RHIC Polarized Proton Operation in Run 22

V. Schoefer for everyone

RHIC Retreat 5/24/2022

@BrookhavenLab

Overview

Tales of woe (greatest hits)

- Blue snake failure
  - Impact on run performance
  - Coping mechanisms
    - Snake current changes, energy scan
- Siemens failure
  - Impact on run performance
  - Assess Westinghouse as polarized proton backup
- Injection kicker resistor
  - Impact to startup and machine performance
- Confounding factors

Tales of triumph

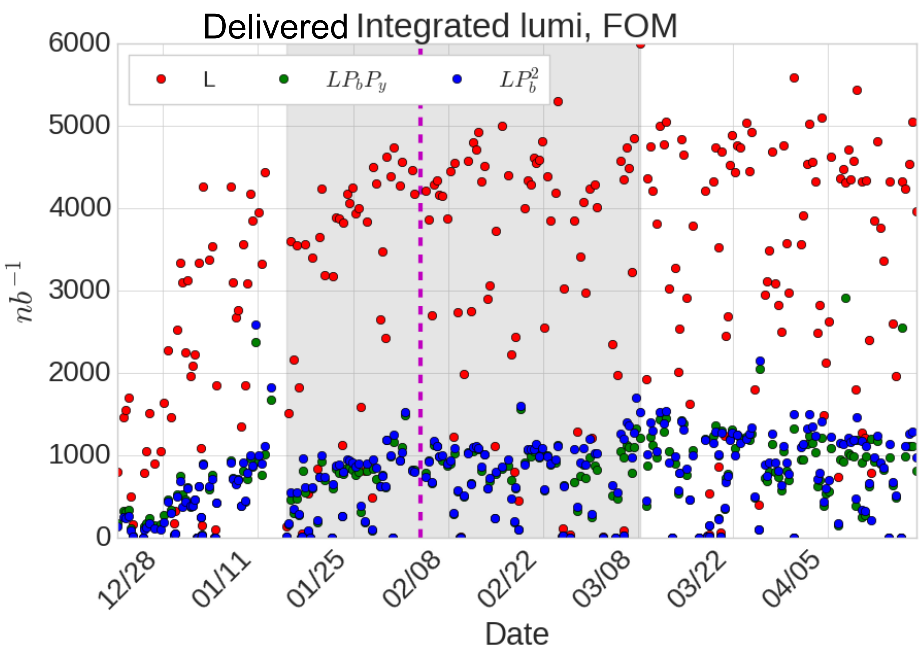
- Spin direction measurements (both at STAR and p-Carbon)
- Split/merge development
- Pre-fire prevention

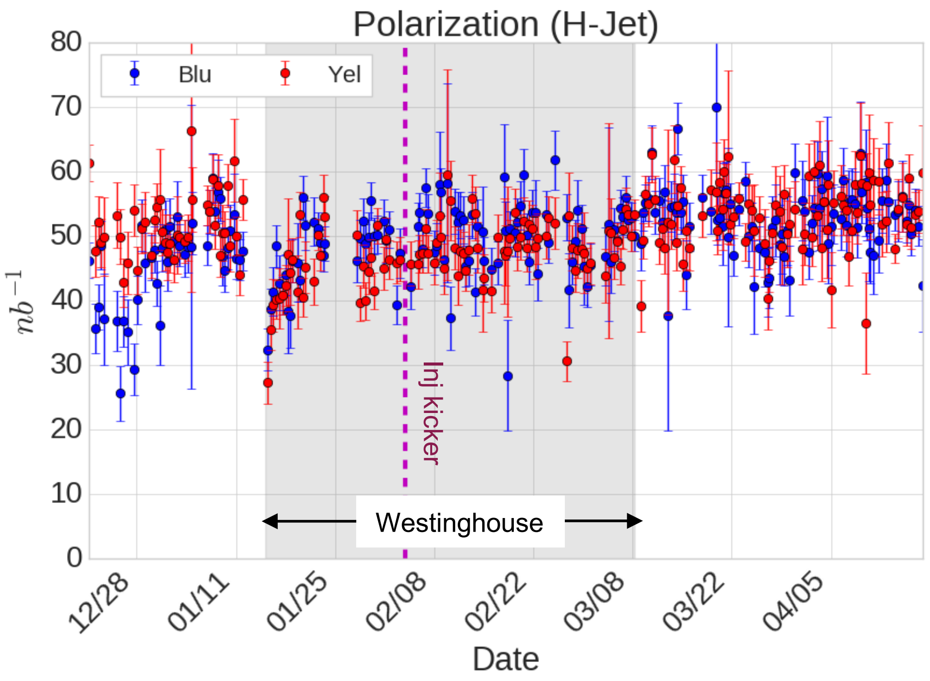
Run Overview

Scheduled physics plan:
20 cryo weeks

- 16 wks 255x255 GeV polarized proton collisions
- ~2 wks (16 days) coherent electron cooling (CeC) experiments
- 2 wks cooldown/warmup

- The plan disrupted by many problems, but chiefly
    - Blue snake failure (two helices in two incidents)
    - RHIC injection kicker resistor problem
    - AGS Siemens motor generator failure
        - operation using Westinghouse





In plots;
GRAY indicates operation with Westinghouse
PINK dashed line indicates injection kicker correction

Brookhaven National Laboratory

Part I: Tales of woe

- The blue snake failure and operation with a partial snake
- The Siemens failure and the costs of operation with Westinghouse
- The injection kicker resistor problem

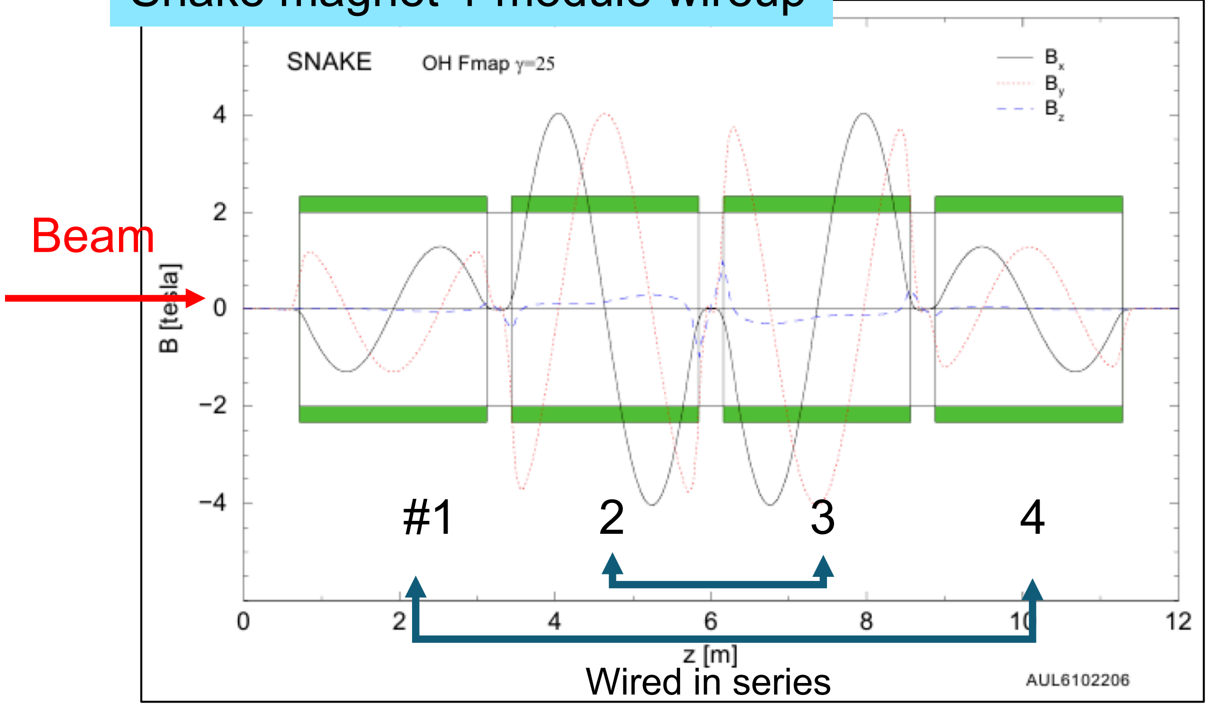
RHIC Snake magnets

Each RHIC snake consists of 4 individual helical dipole magnets (numbered #1-4 in beamline order)

Normally, pairs are wired in series:
- #1 and #4 (“outer” coils)*
- #2 and #3 (”inner” coils)*

* This ‘inner’ and ‘outer’ is CAD physics language. Magnet experts mean some else by these terms!

Snake magnet 4-module wireup



RHIC magnet: single helix

RHIC Snake magnets

- Dec 3
  - Begin first injection of Run 22 on overnight shift
  - Power supply work begins at 0900
  - 1400: PSEG prep work for a controlled switchover the following day results in a lab-wide power outage
- Dec 6
  - Resistance across coil #2 of BI9 snake is verified
  - Plan to use ‘outer’ coils alone #1-#4 as partial snake
- Dec 8
  - Beam induced quench of ‘outer’ coils (very low ~50 counts on BLM at injection)
    - Loose connection on energy extraction resistor, transzorb diode blown
- Dec 10:
  - Quench circuit modifications complete (current limiting resistors), magnet tested returned to service
- Dec 12:
  - “Ordinary” power dip, BI9 snake will not come up to current
- Dec 13
  - Coil resistance on coil #4 verified, meeting to discuss fate of run with one blue snake
- Dec 14-15
  - Verified that coil #1-#3 can be reconnected outside cryostat to function as a partial snake in series

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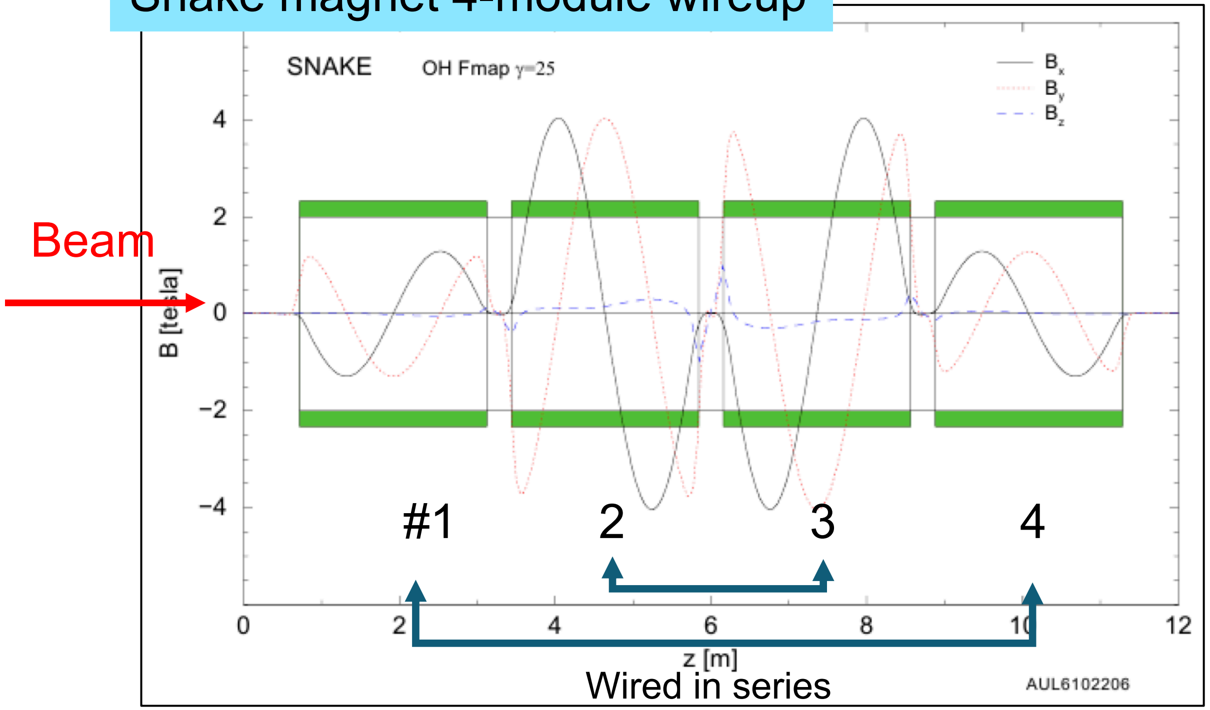

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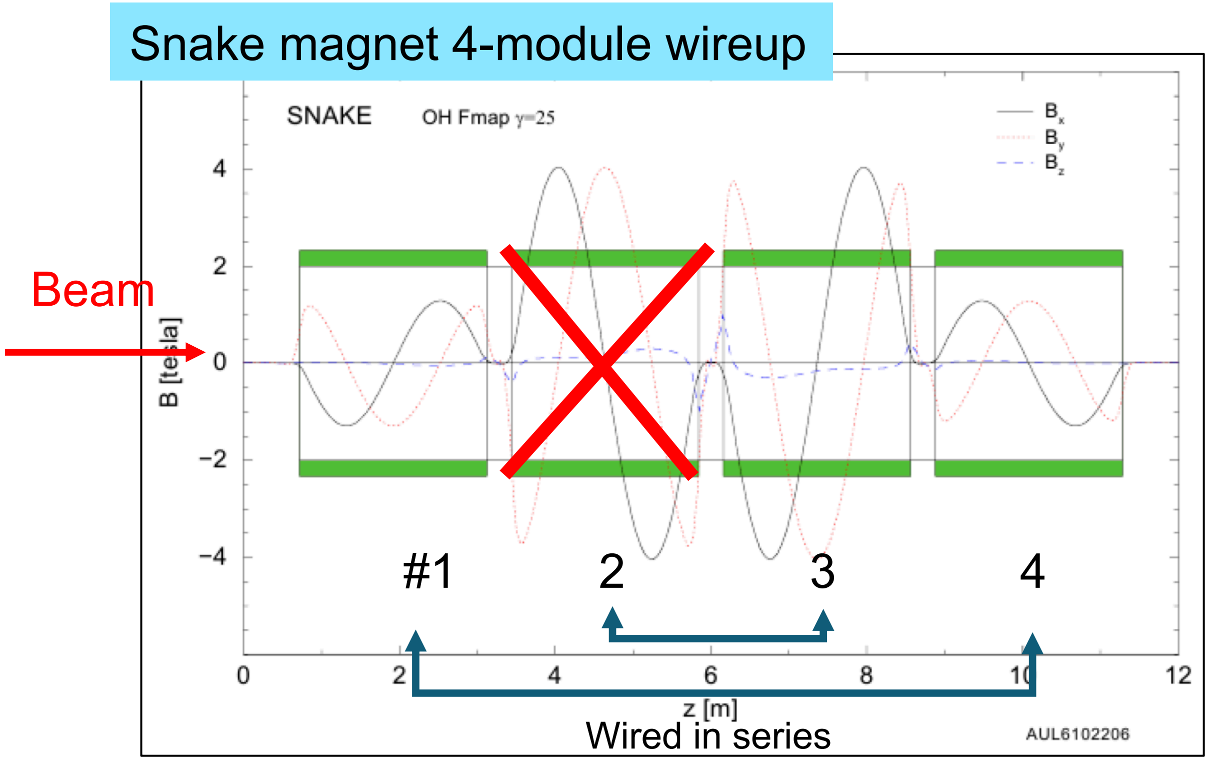

