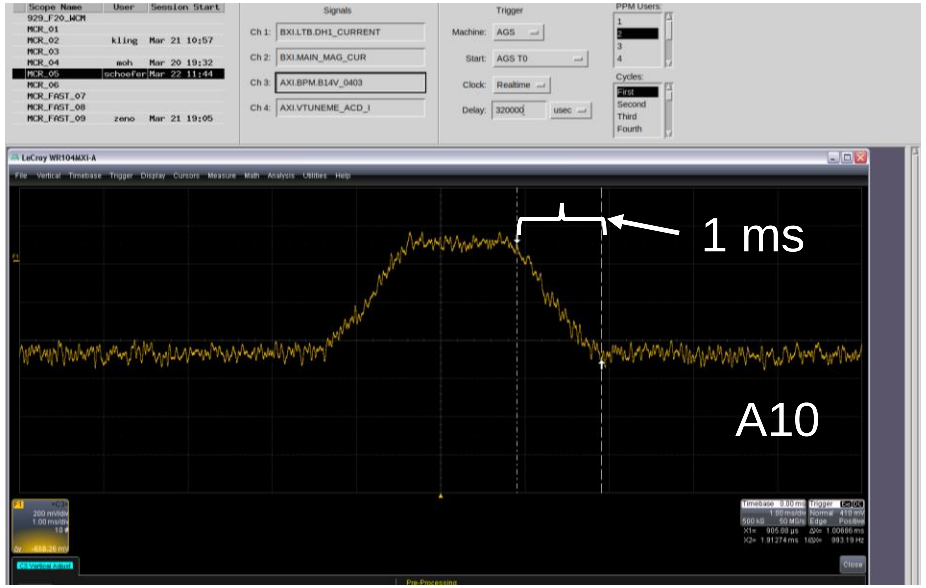
Time response to skew quadrupole pulse

Measure orbit change on analog PUE signal with one quad pulsing to get beam-based time response verification

Flattop is flat? Yes, 1.3 ms flattop
Rise time is as expected? Yes, 1 ms
Pulse delay tolerable? Yes (250 μs by this measure, very close to bench measurement of field response with AGS bem pipe section inserted)







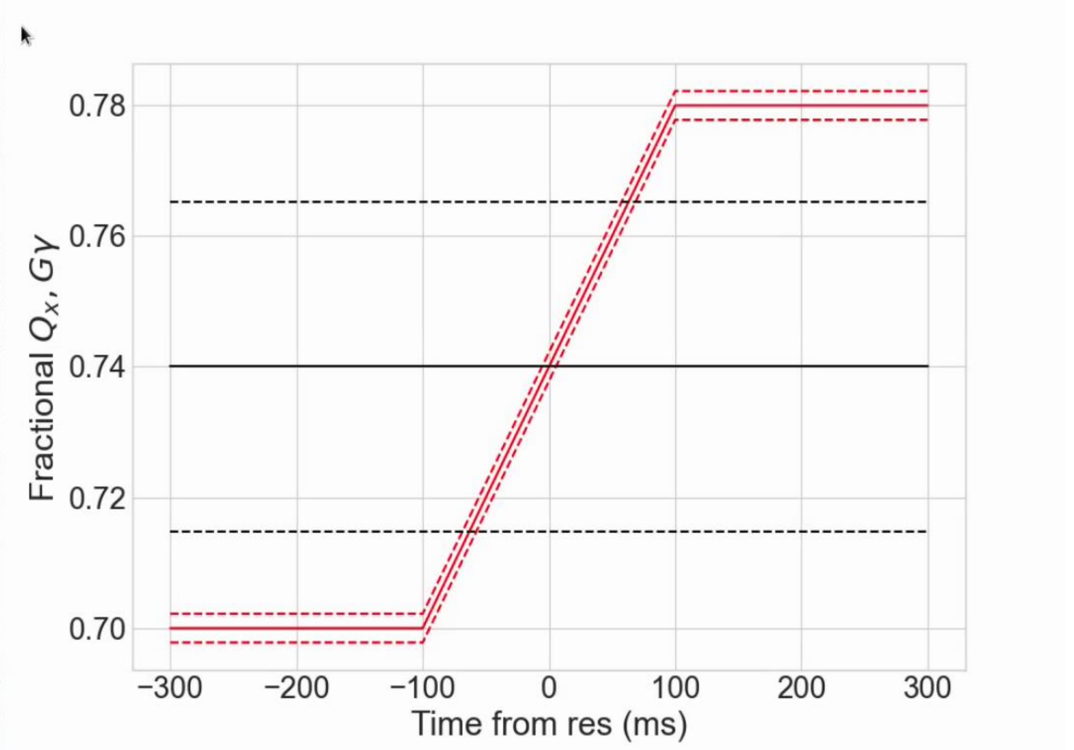
Commissioning: Proof of principle single resonance crossing

- 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}

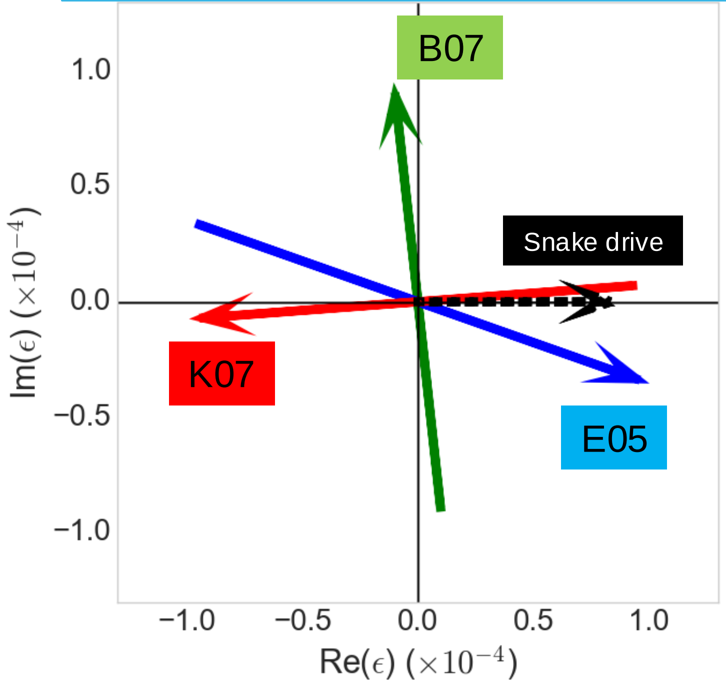
Slow crossing gives measurable 20-25% relative polarization loss

Resonance crossing

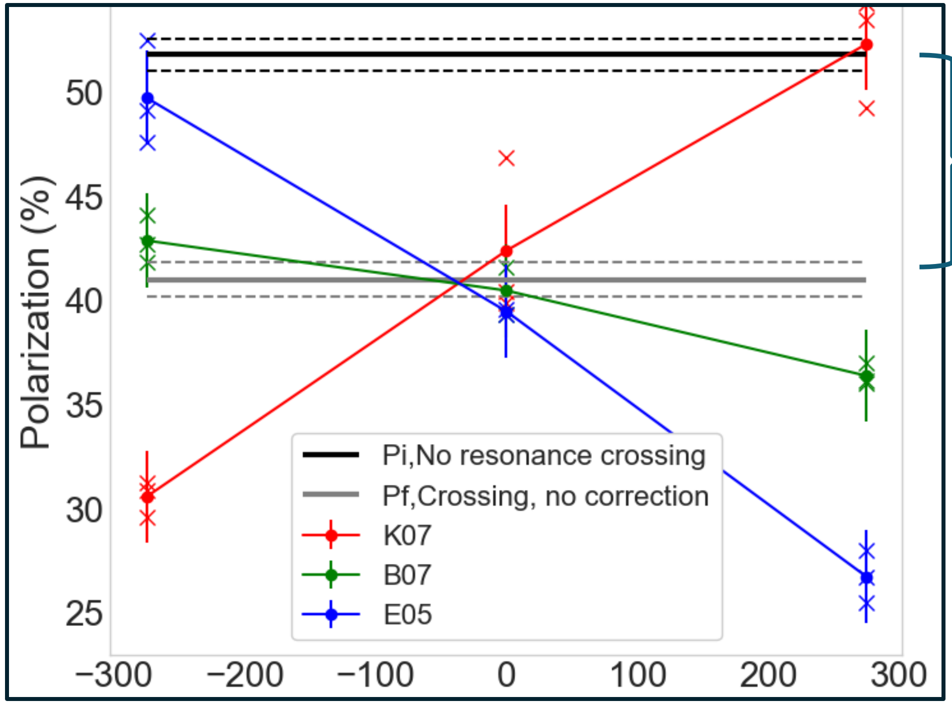


Commissioning: Proof of principle single resonance crossing

Resonance 'portrait' at Gɣ = 45.74



Polarization response to skew strength



P_f/P_i (uncorrected)
0.79 +/- 0.02

$|\varepsilon|_{meas}$ = (7.9+/-0.4)x10^{-5}
$|\varepsilon|_{mod}$ = (7.6+/-0.5)x10^{-5}

