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U.S. DEPARTMENT OF ENERGY

RHIC Polarized Proton Operation in Run 22

V. Schoefer for C-AD

RHIC Retreat 5/24/2022

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Overview

Tales of woe from a difficult run:

- Blue snake failure
  - Coping mechanisms
    - Snake current changes, energy scan
- Siemens failure
  - Impact on run performance

Tales of triumph

- Spin direction measurements (both at STAR and polarimetry)
- Pre-fire prevention

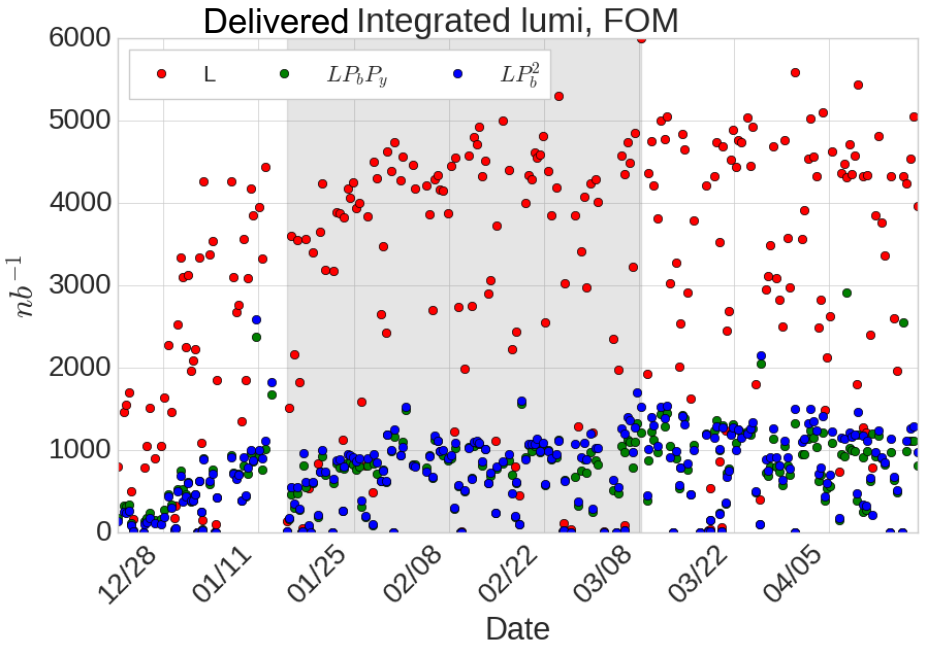
Run Overview

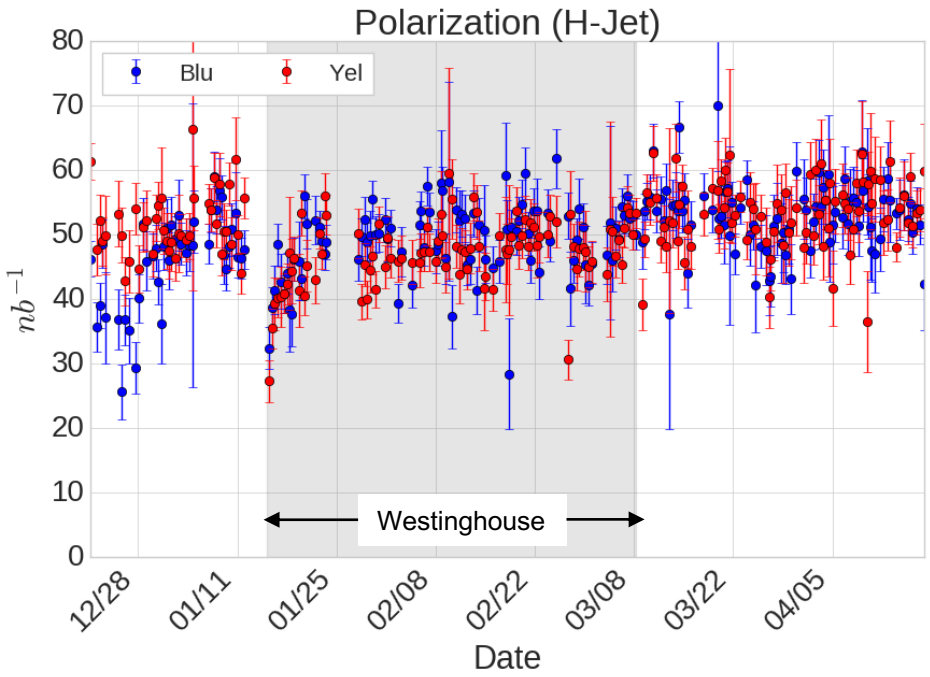
Scheduled physics plan:
20 cryo weeks

- 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)