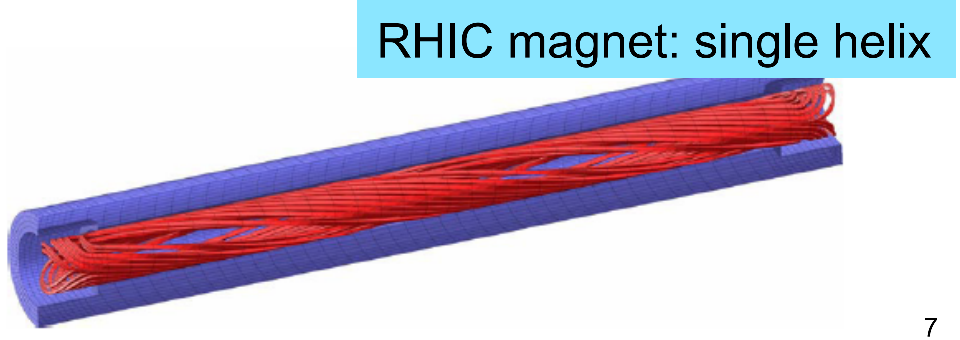

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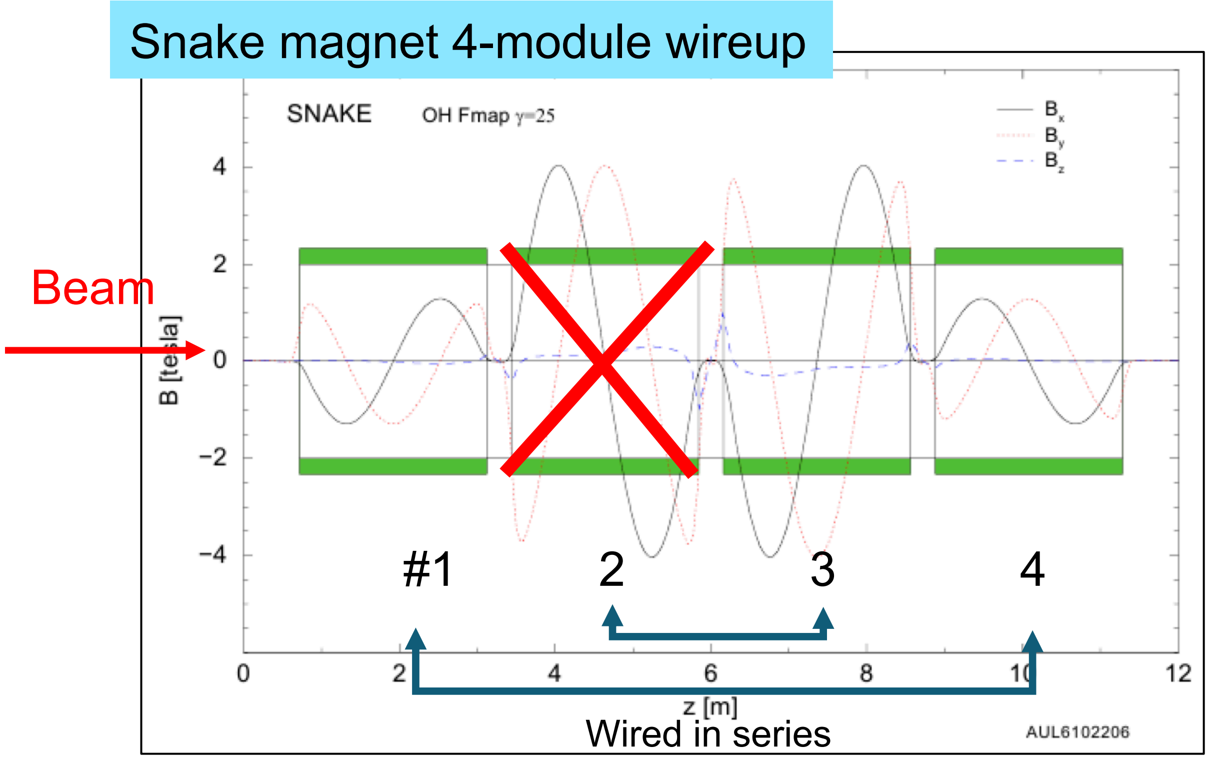

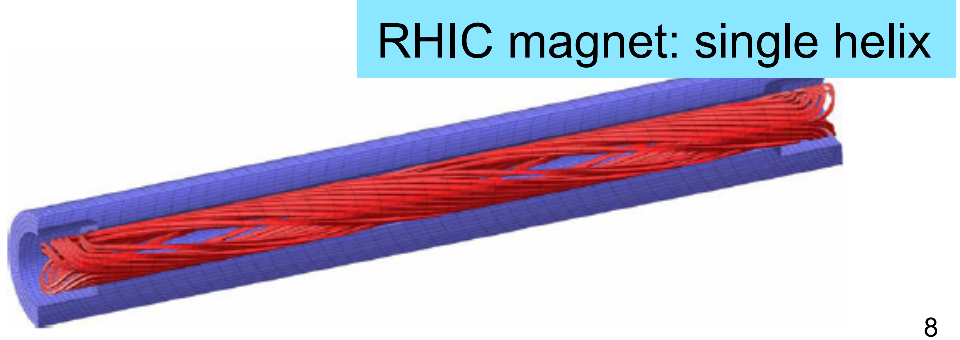

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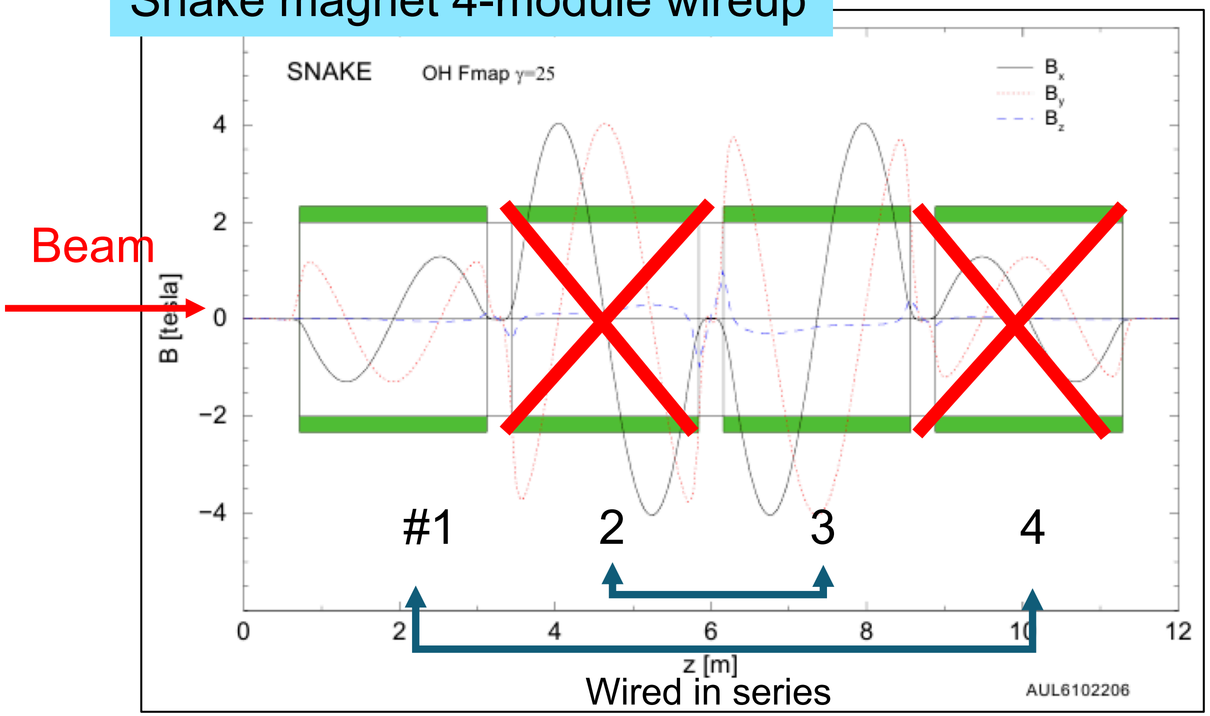

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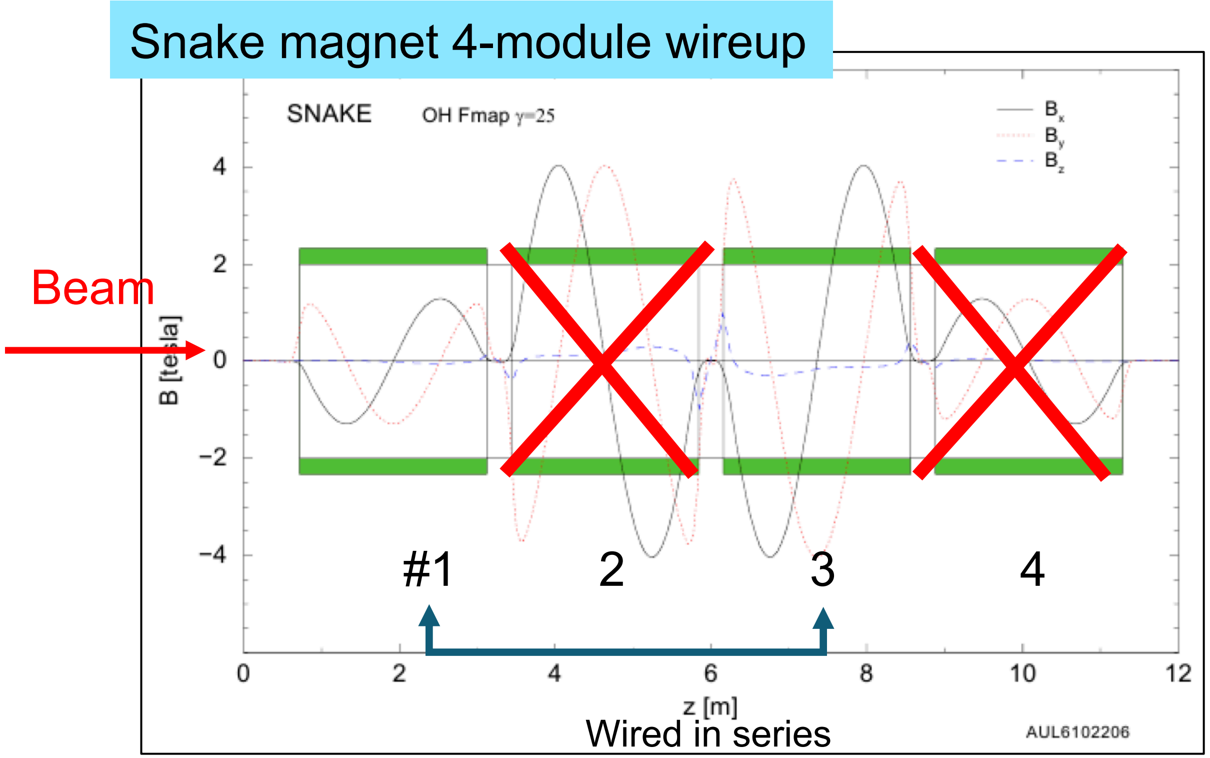
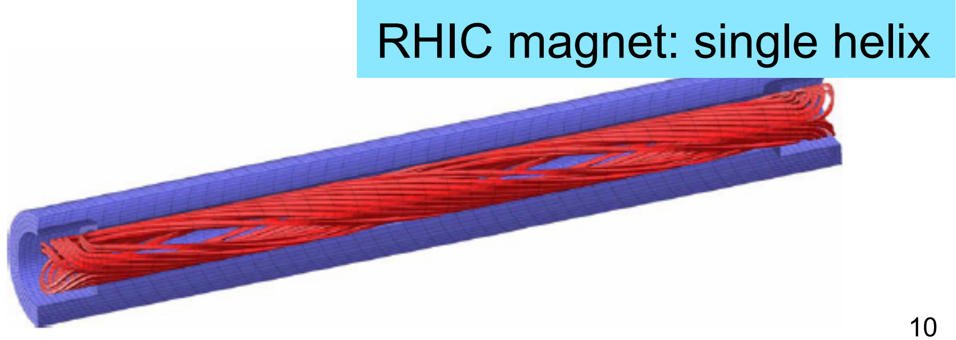




Impact of snake failures: diagnosis and repair

Total time spent on snake equipment diagnosis and modification of bi9 snake (including installation of UPS): ~50 hours

Includes only direct power supply work, not end effects, impact to other scheduling decisions etc.