$|\varepsilon|$ = Res strength
Measured uncertainty is statistical
Model uncertainty is systematic from uncertainty in emittance

Select three skew quads with good relative phasing

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

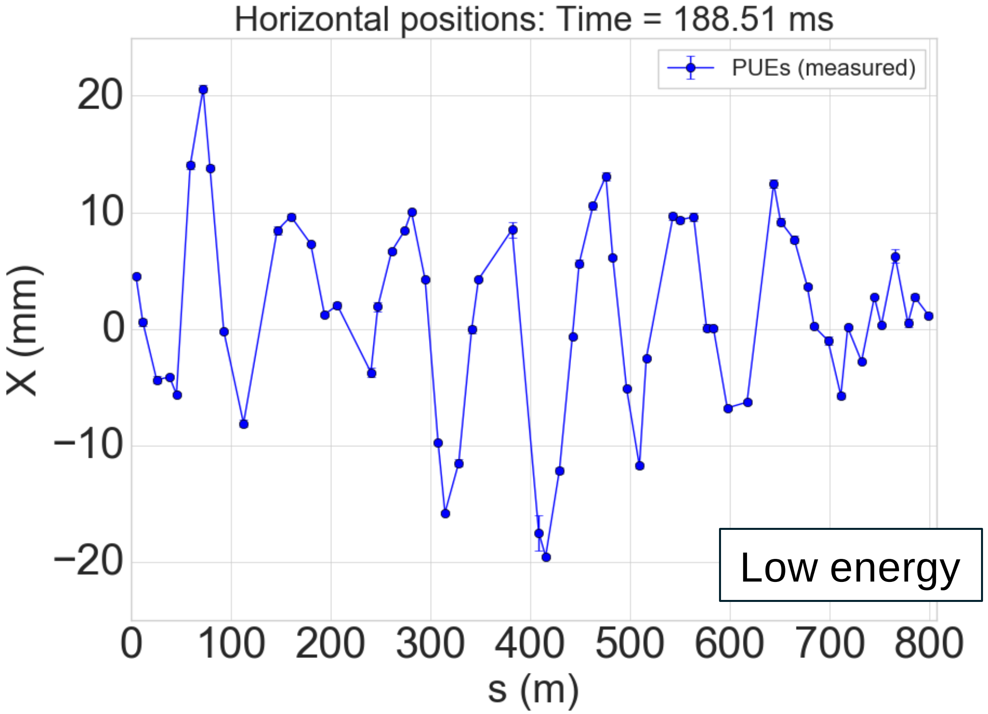
Skew quad arrow length is full current range of supply (arrow head is positive)

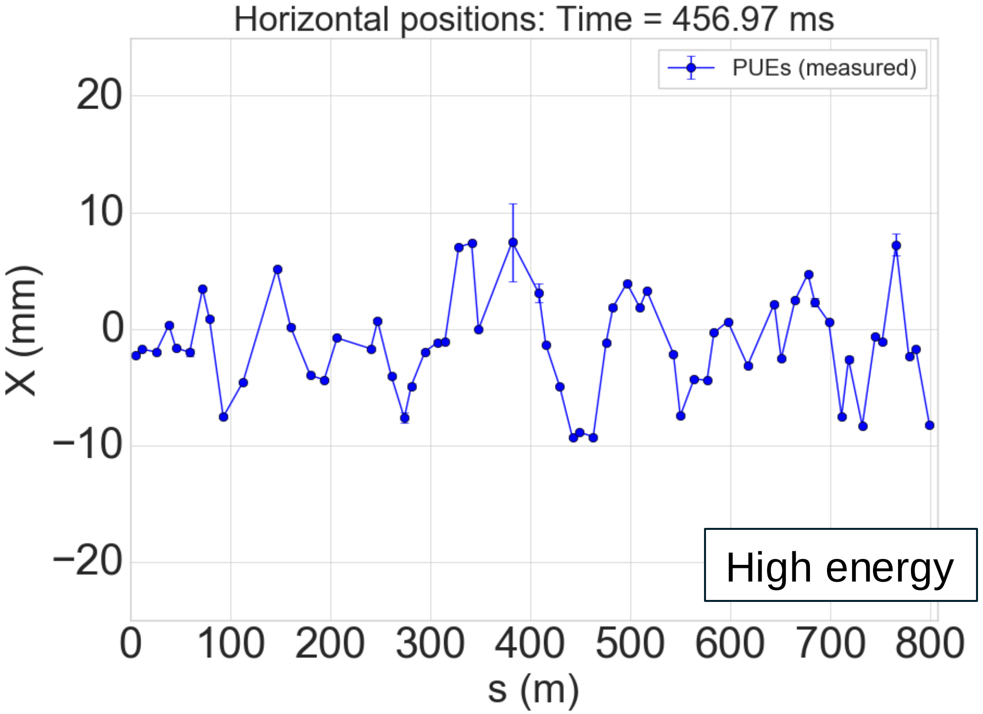
- Phasing of skew quads is as expected
- Demonstration of total correction
- In anti-correcting phase, expect *more* loss from simple Froissart-Stora estimate
  - May be multiple crossings from synchrotron motion during long crossing or flips of high amplitude particles
  - To be investigated in simulation

Orbit effects during acceleration

- 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.
- Low energy: excursions driven by requirements for helical dipoles
- High energy: excursions driven by misalignments

Sample horizontal orbits (at BPMs)





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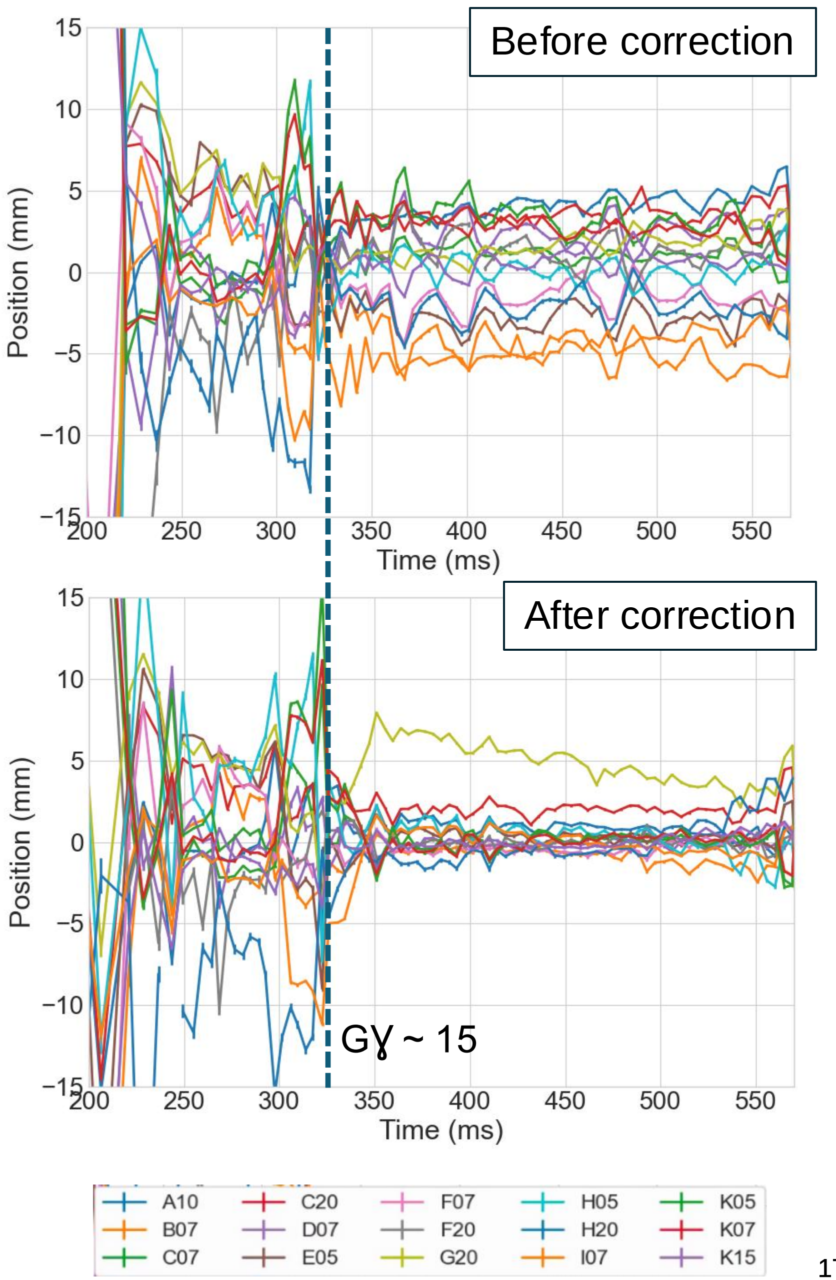
Beam-based centering