Beam work continues during this time, without snakes largely to make conditions as robust as possible to avoid losses around the snakes due to injection and instability

Diagnosing and Recovery(running with different magnet arrangement)			
Date	Duration (hours)	Work description	
12/3/21	2	Figure out why bi9-snk7-2.3 would not come back on after power dip	
12/4/21	8	Diagnosing bi9-snk7-2.3	
12/5/21	3	Diagnosing bi9-snk7-2.3 storage unit 2 open	
12/7/21	3	Running bi9-snk7-1.4 to high current without bi9-snk7-2.3	
12/8/21	3	bi9-snk7-1.4 polarity swapped	
12/9/21	3	Troubleshooting of bi9-snk7-1.4 and found bad ground current monitoring chassis	
12/12/21	1	Power dip and then bi9-snk7-1.4 problem-not much time this day maybe 1 hour looking at the QD	
12/13/21	8	bi9-snk7-1.4 storage unit 4 open-diagnosing	
12/15/21	8	Connecting storage units 1 and 3 onto ps bi9-snk7-1.4	
12/17/21	5	UPS installation	
12/18/21	5	UPS installation	
Total	**50**	**hrs**	over about two weeks

Effort breakdown courtesy of D. Bruno

Partial snake configuration

Partial snake rotates about less than the 'full spin flip' 180°. Here rotation is about 90% of ideal about an axis that is not quite the ideal 45° to longitudinal

Produces imperfection resonances and shift in spin tune

	Full snake	Partial snake	
Rotation angle	180	163	deg
Rotation axis*	42	45	deg
* In horizontal plane, angle w.r.t longitudinal			

Three main worries with one partial snake:

1. Increased polarization loss during resonance crossing
2. Aperture concerns at injection
   1. Helical orbit is slightly larger in radius and different shape inside snake
3. Non-vertical design spin direction (i.e. increased spin tilt)
   1. Depolarization from injection mismatch
   2. Potential longitudinal component at STAR
   3. Systematic error in polarization measurement at IP12 with non-vertical spin

Partial snake configuration: Resonance crossings

Zgoubi tracking anticipated little to no effect on resonance crossing from operation with the partial snake

Tracking validated: AGS to RHIC store polarization transmission in blue very similar to Run 17 (and higher than yellow in Run 22!)

$$\frac{RHIC\ Store\ Polarization\ (full\ beam)}{AGS\ polarization\ (fixed\ target)}$$

	Run 17	Run 22
Blue	0.81	0.79
Yellow	0.81	0.76

Full run averages

Resonance crossing at 393+

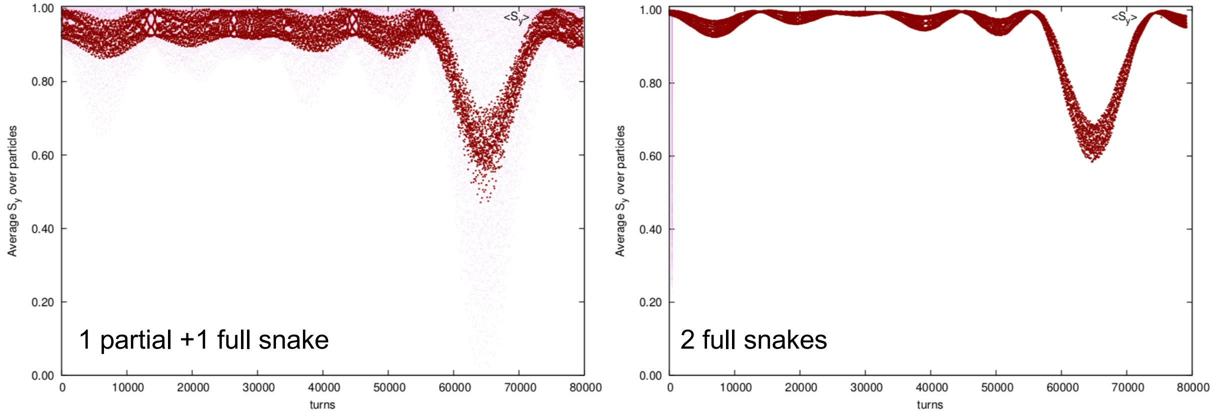
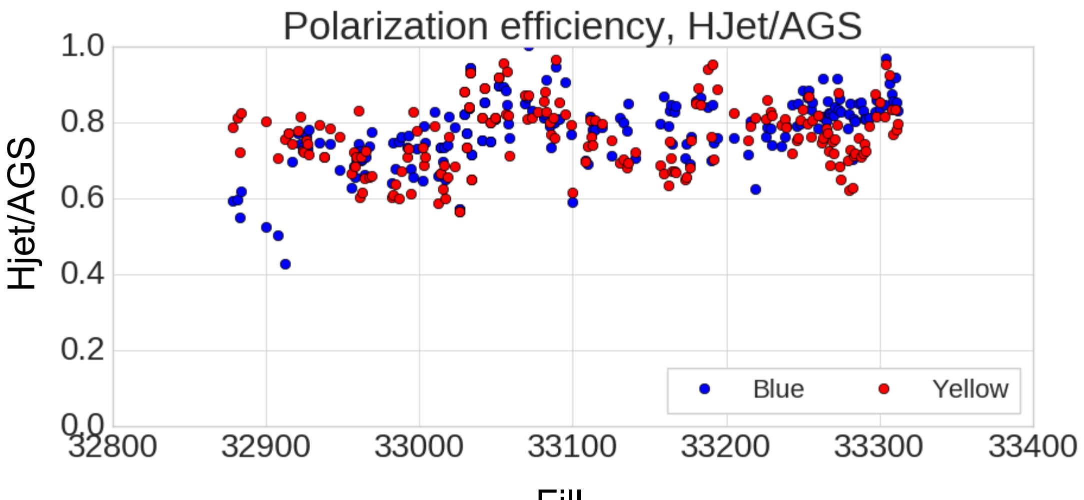


Figure 25: Crossing of 393+Qy. Case of 9 O'clock snake 88% (left), for comparison with Fig. 24, and case with both snakes full (right). Red curve: turn-by-turn $\langle S_Z \rangle$, an average over the 3 particles tracked. Blue: the 3 individual particles.



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Zgoubi tracking anticipated little to no effect on resonance crossing from operation with the partial snake

Tracking validated: AGS to RHIC store polarization transmission in blue very similar to Run 17 (and higher than yellow in Run 22!)

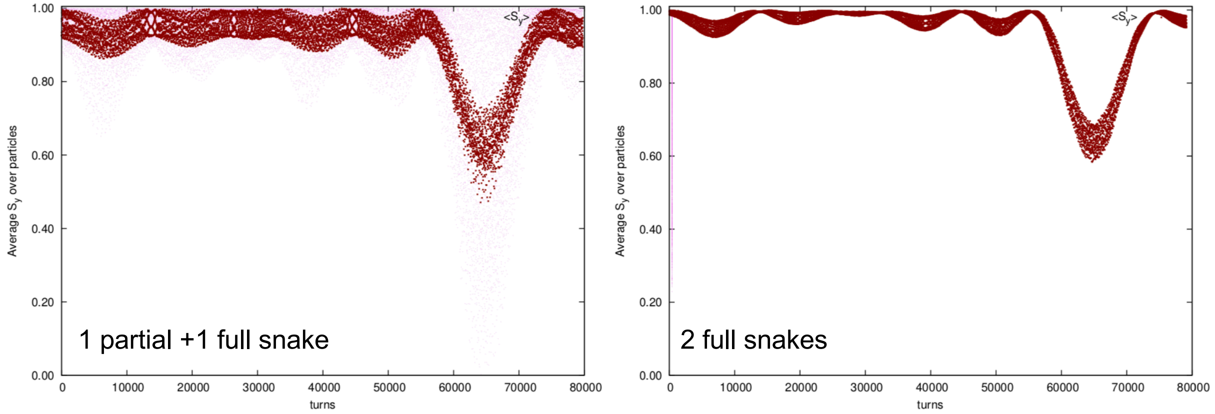
$$\frac{RHIC\ Store\ Polarization\ (swept\ target)}{AGS\ polarization\ (fixed\ target)}$$

	Run 17	Run 22
Blue	0.81	0.79
Yellow	0.81	0.76

Full run averages

Side note: The low Run22 yellow transmission, in a ring with working snakes, is a total mystery to me

Resonance crossing at 393+



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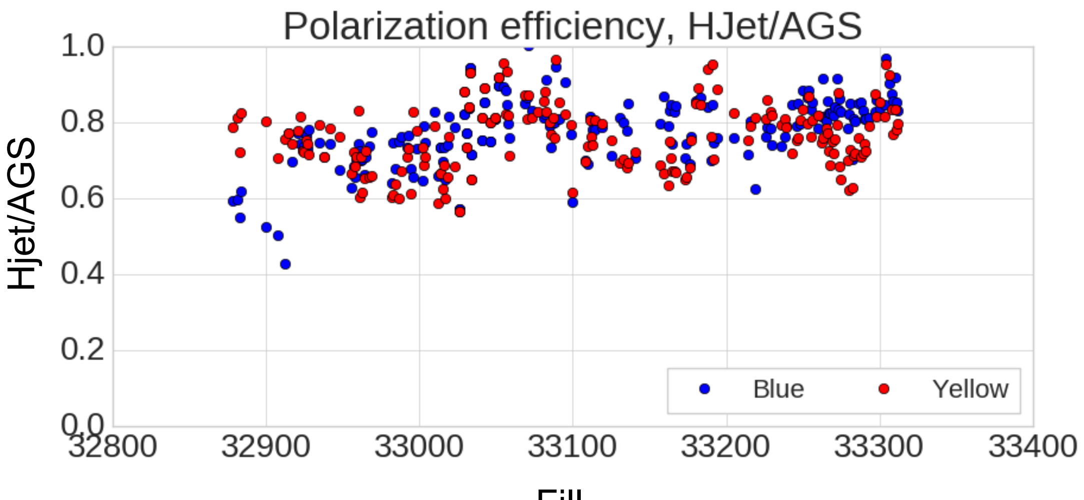


Partial snake configuration

Three main worries with one partial snake:

1. Deteriorated resonance crossing → Actually…not so bad
   (but then why is there *any* polarization loss with full snakes?)

2. Aperture concerns
   1. Helical orbit is slightly larger in radius and different shape inside snake

3. Non-vertical design spin direction (i.e. increased spin tilt)
   1. Depolarization from injection mismatch
   2. Potential longitudinal component at STAR
   3. Systematic error in polarization measurement at IP12 with non-vertical spin

Partial snake configuration: Aperture

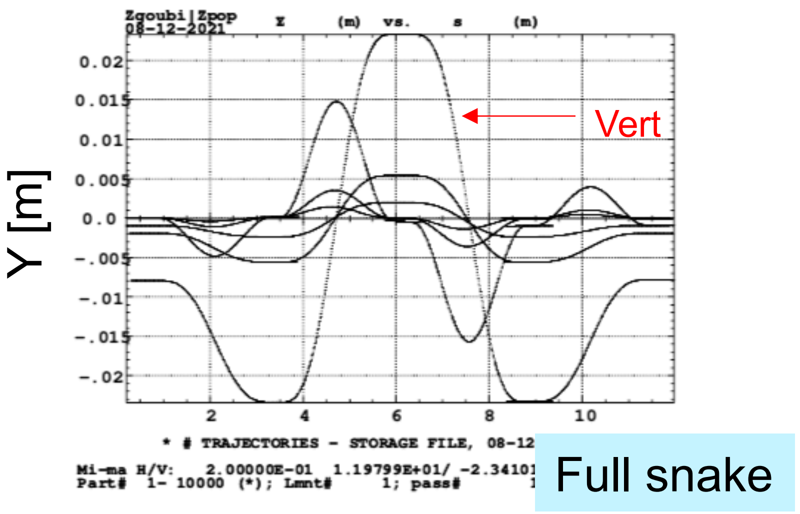
Modeled trajectories:

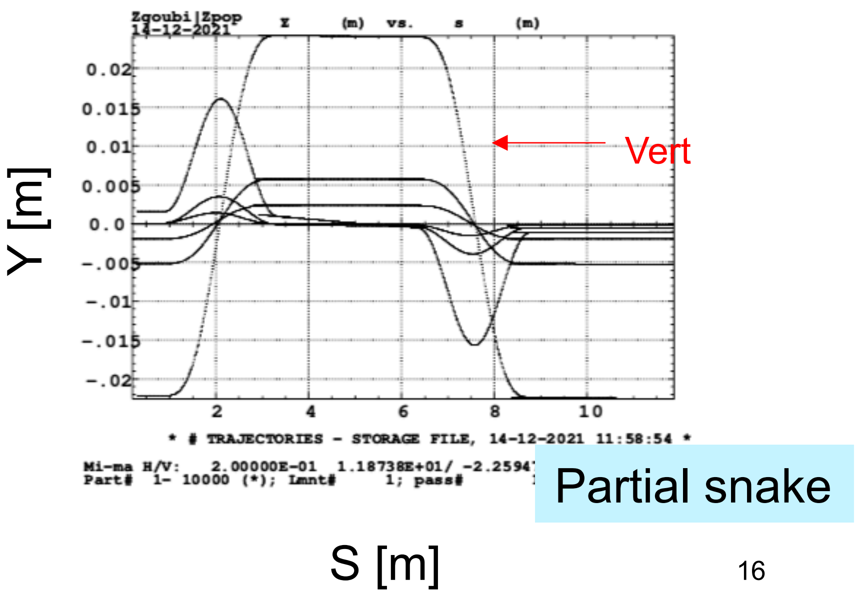
- *maximum* vertical excursion very similar in full and partial snake configuration
- *Shape* and incoming position very different

- Model assumes zero incoming angle (not true in actuality)

- Observation: operation with partial snake at 320 A put beam very close to aperture
  - Tight steering tolerances (sub-millimeter)
  - Continuous lifetime tuning necessary at injection energy
  - Many permit pulls
    - Particularly late in a blue fill: injection loss + injection kicker reflection loss

Trajectories inside snake





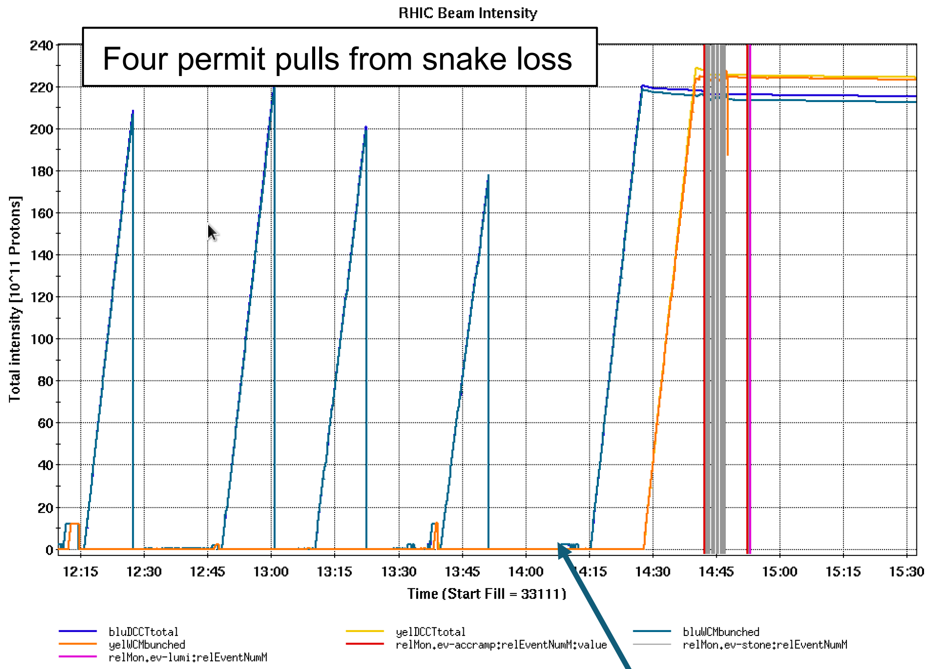
Partial snake configuration: Aperture Sensitivity and permit pulls

Fine tuning of the snake bump necessary to get consistent fills

There were about 250 fills for physics during Run 22

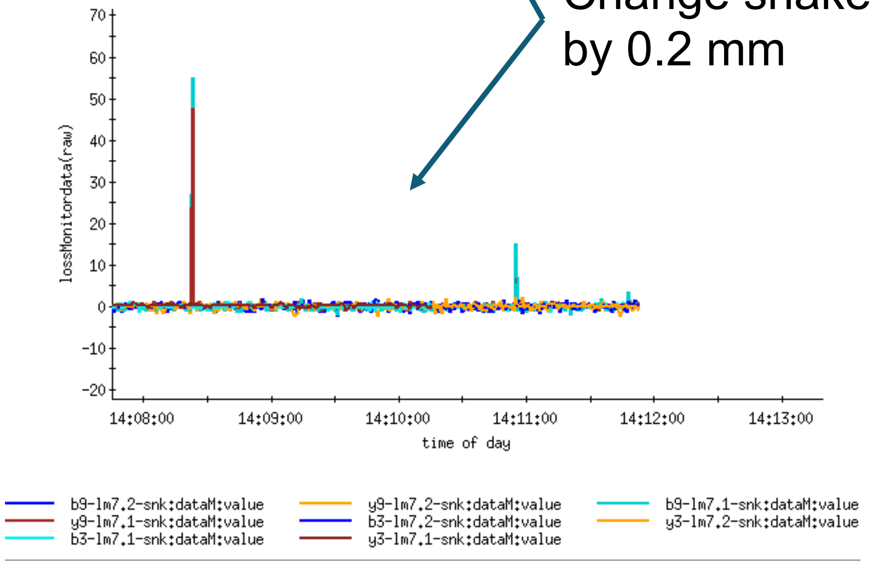
65 permit pulls due to the partial snake BLMs auto-recorded in elog for Run 22, almost exclusively at injection (some early ramp)

RHIC DCCT



Change snake bump by 0.2 mm

Snake BLM signal

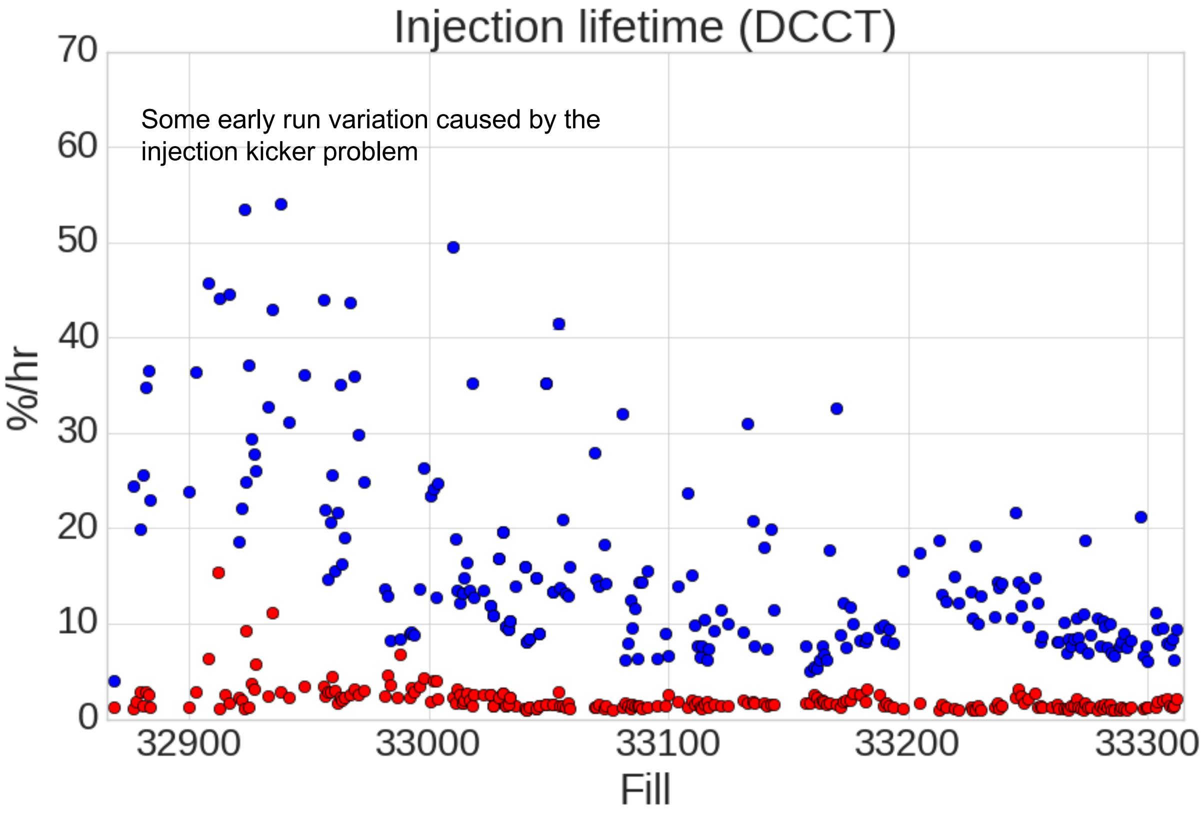


Partial snake configuration: Aperture
Chronic injection lifetime struggle in blue

Beam lifetime at injection both shorter and more variable in blue than in yellow (and compared to history)

Accounts for a lot of the store-to-store variation in luminosity (tentative statement, could be analyzed statistically)

Injection lifetime unusually sensitive to small changes (emittance, etc.).



Partial snake configuration: Aperture

Snake BLM losses, ‘good’ fill

Blue injections cause snake BLM (b9-lm7.1) losses

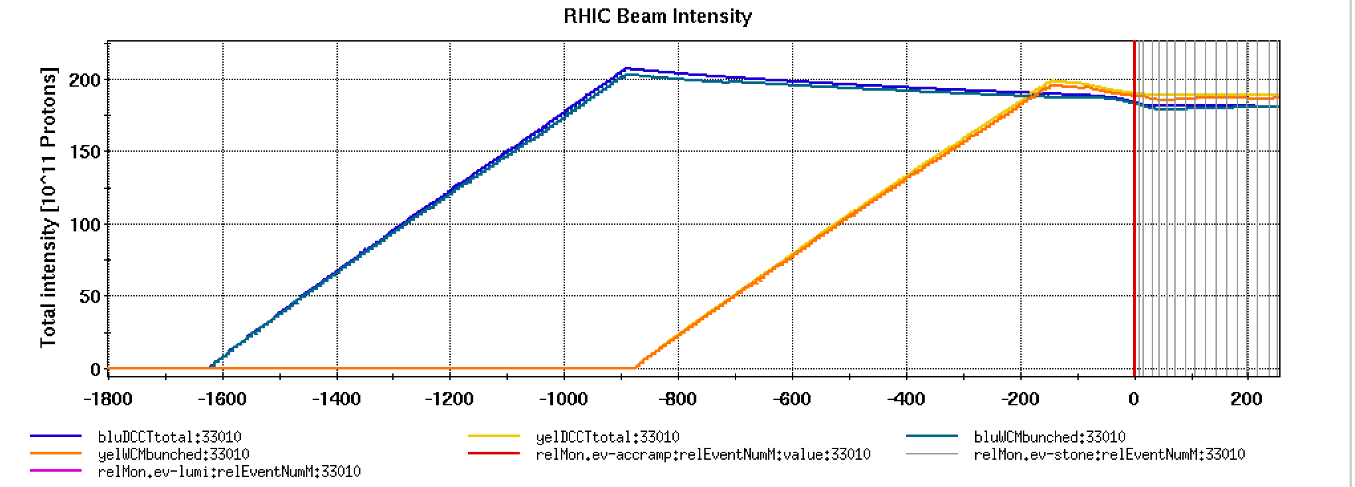
Losses from blue injections seen by the adjacent yellow snake BLM large even than anything from yellow injections

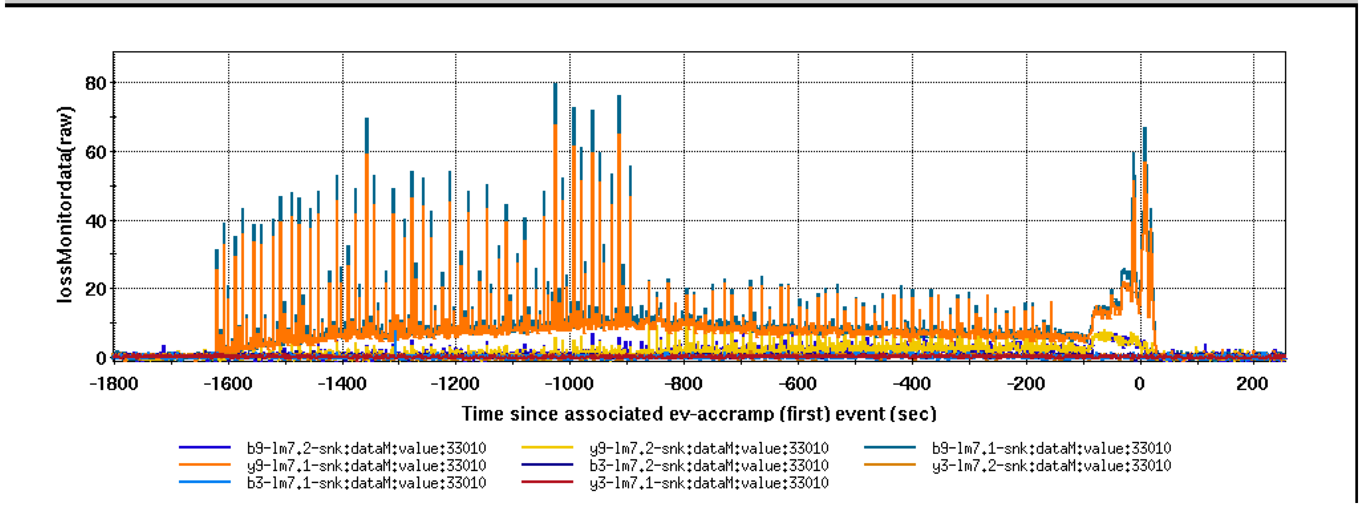
Evidence of accumulating circulating loss

Early ramp losses, drop quickly to zero as the rigidity increases

Proposed solution: Adjust optics near snakes to allow nearer-to-ideal zero angle incoming trajectories

(not implemented due to time and worries about Marusic-free adjustments of the ramp)
Still worth looking at for Runs 24,25 and EIC life with 6 snakes





Partial snake configuration

Three main worries with one partial snake:

1. Deteriorated resonance crossing → Actually…not so bad

2. Aperture concerns
   1. Helical orbit is slightly larger in radius and different shape inside snake → ”Solved” mostly by continuous operator and specialist attention

3. Non-vertical design spin direction (i.e. increased spin tilt)
   1. Depolarization from injection mismatch
   2. Potential longitudinal component at STAR
   3. Systematic error in polarization measurement at IP12 with non-vertical spin

Partial snake configuration: Stable spin direction

The stable spin direction with a partial snake is inherently non-vertical *at all energies*

- Potential for coherent depolarization at injection energy (where spin tilt typical very small, ~0 deg)
- Complicates the (much studied) spin tilt problem at store energy normally due only to *errors, now has a contribution from the snake*

Two main compensating efforts:

1. Adjust the ‘healthy’ full snake at 3 o’clock to compensate for partial snake effects
2. Energy scan: pick a new (nearby!) store energy with better spin closed orbit

Partial snake configuration: Stable spin direction (INJECTION)