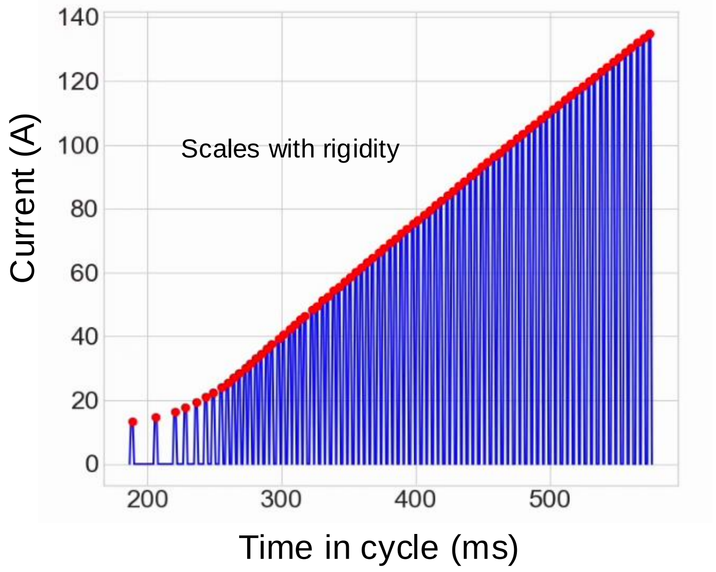
- No BPMs at skew quadrupole locations

- Beam-based orbit offsets measured and corrected
  - Skew quads pulsed individually, infer offset from vertical orbit change + model
- Orbits at low energy (below transition Gɣ ~ 15) *not* corrected
  - Model infrastructure needs to be developed to correct orbit including design orbit specification with backleg windings, injection and snake related manipulations

Horizontal position at skew quad



Sk. Quad current function for orbit measurement

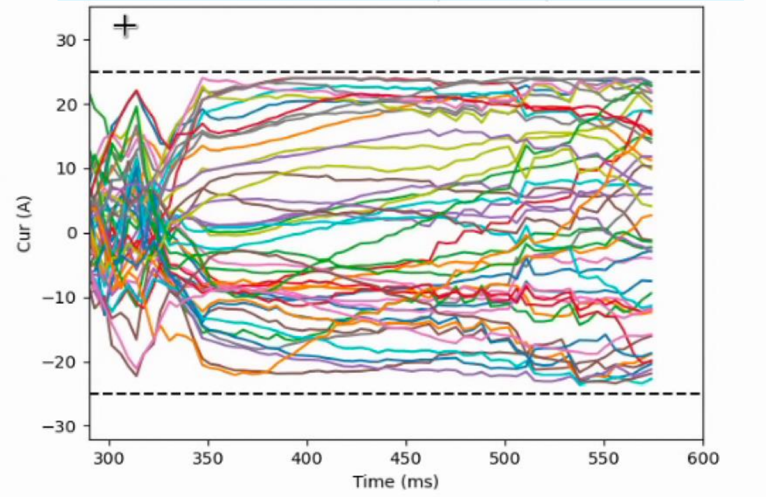


Orbit effects

- Centering using orbit steerers accomplished to <2 mm at 13 of 15 locations
- Correction objective *only* at skew quad locations
- Outliers at C20 and G20: too demanding on orbit correctors (omitted from most corrections)

- Global orbit (at BPMs) not significantly better

AGS Hor Orbit Corrector Currents

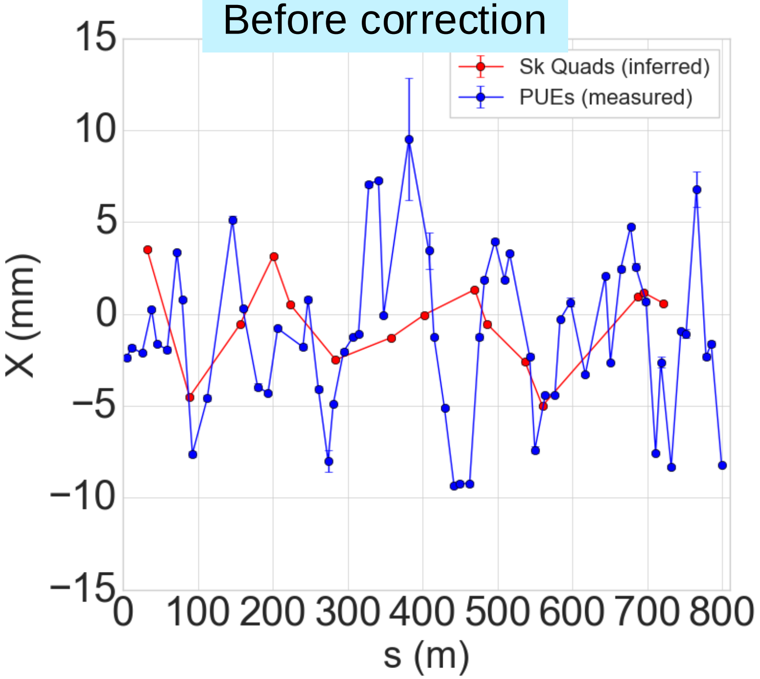


Correction in the model above 99% still possible without C,G20

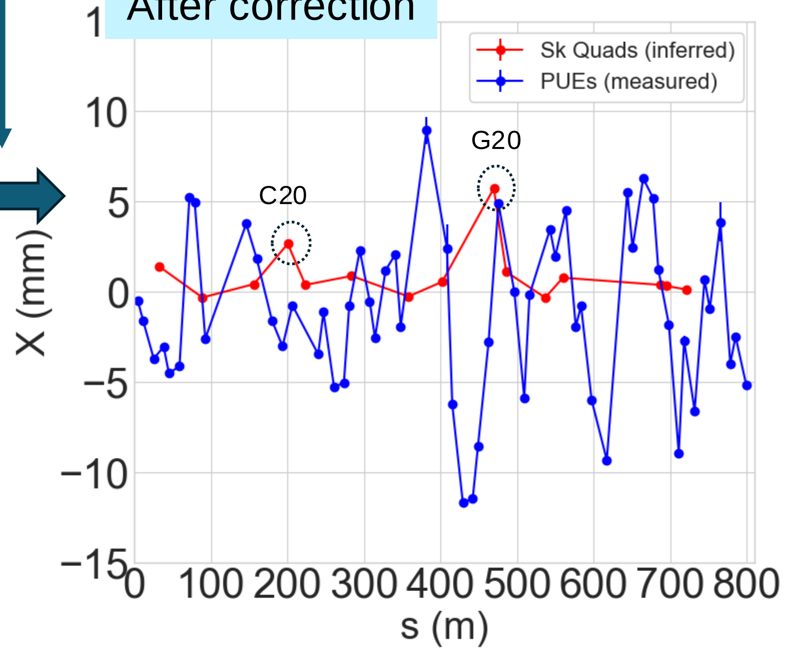
Magnet realignment planned for Run 24 → 25 shutdown to improve base orbit

Discussing adding correctors, upgrading existing correctors

Before correction



After correction

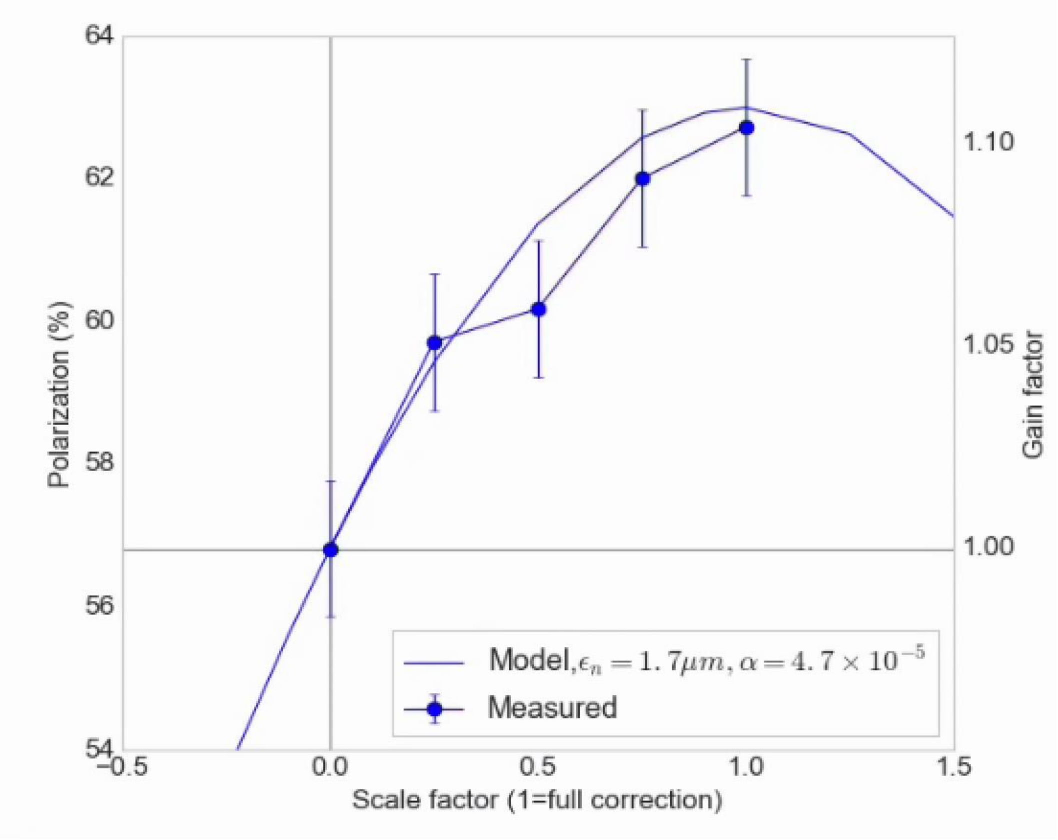


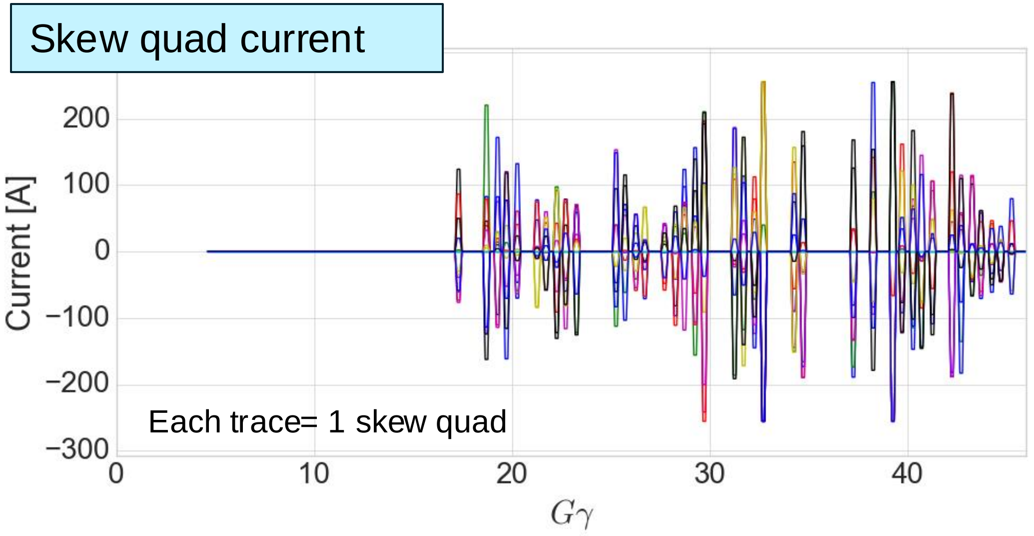
Ramp implementation and Polarization

- Early attempts:
  - High energy pulses only (avoids difficult low energy optics)
  - Omitting several pulses with too large orbit excursions

  - Within statistical error of model in terms of gain factor over uncorrected polarization

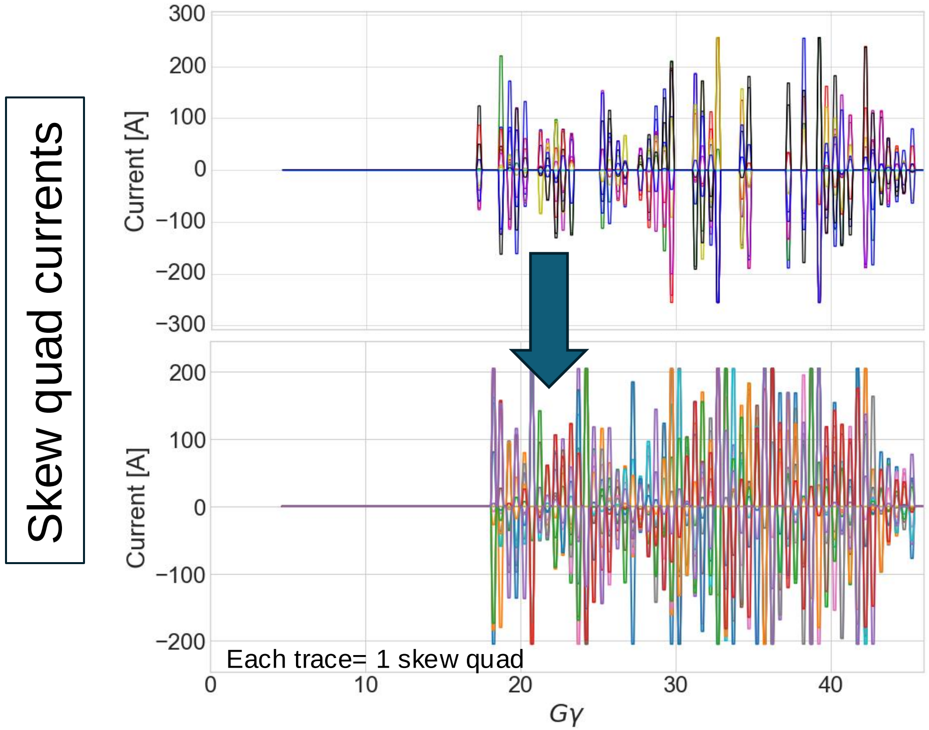
Correcting only resonance above transition

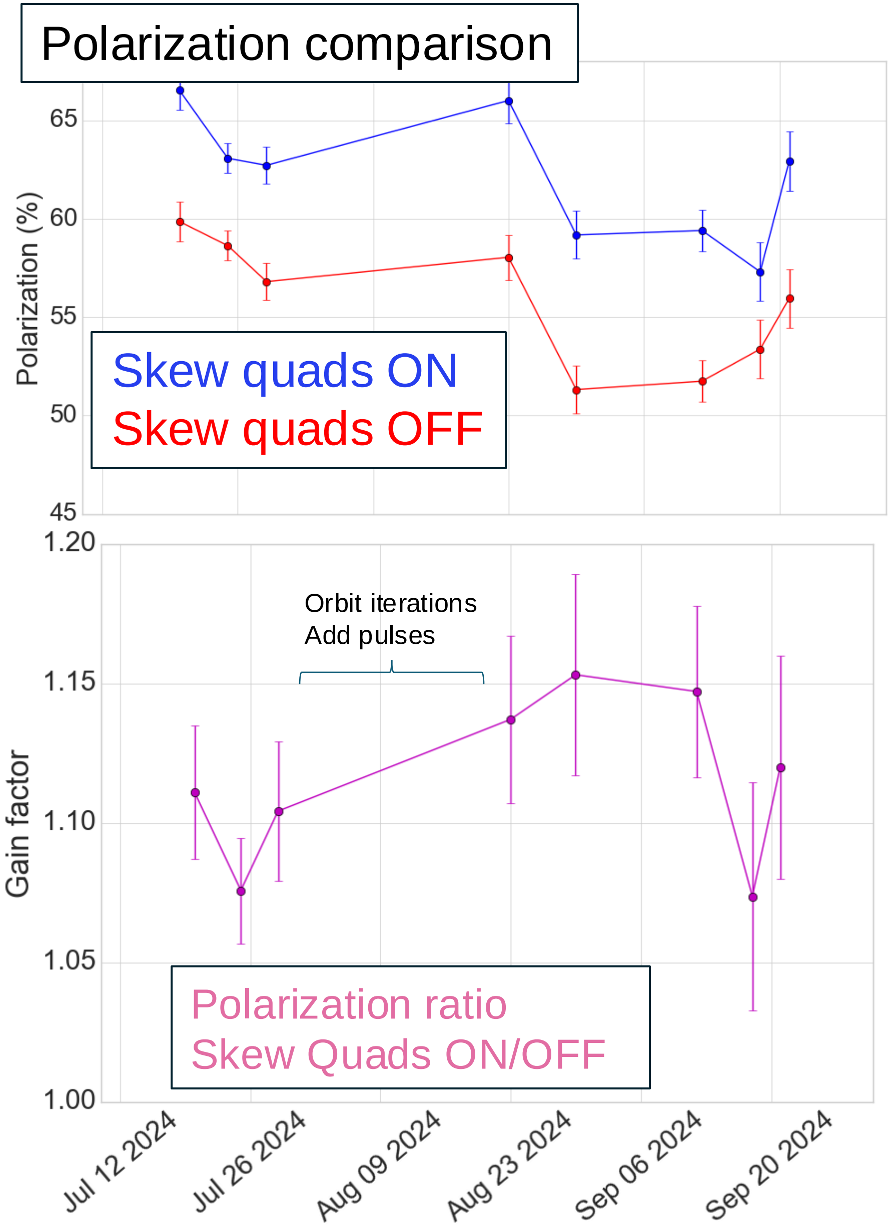




Skew quadrupole commissioning: ramp and polarization

- Enabling more pulses via
  - Incremental orbit improvements
  - Included model-predicted orbit response of the skew quads in the optimization to minimize resulting vertical rms, constraints now:
    - Resonance strength, |ε| = 0
    - Tune shift from coupling, $\Delta Q_y < 0.005$
    - Vertical $|M_{orm}*(k_{skew}*x_{skew})|_{max} < 2$ mm
      - Requires some increase in quad current