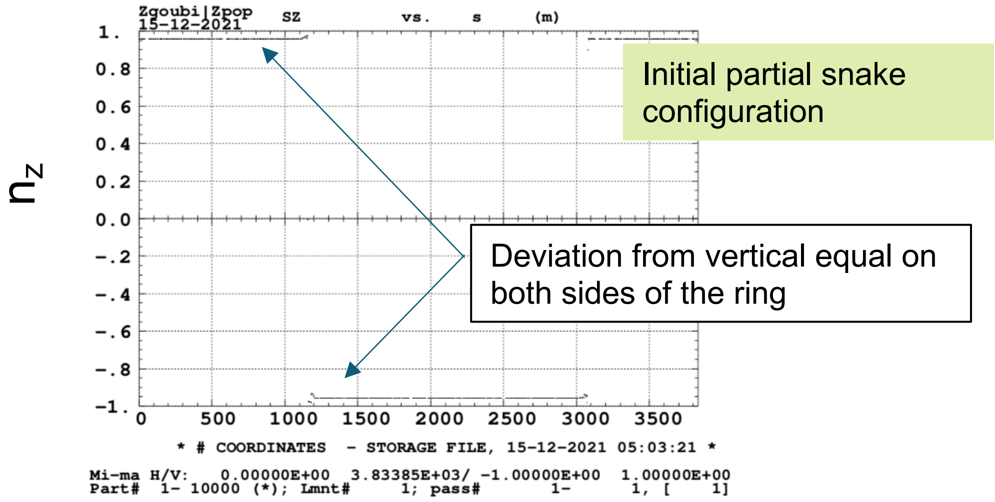
From start of run to Dec 20th:
Partial snake constant 300 A, BO3 snake 'nominal'

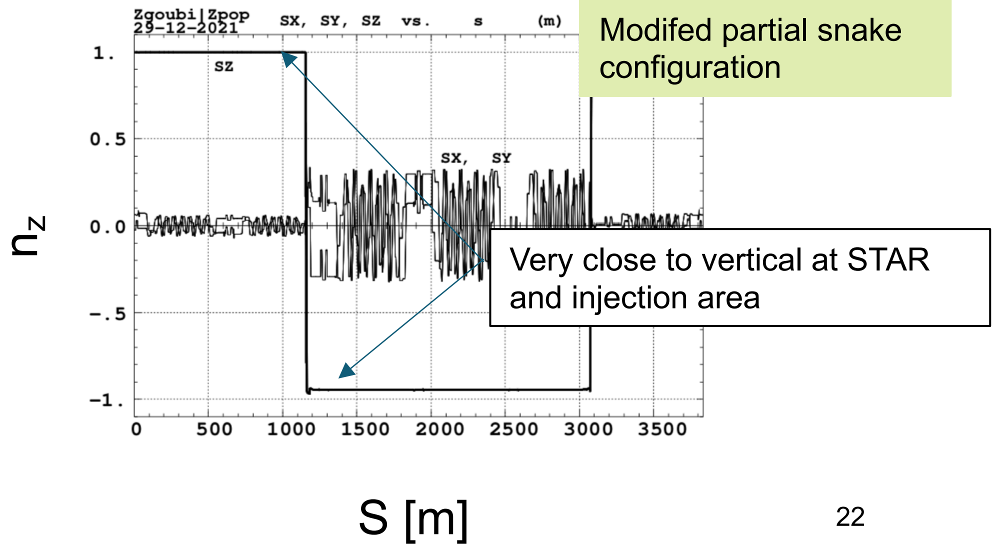
Dec 20th to Dec 29th:
Partial snake ramped 300->320 A during acceleration
(better store, injection unchanged)

Dec 29th onward:
Partial snake constant 320 A, BO3 snake modified to make spin direction at STAR/injection point closer to vertical at the expense of larger tilt in other half of ring

	Snake Current [A]	
	Original	Final configuration
Partial snake (#1,3)	300	320
BO3 full snake (inner)	323	323
BO3 full snake (inner)	100	130

Stable spin direction





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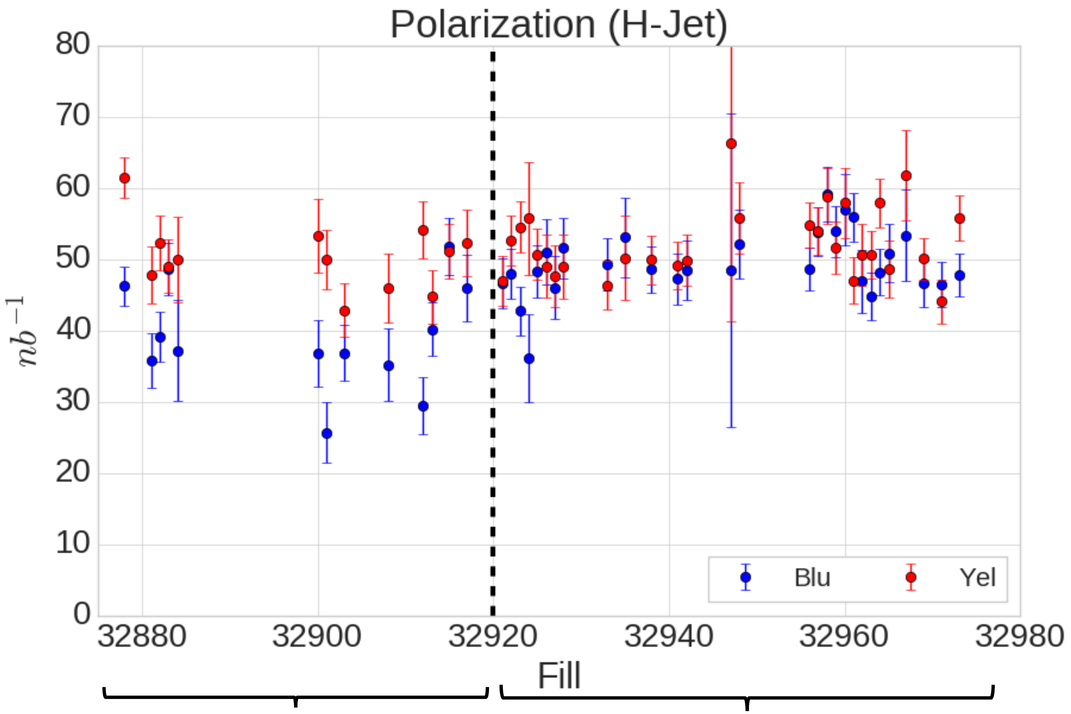


BI9 partial snake: ramped 300->320 A during acceleration

BO3 snake: 'nominal' full snake

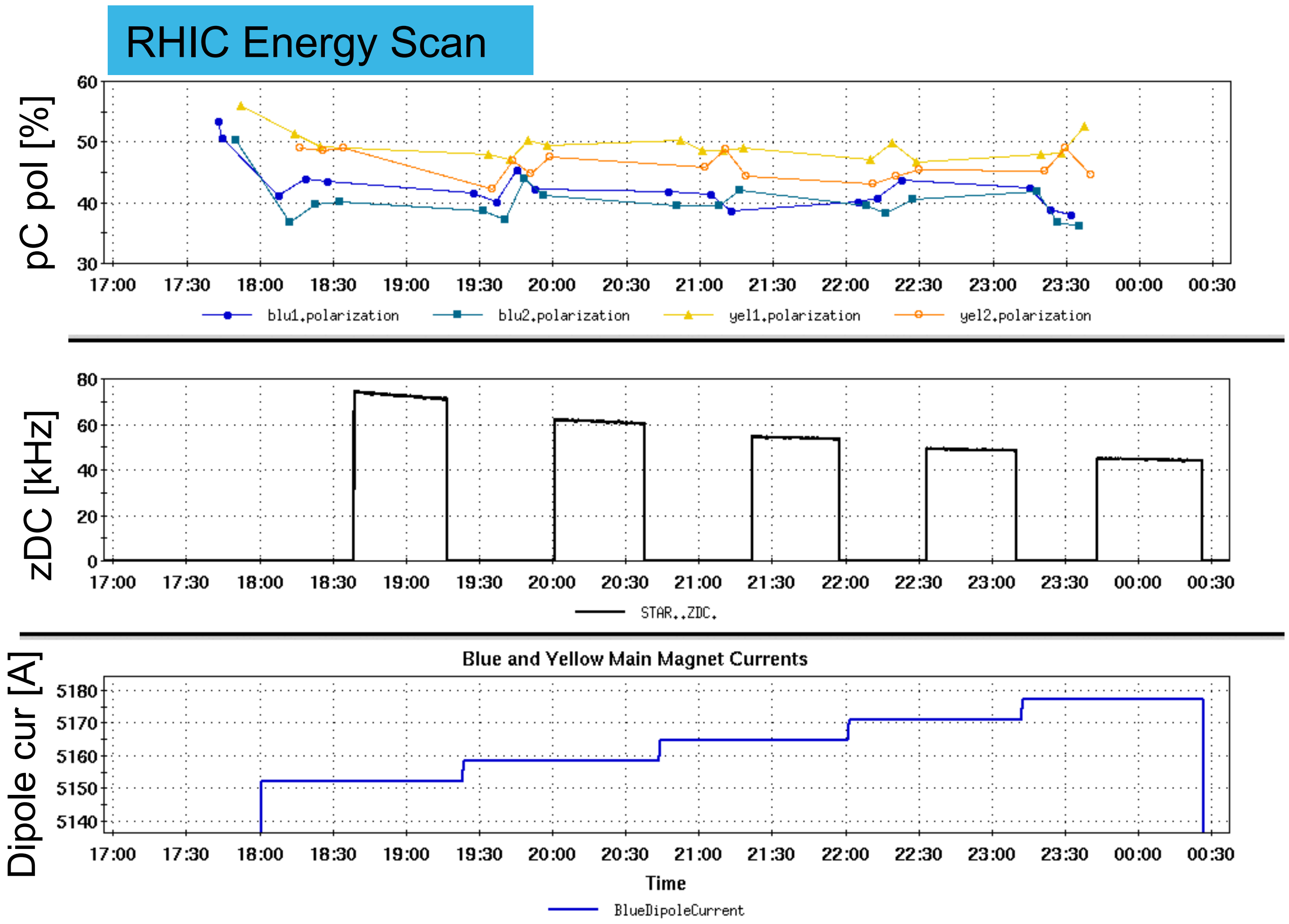
BI9 partial snake: constant 320 A

BO3 snake modified to compensate

Polarization improves from ~30's to ~50% due largely to improved injection spin matching

Partial snake configuration: Store energy scan

- Energy scan fill 32920:
  - Motivated by Run 17 results showing large rotation of stable spin for small change in energy
  - Gg=485 to 487 (nominal flattop is Gg=487)
  - Goal was to measure rotation of stable spin direction at STAR and the pC polarimeters to minimize longitudinal component
  - Address both the intrinsic non-vertical spin direction resulting from a partial snake in blue and residual spin tilt from orbit imperfections (present in blue and yellow)

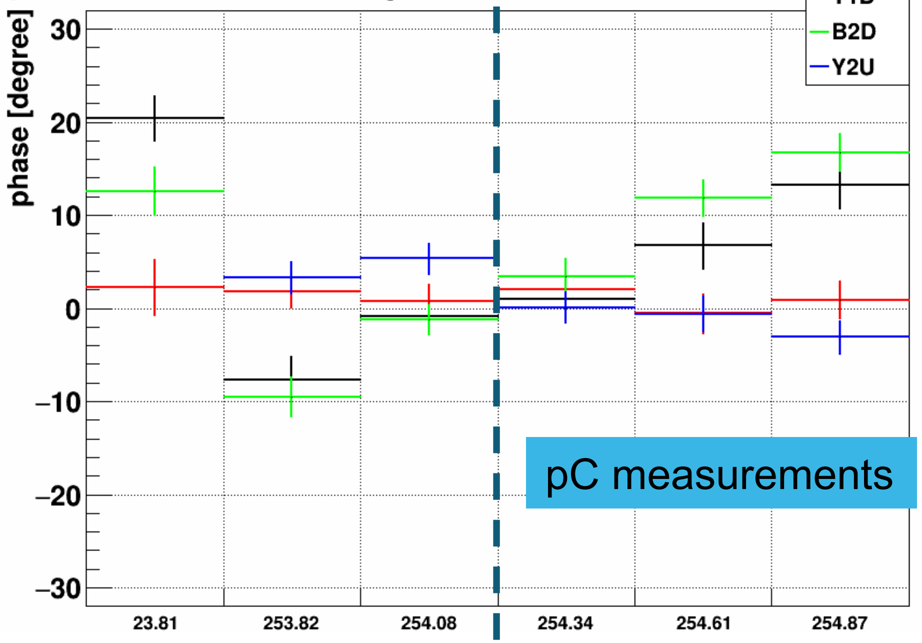


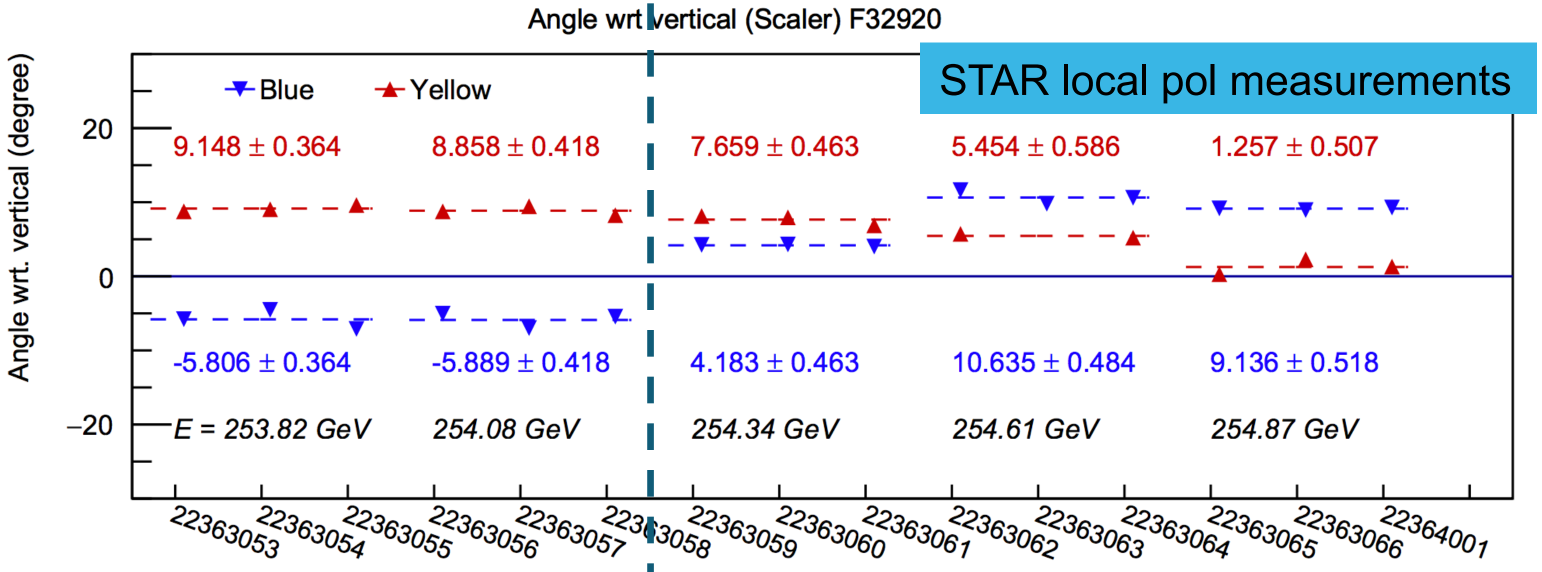
Partial snake configuration: Store energy scan

- Transverse tilt angle measured as a function of energy at both pC and STAR
- Minimum transverse component at both pC and for blue beam at STAR near *254.2* GeV.
  - Remaining residual in yellow, particularly at STAR

	Fill <32934	Fills >=32934
Rigidity [Tm]	850.141	847.958
Etot [GeV]	254.868	254.213
Gamma	271.635	270.938
Ggamma	487	485.75

Spin transverse angle measurements





Partial snake configuration: Store energy scan

- Energy change improved blue orientations (the ‘difficult’ ring)
- Yellow not much improved
    - Thinking at the time was that in yellow, with two ‘healthy’ snakes, had more corrective knobs

- Total asymmetries during the energy scan were largely constant – gave some confidence we were not just ‘hiding’ a huge tilt in the longitudinal direction

- Leaves the problem of measuring the total spin orientation, including longitudinal (to be discussed later)

Change in transverse angle (degrees)

	Energy [GeV]:	*255*		*254.2*
BLUE	pC	18	-->	0
	STAR	5	-->	0
YELLOW	pC	-1	-->	5
	STAR	5	-->	7

Uncertainty for these measurements,
pC; ~3 deg
STAR local pol measurement: ~0.5 deg

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→ Re-calculated settings for the working blue snake to improve matching

Energy change to re-orient spins at key locations

Part I: Tales of woe

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- The Siemens failure and the costs of operation with Westinghouse
- The injection kicker resistor problem

Siemens vs Westinghouse

Jan 12th: Siemens AGS main magnet motor generator fails in the evening

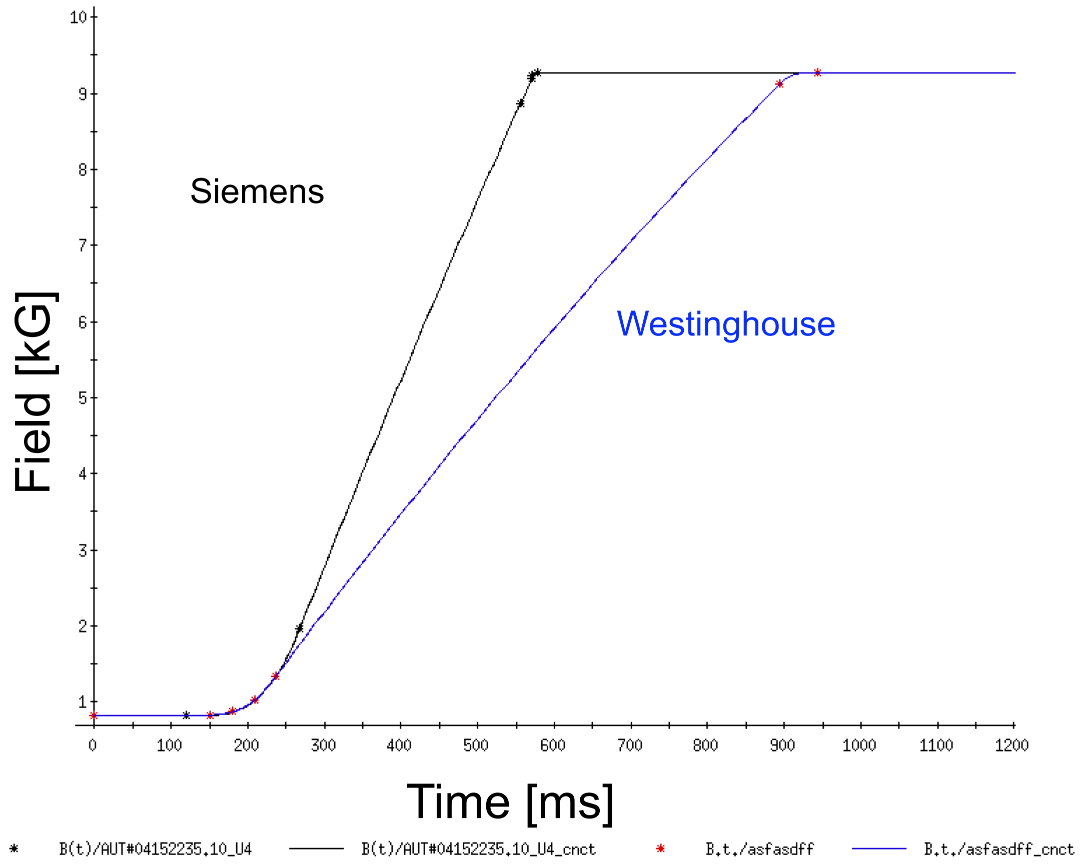
Jan 14th: Westinghouse brought on as backup on

Westinghouse has three main drawbacks relative to Siemens:
1. Slower ramp rate (factor of 2)
2. Slower 'rollover' from max ramp rate onto the flattop
3. Field stability (reproducibility shot-to-shot)

All three have impact on polarization transmission

For this talk: only discussing field stability

AGS main magnet field



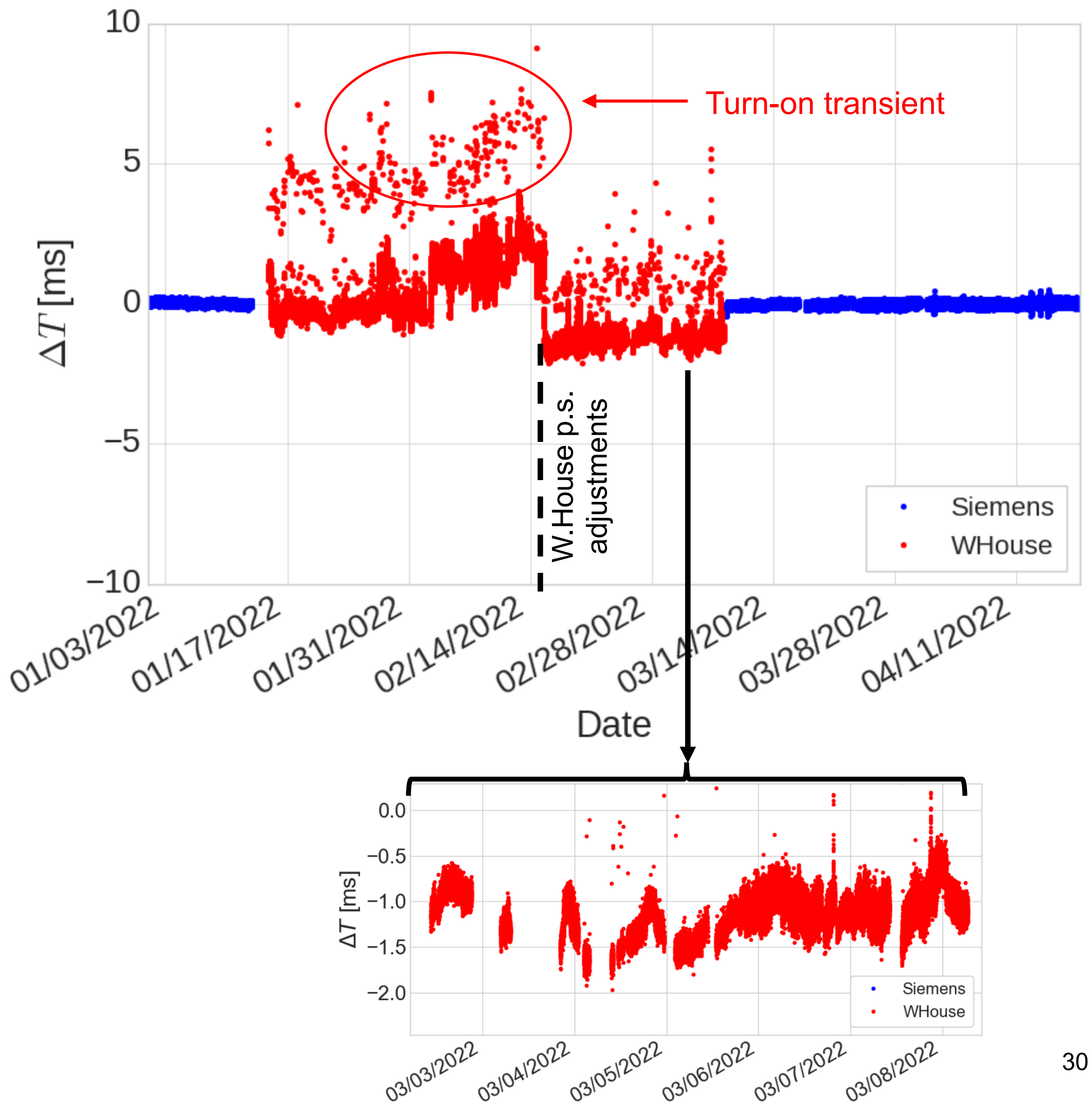
Siemens vs Westinghouse: Field Stability

Long term stability

- Time scale of hours
- Better after 2/16 power supply adjustments
  - Gain adjustments, potentiometer upgrade…
- Still up 0.5-1 ms over a day
  - Jump quad tolerance is 0.1-0.2 ms

- Drift is too much, too fast to keep up with recalculation of resonance timing

Drift in time of arrival at B=9778.6 G (~36+)



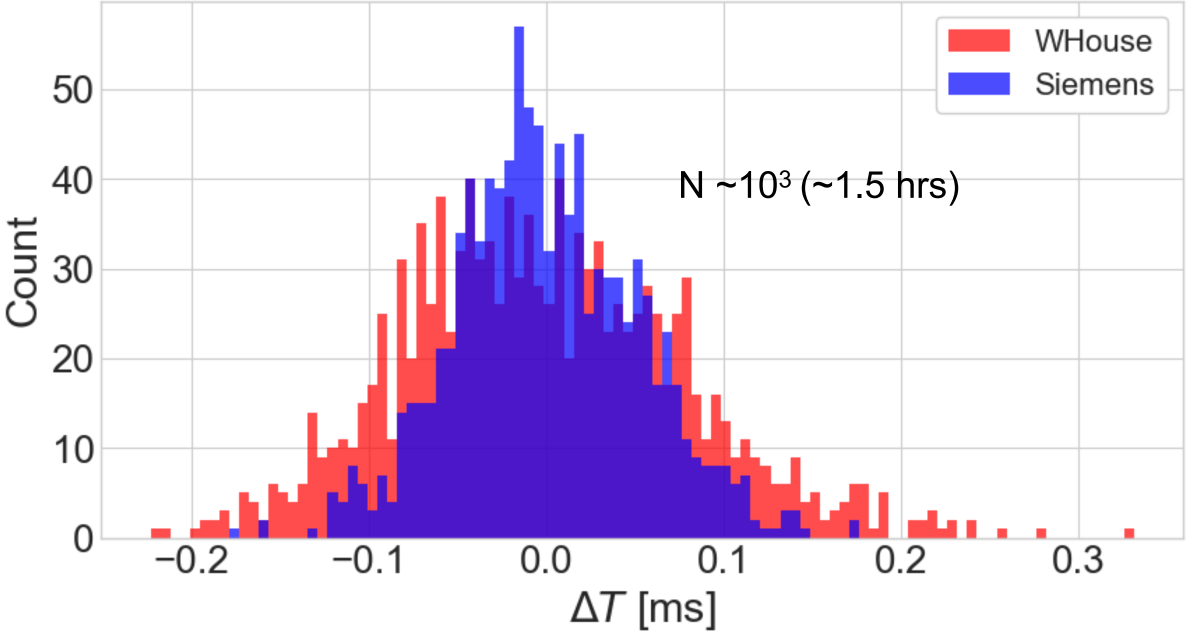
Field Stability: Siemens vs Westinghouse

Shot to shot stability

Histogram ~10^3 cycles (detrended)
σ_{WH} = 80 μs
σ_{Siem} = 50 μs

Jump quad tolerance is 100-200 μs

Westinghouse does have worse shot-to-shot variation, (especially in the tails) but maybe tolerable.