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Low energy resonance correction

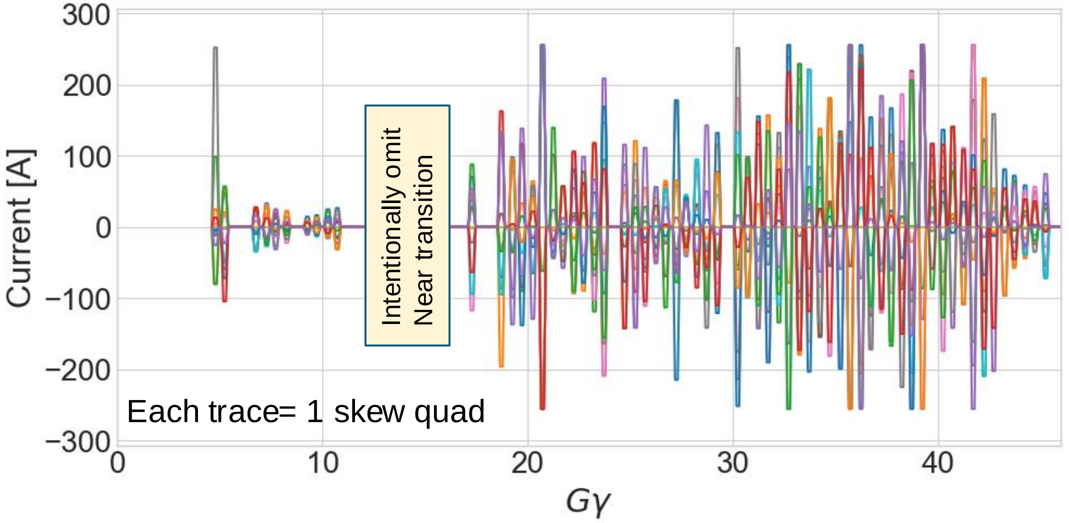
Benefit from low energy pulses (Gɣ < 15) expected to be ~3-4%
Measured benefit ~1%

In some cases negative, less reliable correction

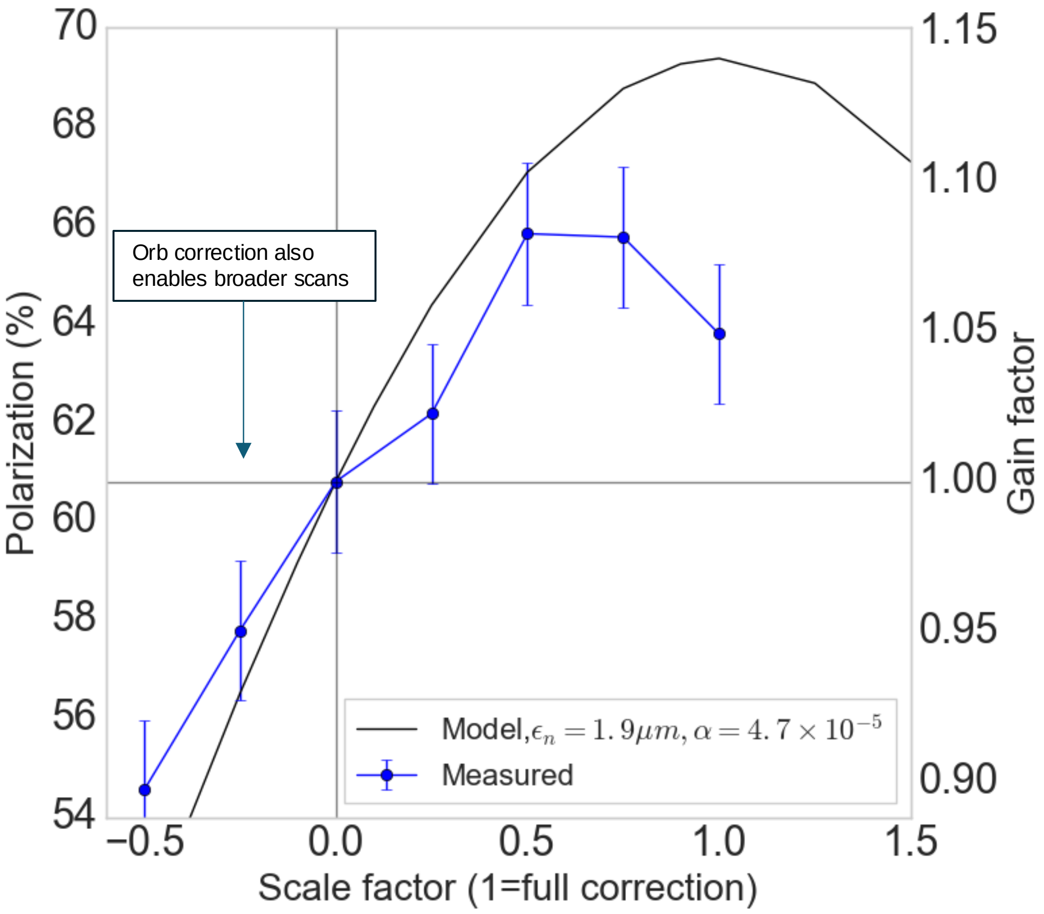
Not totally understood – possible culprits:

- Model error is highest at low energy (snakes, orbit feed-down)
- Q_x closer to Q_y: residual coupling from errors will change the drive term addressed by the skew quads
- Near Gɣ = 9 =0+Q_y, very small correction strengths required (easy to provoke extra resonance terms from coupling)

Skew quad currents



Correcting scaling, full cycle



Operations with skew quad correction

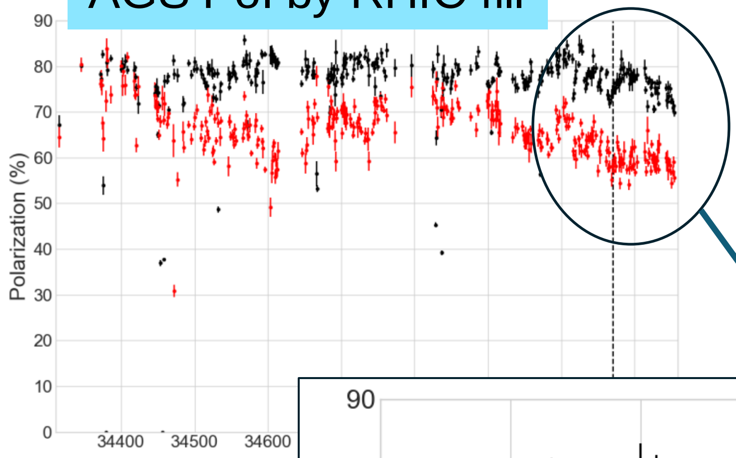
Last ~3 weeks of RHIC polarized proton operation, beam delivered from a skew quad correction setup rather than tune jump