Siemens vs Westinghouse polarization

Switch back to Siemens on March 8th

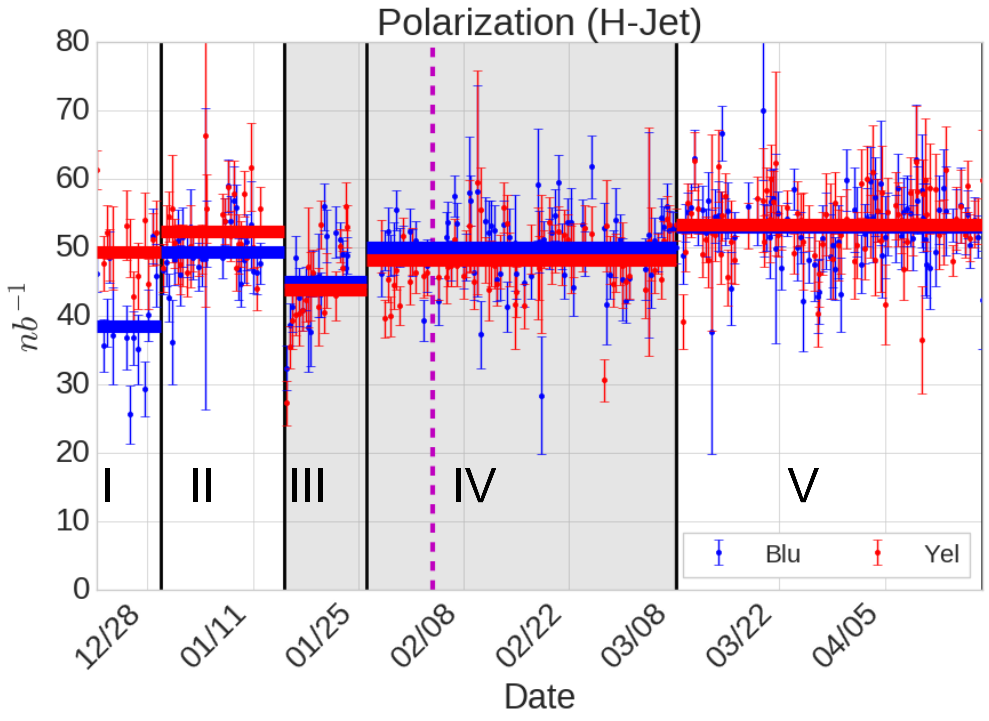
Attempt to compare Siemens to Westinghouse fairly

Compare steady state running with each over comparable time periods

Comparing polarization during periods IV and V on the right excludes most of the setup transients

Cost of operation on Westinghouse: 8% (relative) polarization drop, ~15% hit in the FOM

That is: 7.5 weeks on Westinghouse was equivalent of a loss of 1 week of FOM integration (purely due to lower polarization, not counting failure time)



Polarization by period					
	Fill start	Fill end	Note	**Blue**	**Yellow**
I	32878	32920	Siemens, non-optimal BI9 snake	**38.5**	**49.4**
II	32921	32981	Siemens, optimal BI8 snake	**49.3**	**52.3**
III	32982	33020	Westinghouse setup	**45.0**	**43.9**
IV	33021	33167	Westinghouse nominal	**50.0**	**48.1**
V	33168	33312	Siemens nominal	**53.0**	**53.4**
Full Run				***50.0***	***50.5***

Siemens vs Westinghouse polarization: looking forward

Conclusions and suggestions regarding Westinghouse

1. The Siemens failure could have lasted the whole run.
    1. A 20 week polarized proton run on Westinghouse is the equivalent of 3 weeks shorter than a run on Siemens. This is a not a strong backup. For days: yes, For weeks: barely, for a run: no.
2. We should *definitely* do more analysis to account for how much each effect (ramp rate, rollover, jitter and drift) impact polarization
    1. Looks like drift is more important than shot-to-shot
3. Investigate the use of a software feedback loop to combat drift (provided it is a strong enough effect).

Part I: Tales of woe

- The blue snake failure and operation with a partial snake
- The Siemens failure and the costs of operation with Westinghouse
- The injection kicker resistor problem

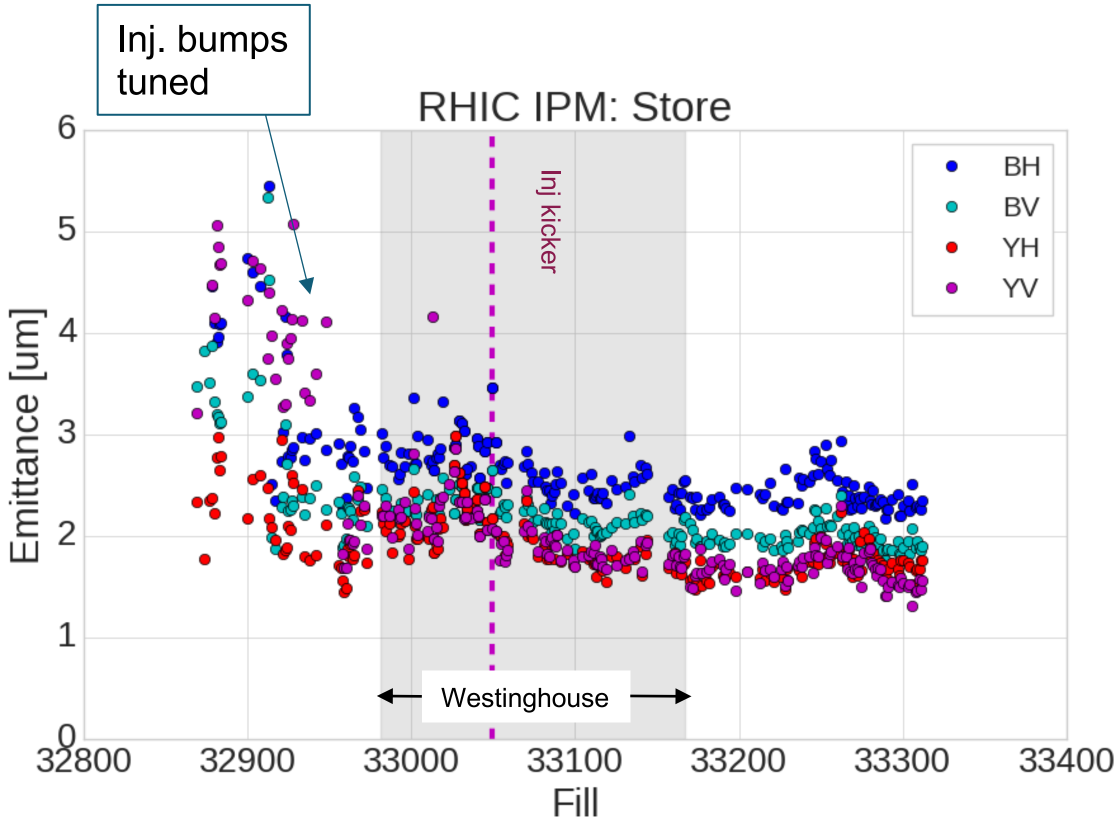
Injection kicker resistors

For normal transfer rigidity (~81 Tm), 25 Ω terminating resistors used in the kickers (higher current, poorer pulse shape)

Swapped out for 40 Ω resistors for the low energy run to improve performance with the long bunches…but the kick amplitude is lower (not an issue at low energy).

The 40 Ω resistors inadvertently installed for Run 22 (transfers at 79 Tm), resulting in a too-weak kick by 10-15%

Indications as early as the first week of injection (Dec 10th) but understanding and diagnosis complicated and delayed by other operational difficulaties (i.e. the snake failures).



Impact of injection kicker resistor error:

1. Large emittances
2. Time spent threading and maintaining efficiency through injection area
3. Slowed startup

Very hard to quantify because of entanglement with snake problems

Confounding factors

‘Big ticket’ difficulties centered around: AGS polarization (Siemens vs Westinghouse) and AGS to RHIC beam transfers (snake aperture, injection kicker)

Other ‘auxiliary’ problems:

- AGS polarimeter noise: large fluctuations (high χ^2) made consistent measurement, diagnosis, scans difficult. Ultimately traced to a timing issue
- AtR transformer saturation: difficult to assess injection losses
- AGS DCCT calibration pulse miscalibrated: difficult to assess AGS extraction loss (many hours chasing geese…)

Having to cope with many little problems makes coping with big failures (when they arise) much more difficult.

Part II: Tales of triump(ish)

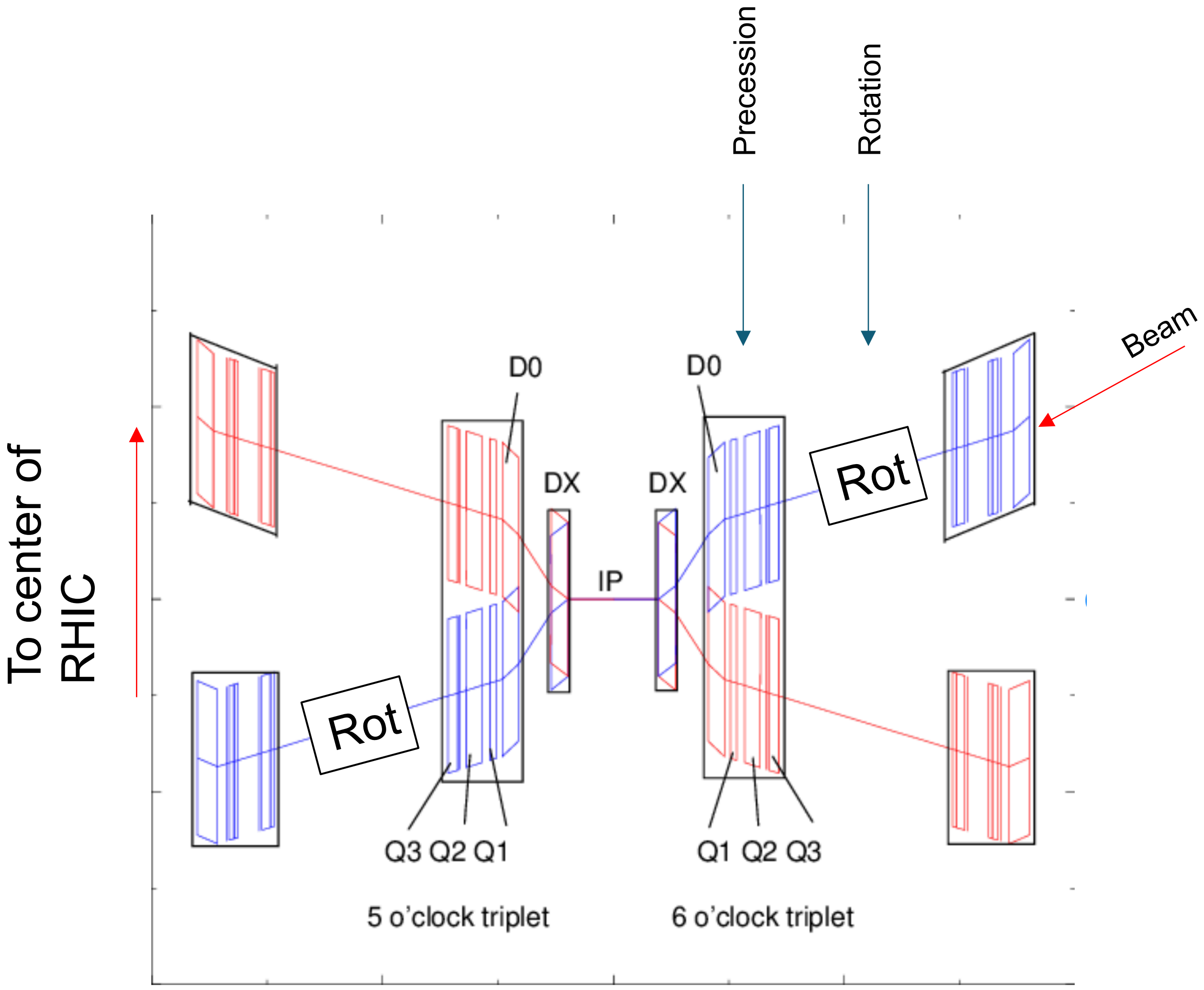
- Spin direction measurements
- Split/merge development in the injectors
- Pre-fire protection

Spin direction at STAR

Idea of measurement (Elke Aschenauer):

- Longitudinal component is invisible to local polarimeery
- Ramping up rotators *as if* for a longitudinal run normally rotates the *vertical* component into *longitudinal*
- That same rotation transforms any original longitudinal residual into a transverse direction
  - Invisible is now visible

- Analysis is straightforward, but not trivial. The precession in the DX/D0 system is ~100 degrees at 254.2 GeV. Not negligible.