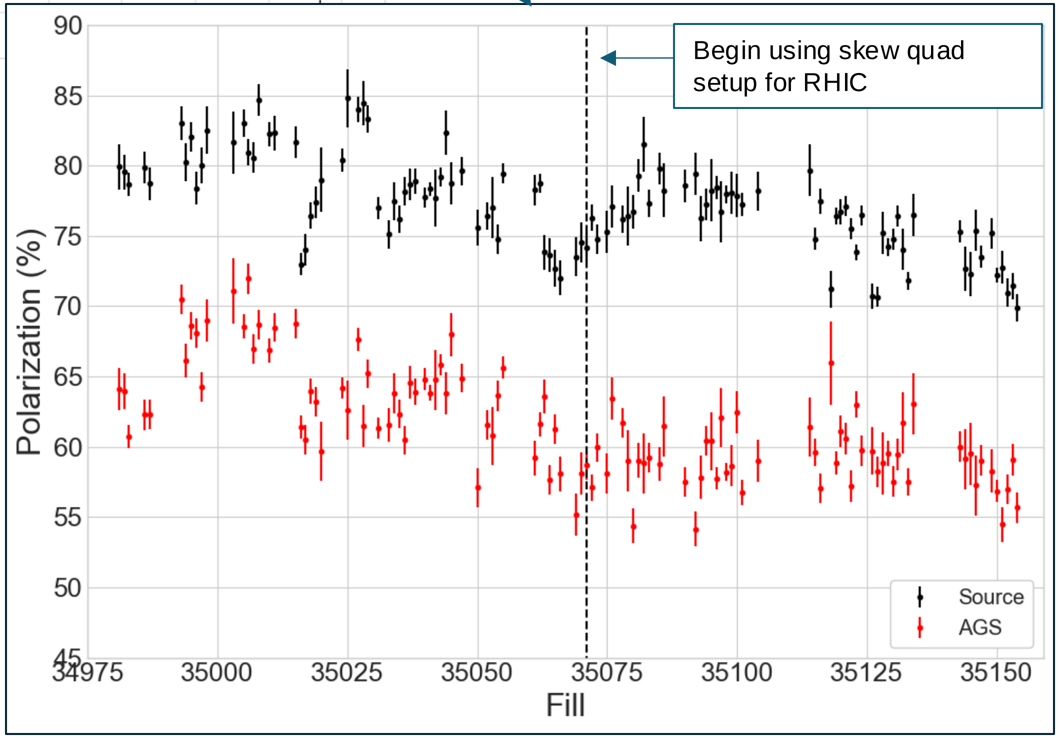
No significant downtime of skew quad system

Performance similar to tune jump, especially at highest intensity

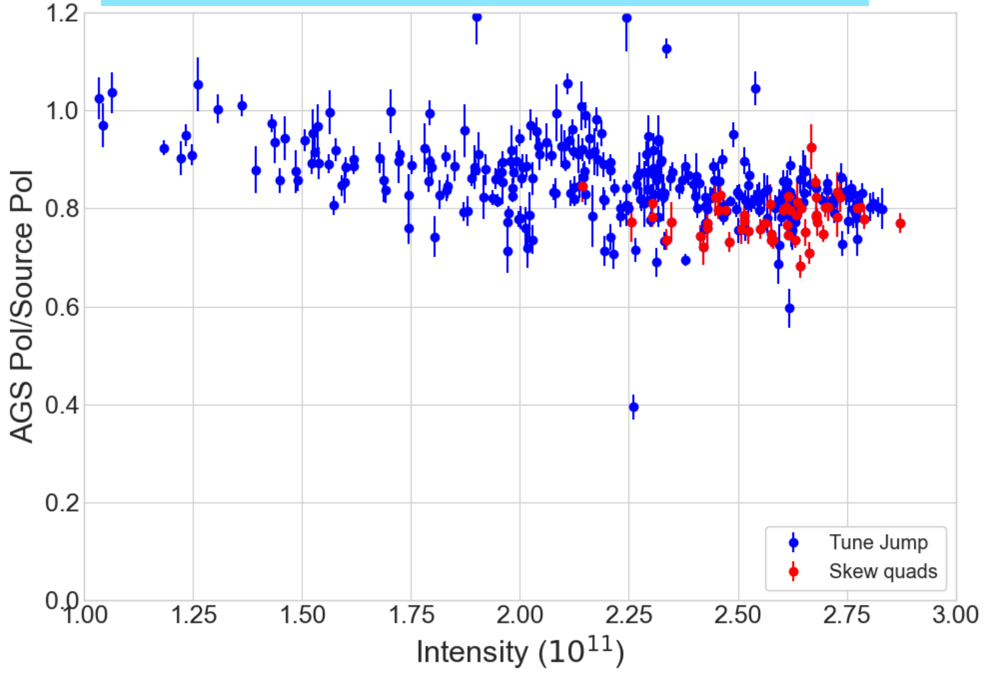
Coincides with relatively low polarization in all AGS setups

AGS Pol by RHIC fill





AGS Pol/Source Pol, by RHIC fill



Prognosis

- Gain factor over uncorrected case (after initial orbit iterations):
  - Average: 12.6% +/- 1.5 % (relative)
  - Peak 15%

- Polarization gain from resonance at high energy in good agreement with model predictions
  - Model generally more accurate at higher energy

- +1% possible from including resonances in the ‘transition gap’
  - Requires some model infrastructure

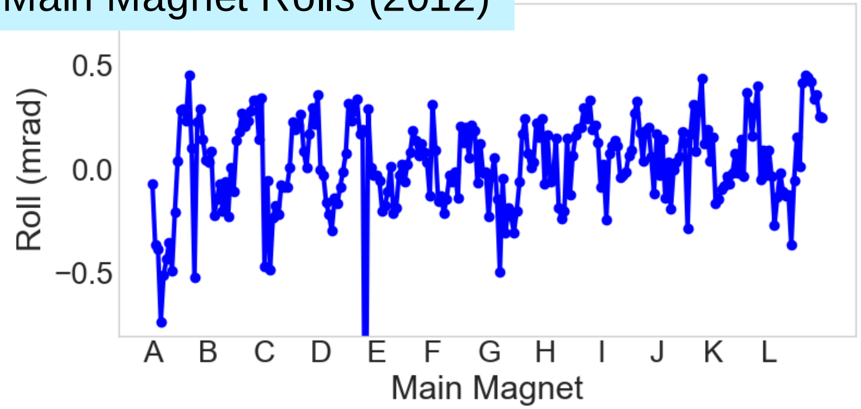
- +3% possible from improving model for low energy resonances

- Losses from residual coupling resonances, not included in the idealized model need to be estimated
  - Unknown magnitude

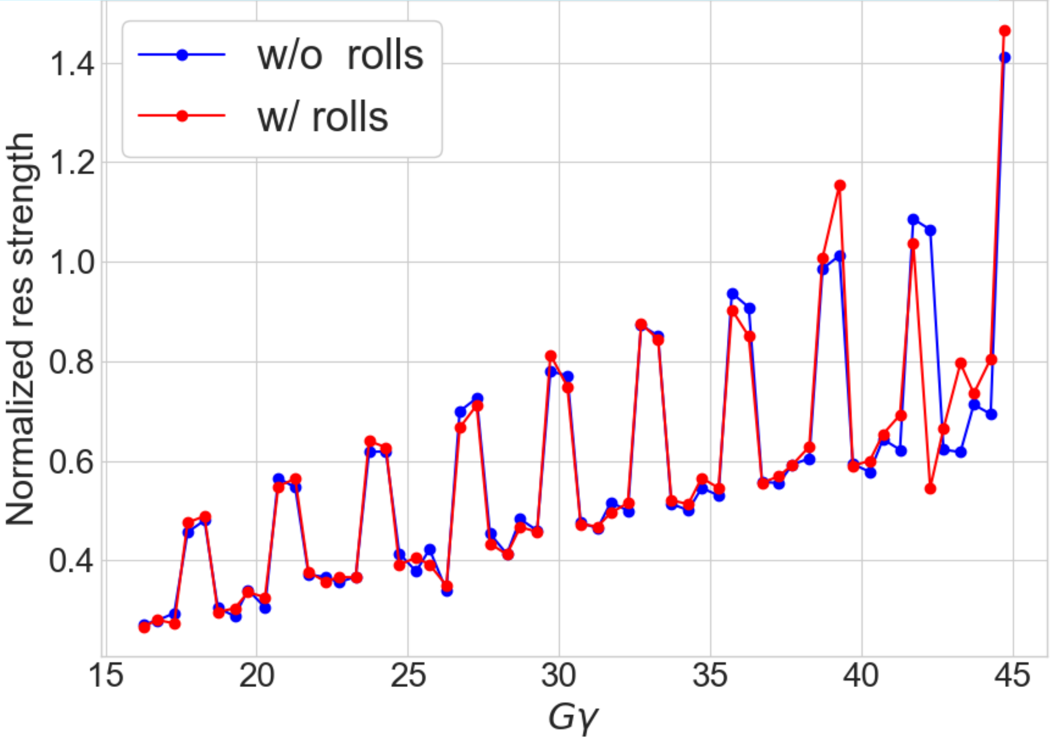
Main magnet roll

- Using survey data from 2012 and the Bmad model, polarization loss from residual coupling can be estimated
  - Rolls in main magnets is systematically toward backleg of the “C” shape: switches every 10 magnets
- Clear effect on resonance strength at highest energies
  - Impact on polarization estimated to be small (<0.25% total)
- Further model work planned to investigate sensitivities at low energy
  - Lattice structure might make it easier to provoke depolarization

AGS Main Magnet Rolls (2012)



Resonance calculations with 2010 main magnet rolls



Small impact at high energy
Working on the low energy model

Future work

Run 25 AGS development time planned behind RHIC for most of the run (including behind Au operation)

- Up to 8 weeks of RHIC operation possible for polarized protons

- AGS Survey and realignment planned for this shutdown Run 24 → 25
  - Simplifies/improves machine-model match at low energy
  - Relaxes required skew quad corrector strength (do not have to include skew quad orbit response constraint)

- Resonance correction is heavily model dependent → Develop models with realistic machine errors included
  - Requires continued development of the Bmad version of the lattice (to replace SPRINT) for inclusion of all effects
  - Rolls and vertical displacement in sextupoles both contribute to unknown sources of depolarization that could be addressed with skew quad correctors
  - Longer term: TBT BPMs planned to characterize local optics, including coupling
  - All model efforts synergistic with the overall Machine Learning/digital twin effort (see G. Hoffstaetter talk) and efforts to fully characterize other sources of polarization loss

- Beam measurements
  - More precise characterization of low and high energy resonance contributions and corrections
  - More single resonance crossing experiments: focusing on difficult to correct resonances at high energy and some low energy resonances
    - Simulation required to fully understand effects of slow crossing
  - Measure correction effect with currents calculated using realistic machine errors

Summary

- Magnets and power supplies delivered and installed in time for commissioning in Run 24
- All commissioning tasks completed successfully: polarity checks, proof-of-principle experiment, orbit centering, demonstration of correction effect during acceleration
- Gain factor in dedicated experiments of up to 15% measured, long term average 12.6%
  - Exceeds the performance of the tune jump in dedicated measurements
  - Similar performance to tune jump in longer term operation (in first commissioning run)
- Correction effect consistent enough in operation to replace the tune jump as the default system for horizontal resonance correction
- Identified areas for further improvement/study:
  - Improve orbit control and alignment
  - Simulate effects of machine errors
  - Study factors affecting the efficiency of the low energy resonances

Backup slides

Timeline details

- Dec 2023: 14/15 magnets in hand and measured (last one held at local power supply vendor for supply testing)

- Jan 2024 - Apr: Delivery of power supplies 3-4 supplies every few weeks
  - Installation, modification and testing on a continuous basis

- Feb 5th: *unpolarized* beam available in AGS (cold snake and polarized source both unavailable)
  - Feb-March: Skew quad polarity tests, development of other proton setups

- Mar 29th: Cold snake available: enables start of orbit correction/centering development since orbit/optics in operational configuration

- Apr 10th: All 15 magnets and supplies available for testing

- Apr 20th: Start of RHIC beam operation, first injections

- Apr 24th : Polarized source available → polarized proton beam available in AGS for first time this run

- May 4th: Proof-of-principle single resonance crossing experiment: demonstrates skew quad correction principle
  - May – Sep: Interleaved development in AGS and RHIC operation. RHIC takes beam from the 'tune jump' setup

- Sep 7th: RHIC begins taking beam from the skew quad setup
- Sep 30th: End of RHIC and AGS polarized proton operation (RHIC switches to Au, proton Linac goes to shutdown)

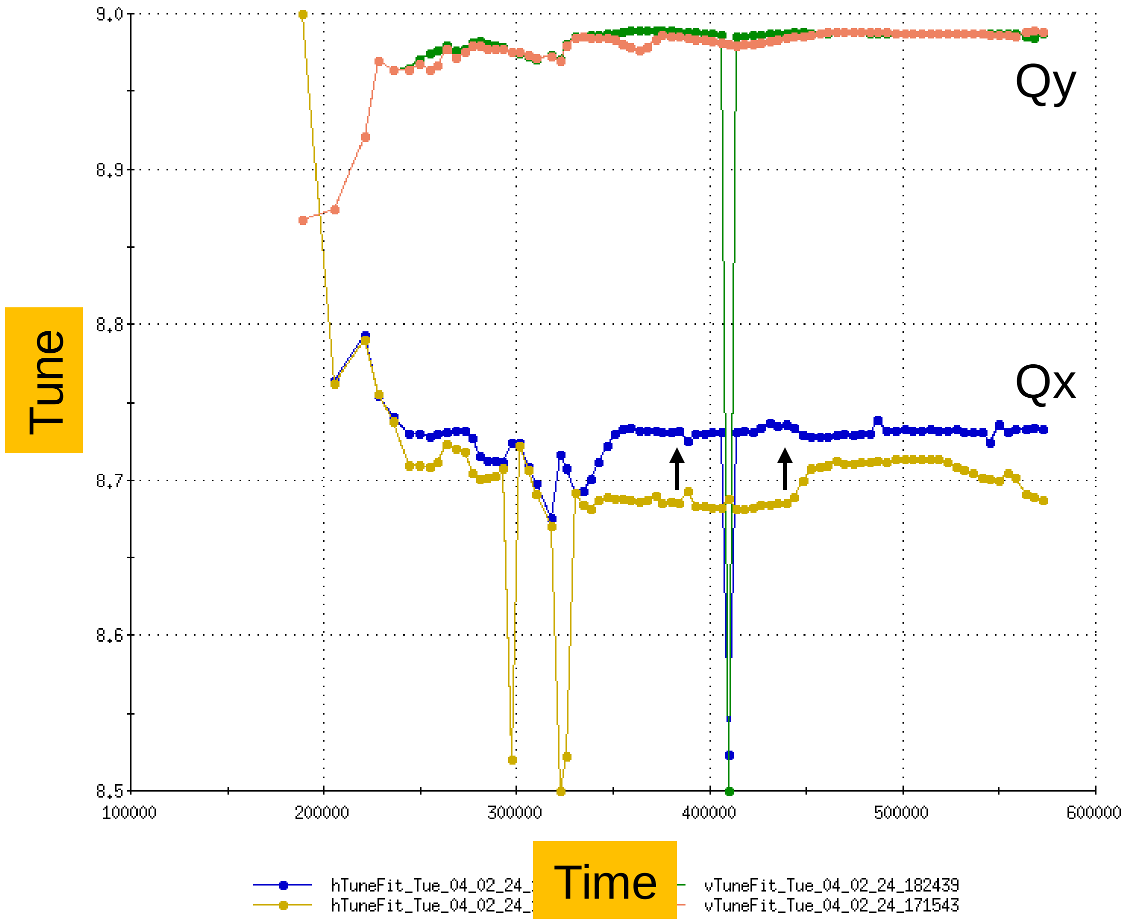
Tune change for resonance timing

Power supply ramping constraints require a minimum 3.7 ms between pulses

Time between resonance depends on tune: Gɣ ~ N +/- Q_x

Tune jump setup has a base tune of 8.7 (jumps up to 8.74)

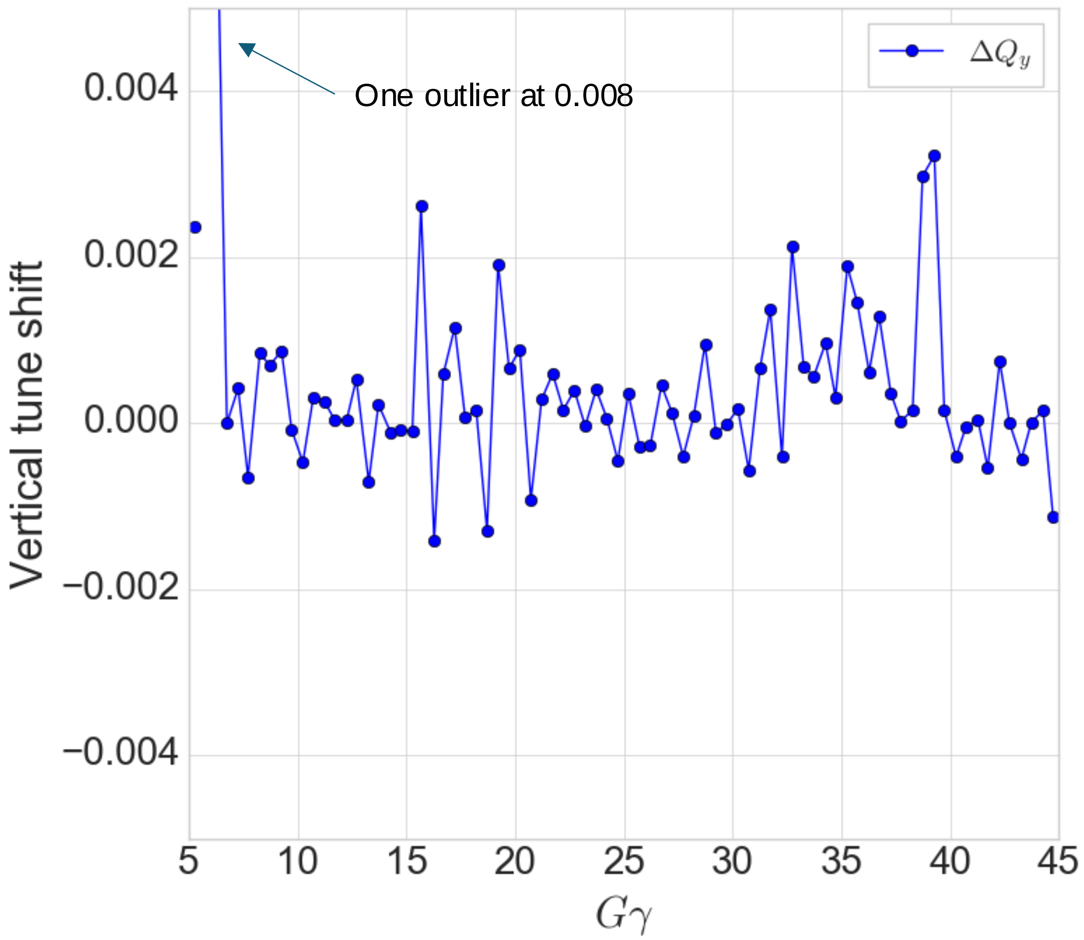
Skew quad setup requires at least 8.72. Operations at 8.73