Spin direction at STAR

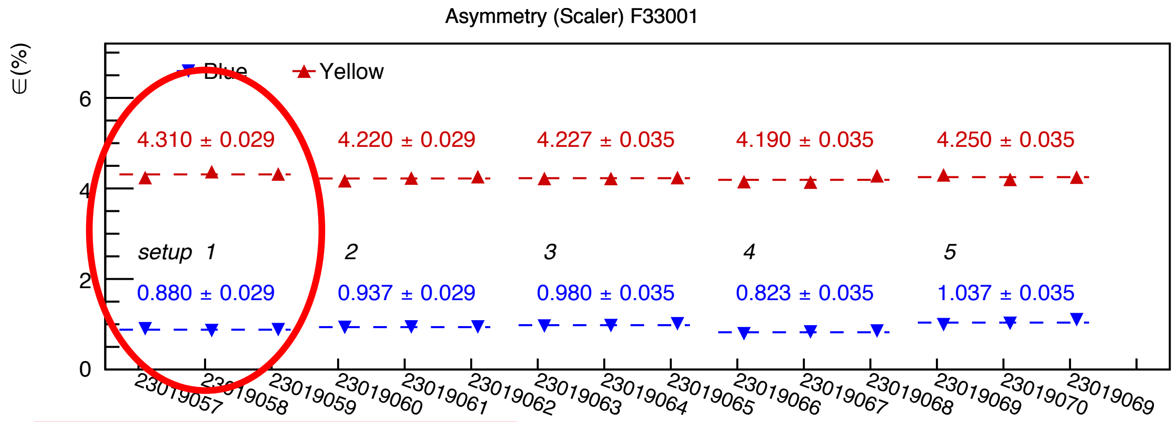
Rotator experiments showed small residual longitudinal component in blue and almost none in yellow (not shown)

'Small' means <0.1 (for |S| =1)

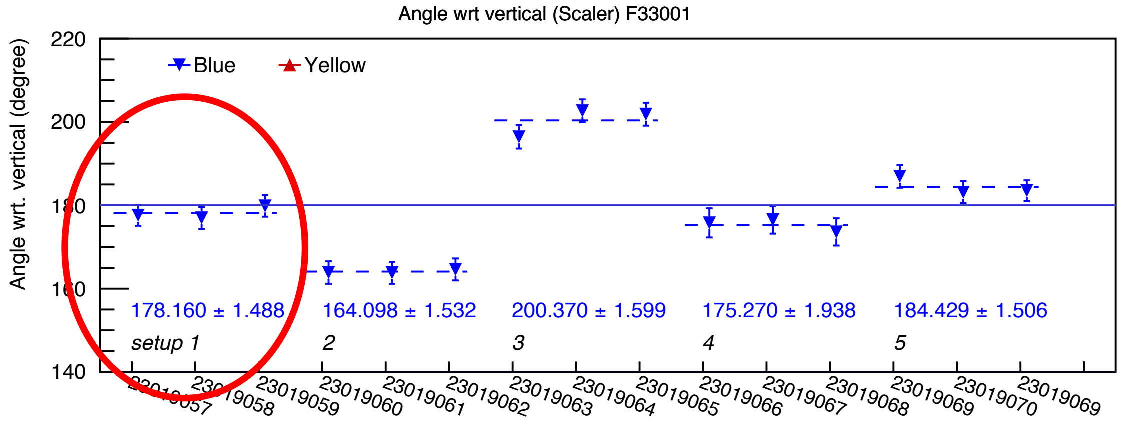
Analysis during the run done with 'legacy' algorithms designed to aid and tune actual longitudinal running – not ideal for analyzing this situation

V. Ranjbar developed better analysis algorithms, inputs to be derived from zgoubi model from F. Meot. Careful analysis and writeup over the shutdown…

STAR Local pol results: BLUE rotators on



Asymmetry is low
Spin is mostly longitudinal



Measurable transverse residual has information about original 'unrotated' longitudinal component

Spin direction at p-Carbon

Idea of measurement:

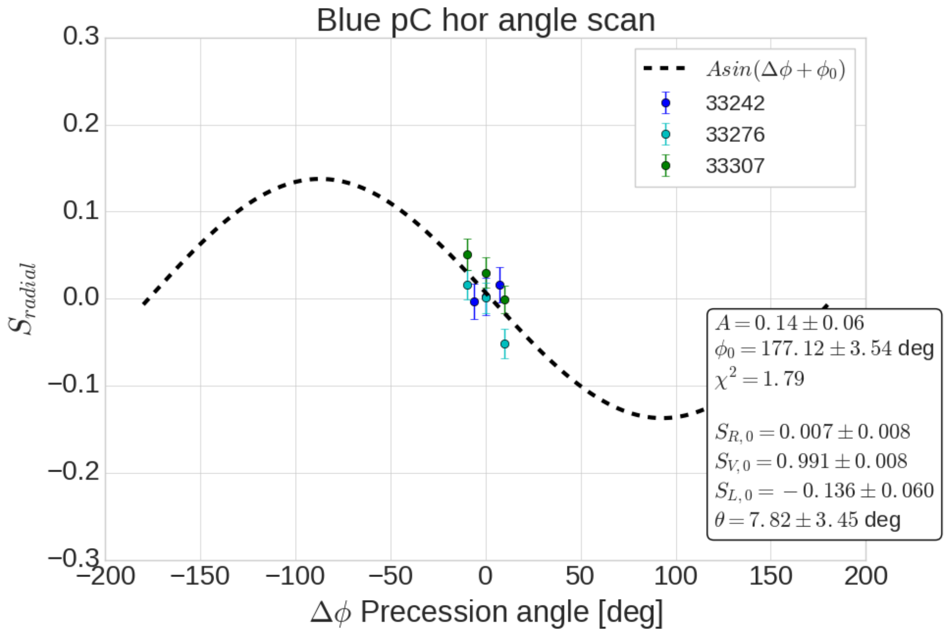
- Introduce horizontal orbital angle ψ at the pC polarimeter
- Precesses the stable spin direction about vertical by Gɣ* ψ
- Any 'hidden' longitudinal component should precess into radial and become visible

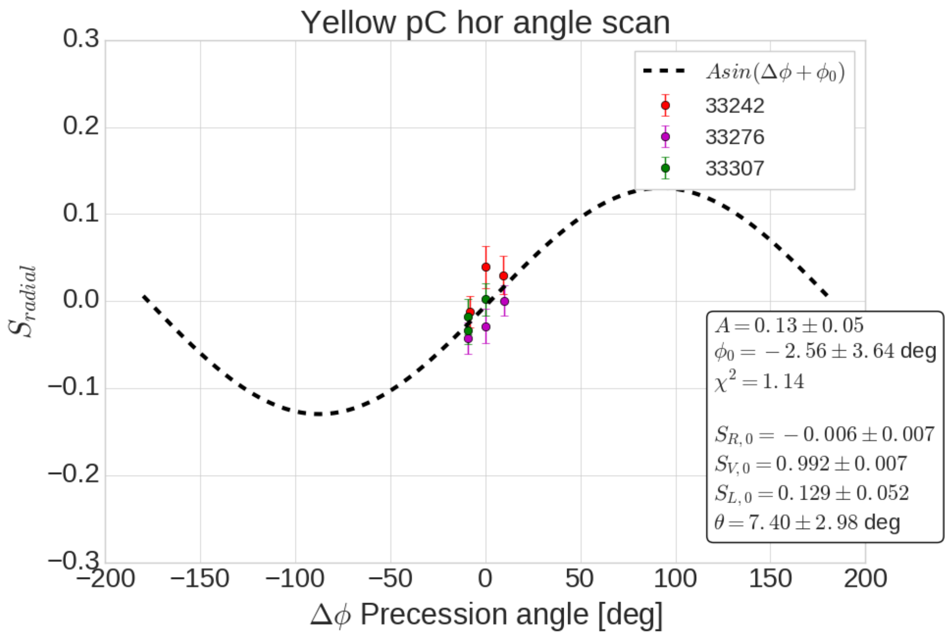
Achievable orbit angle +/- 350 μrad
Achievable spin precession +/- 9 degrees

Results required: ~100 pC measurements over 3 sessions

Spin tilt away from vertical is about 7 deg in both rings, phased longitudinally.

Transported to the H-Jet, this makes the correction to the Jet polarization of order 1% (relative). *Preliminary, needs careful writeup and scrutiny (correct coordinate frames, signs…etc).*





Injectors: Split/merge development

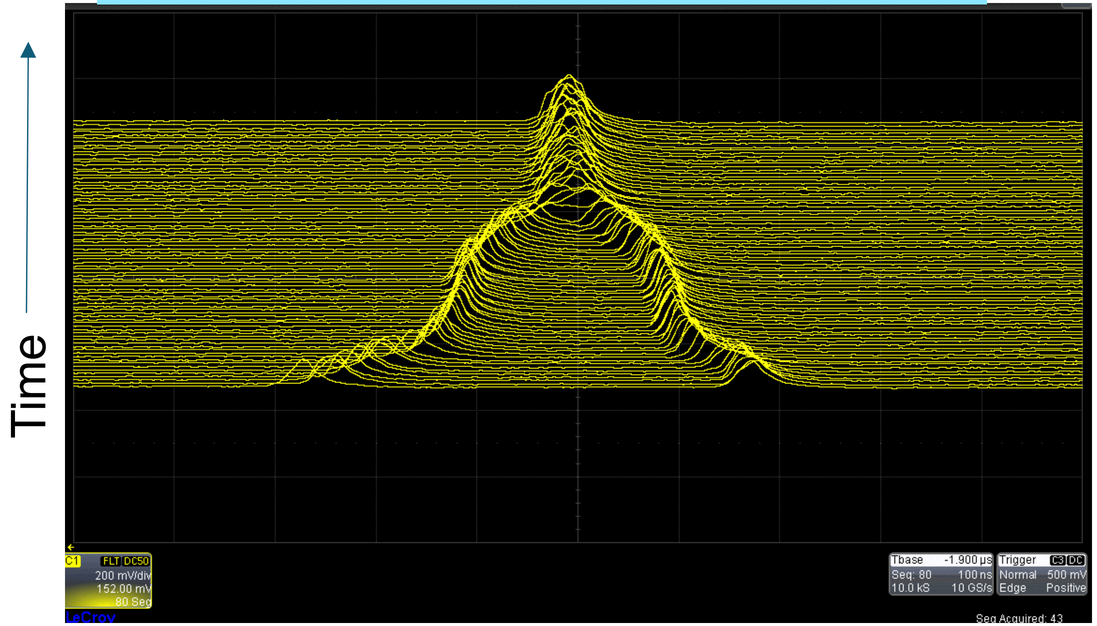
Motivated by Run 13 observation that a normal proton bunch, split in two in the Booster longitudinally had lower transverse emittances and higher polarization at AGS flattop

Merge on the AGS flattop is very slow to maintain adiabaticity (~ 1 sec).

Minimum longitudinal emittance growth from merge achieved ~25% relative to normal operation. 'Standard' setup ~ 1 eVs, merge 1.23 eVs

Split/merge used for RHIC fills from 12/27-1/12 (then interrupted by Siemens failure)

Merge of AGS proton bunches at flattop



Impact on emittance and polarization: Not obvious that split/merge does better than the dual harmonic 'stretching' of the bunches we do already. I.e. The dual harmonic makes space charge 'small enough' that we avoid harmful threshold effects (at intensities below 2.4 x 10^{11})

Deserves more careful, quantitative study both of the data taken and of space charge effects in the AGS more generally.

Pre-fire prevention

Delayed mode relays engaged for all physics fills

Not one store ended in an abort kicker pre-fire

First time in a high energy run!

A few incidents of pre-firing *without* the protection engaged

- One hysteresis ramp without beam
- at least one low intensity setup ramp (yellow, 12/8/21…I had thought there were none at all…)

More from Angelika later….

Operations and Maintenance

- Extraordinary adaptability and flexibility
- Zero beam-induced snake quenches from operations
  - Can only happen with careful attention for weeks on end
- Absorbed lot of AI-related responsibilities

An operator successfully completes a blue fill

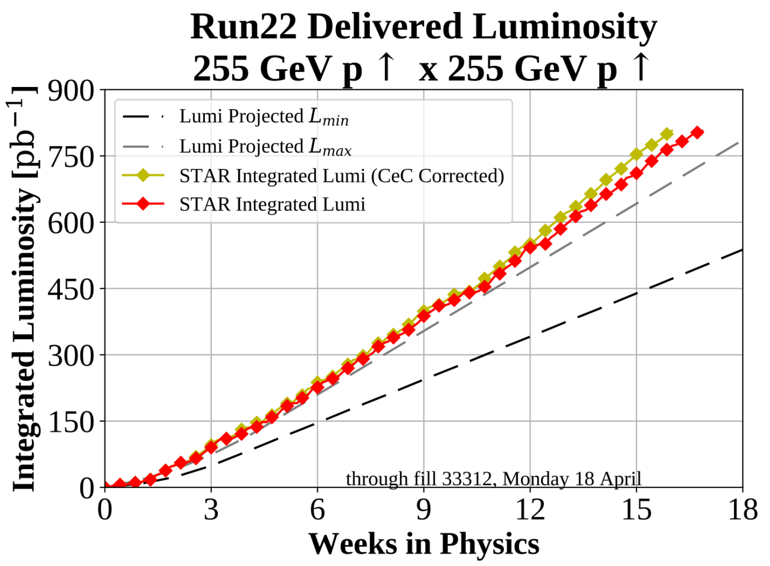
Final Score

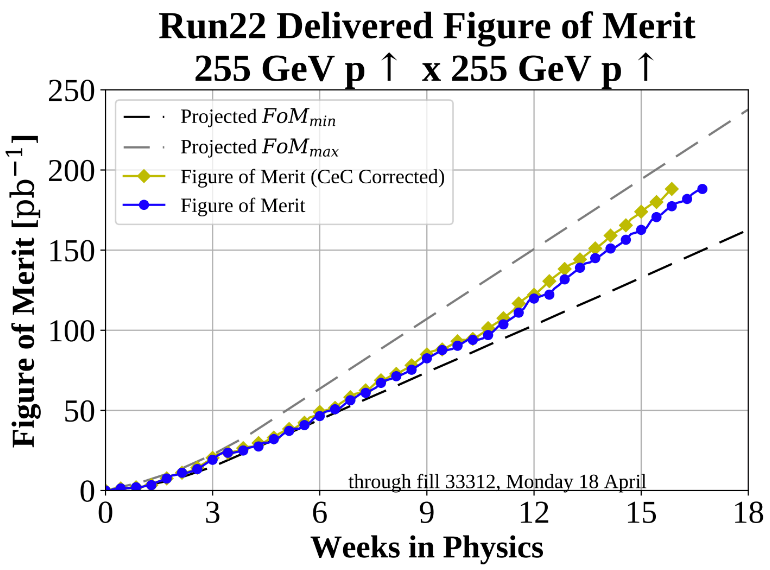
Delivered luminosity and figure of merit were, in the end close or above targets (right)

Sampled figures of merit above target or *painfully* close

Sampled Figure of Merit [pb^{-1}]

	Target	Sampled	% of goal
$L P_b^2$	120	128.6 pb^{-1}	107%
$L P_b Py$	120	117.2 pb^{-1}	97.7%





Summary

- Run 22(supposedly a repeat of Run 17) was extremely difficult due to a number high impact ‘surprise’ challenges

- Coming anywhere near meeting the goals is a testament to
  - Expertise of the technical and engineering staff to address the failures well, quickly and safely (in both CAD and the Magnet Division)
  - Expertise of the physics staff in reformulating solutions to problems (over and over and over)
  - Expertise of the operations and maintenance staff in maintaining top performance possible in whatever state we were on on any given week.

- In addition to meeting goals
  - we achieved better measurement of total spin orientation at STAR and the polarimetry than ever before
  - Commissioned import machine protection equipment