Tune shifts from skew quads

Design goal was vertical tune shift <0.005

Operationally mostly <0.002



Partial snake resonances are 'hybrid' resonances

M.Bai showed *horizontal closed orbit motion* can interact with a vertical intrinsic to produce a set of sideband resonances*.

Similar procedure shows *horizontal betatron motion* can interact with the snake spin kick in the same way

$$\frac{d\Psi}{d\theta} = -\frac{i}{2}\begin{pmatrix} F & -\xi \\ -\xi^* & -F \end{pmatrix}\Psi$$

$$\xi = i\, Xs\, \delta(\theta - \theta_s)$$

$$F = G\gamma - (1 + G\gamma)x''(\theta)\rho$$

$$\Psi = \exp[\frac{i}{2}\sigma 3(G\gamma\theta - (1 + G\gamma)x'(\theta)\rho\,]\tilde{\Psi}$$

→ *spin precessing frame*

$$\frac{d\tilde{\Psi}}{d\theta} = -\frac{i}{2}\begin{pmatrix} 0 & -\tilde{\xi} \\ -\tilde{\xi}^* & -0 \end{pmatrix}\tilde{\Psi}$$

$$\tilde{\xi} = i\, Xs\, \delta(\theta - \theta_s)\; e^{-i(G\gamma\theta - (1+G\gamma)x'(\theta))}$$

$$\tilde{\xi} = i\, Xs\, \delta(\theta - \theta_s)\; e^{-i(G\gamma\theta - (1+G\gamma)x'(\theta))}$$

$$x'(\theta) = \widetilde{x'}\sin(\nu_x\theta)$$

Expansion to get trig out of the exponent. Keep linear terms and Fourier transform:

$$\varepsilon_K = \frac{iX_s}{2\pi}\int \delta(\theta - \theta_s)\, e^{-iG\gamma\theta + iK\theta}\left[1 - \widetilde{x'}\,\frac{1 + G\gamma}{2}\; e^{\pm\nu_x\phi(\theta)}\right] d\theta$$

Brookhaven National Laboratory

*Phys Rev Lett, Vol 84, 6, 2000

Partial snake resonances are ‘hybrid’ resonances

$$\varepsilon_K = \frac{iX_s}{2\pi}\int \delta(\theta-\theta_s)\, e^{-iG\gamma\theta+iK\theta}\left[1-\widetilde{x}'\,\frac{1+G\gamma}{2}\;e^{\pm\nu_x\phi(\theta)}\right]d\theta$$

Term 1: Amplitude $X_s/2\pi$, non-zero when $G\gamma = K$, snake imperfections

Term 2: Amplitude ~ $\widetilde{x}'$, non-zero when $G\gamma \pm \nu_x = K$, intrinsic resonance driven by the phase modulation of the snake imperfections

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What if another intrinsic resonance is present at frequency v_x: $\xi = i\, Xs\, \delta(\theta-\theta_s) + \varepsilon_x e^{\pm\nu_x\phi(\theta)}$

$$\varepsilon_K = \frac{iX_s}{2\pi}\int \delta(\theta-\theta_s)\, e^{-iG\gamma\theta+iK\theta}\left[1-\left(\widetilde{x}'\,\frac{1+G\gamma}{2}+\varepsilon_x\right)e^{\pm\nu_x\phi(\theta)}\right]d\theta$$

A second intrinsic resonance at the horizontal betatron tune can be used to cancel the partial snake resonance term.

Easiest way to make one is with betatron coupling

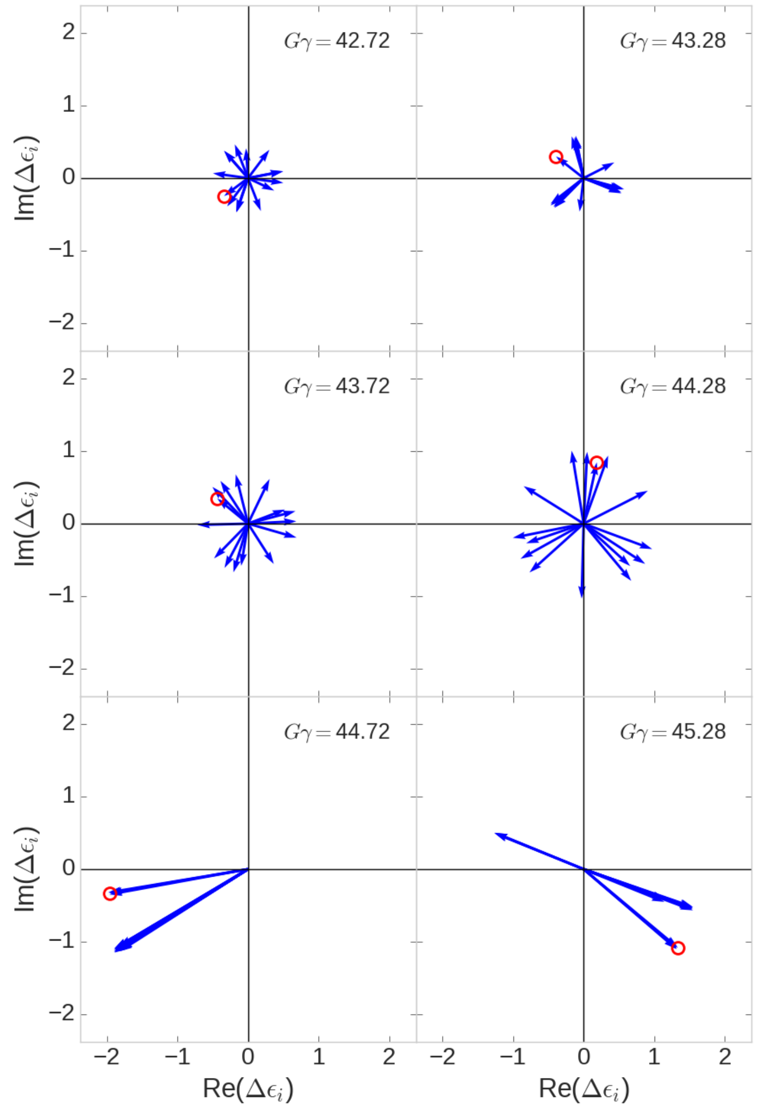
Partial snake resonance suppression with betatron coupling

In principle minimizing resonance strength (calculated with SPRINT) and coupling (two complex numbers) takes 4 skew quads

BUT:
There are 82 such linear algebra problems to solve
AND:
Phasing between skew quadrupole terms and snake terms varies wildly resonance to resonance
AND:
Correction vectors are frequently parallel, especially near strong vertical intrinsic resonances

Solution strategy: search for a solution with a distributed number of weaker, fast ramping skew quadrupoles

Skew quad correction vectors (last six hor resonances)



Phase offset chosen so that snake drive term is purely real
Red circle marks the same skew quad in each frame, phase changes rapidly from resonance to resonance

Horizontal resonance strengths in the AGS

- Two snakes, separated by 1/3 circumference
  - Modulated resonance amplitude highest near Gɣ = 3N (when snakes add constructively)
- Horizontal resonances occur every 4-5 ms at the standard AGS acceleration rate

Horizontal Resonance Amplitudes in AGS