  - AGS Siemens motor generator failure
    - operation using Westinghouse
  - 2-3 week cryo upgrade schedule overrun delay at start of run, offset by 2 week extension of run at the end

In plots;
GRAY indicates operation with Westinghouse





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The helical dipole failure

RHIC Snake magnets

Two snake magnets in each ring (at 3 and 9 ‘o’clock)

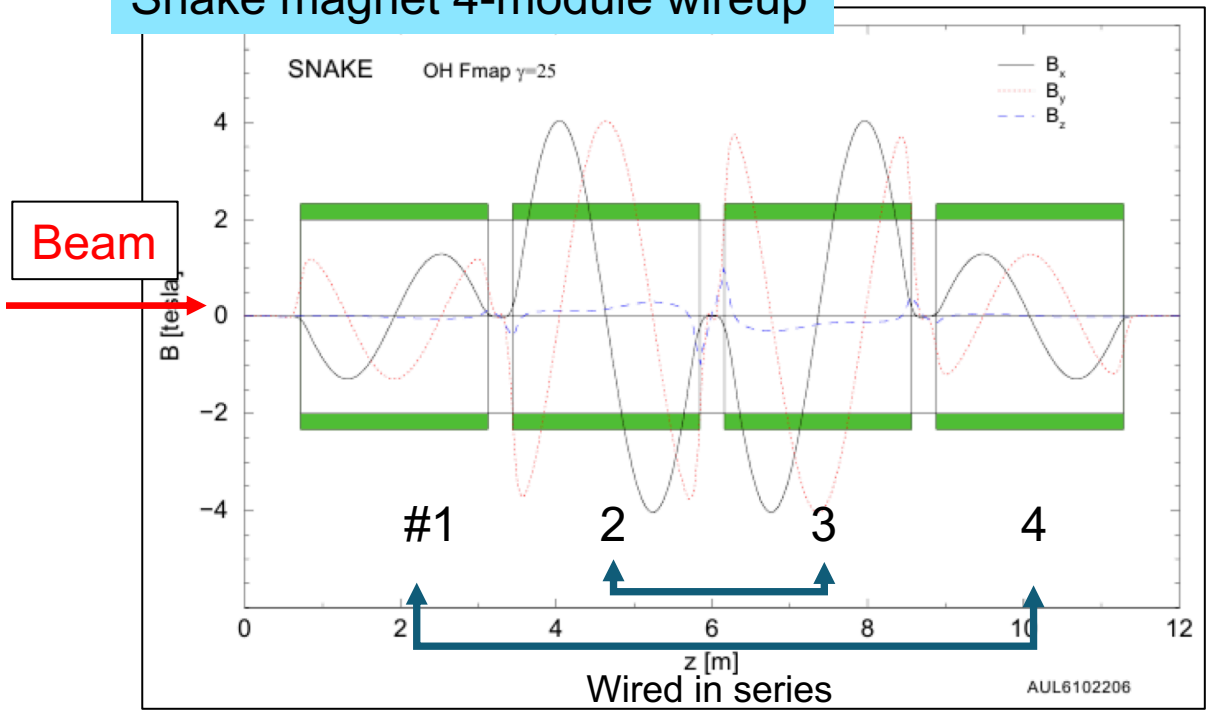
Full spin flip insures resonance avoidance because of energy independent:

- vertical stable spin direction
- spin tune = 1/2

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)

Snake magnet 4-module wireup

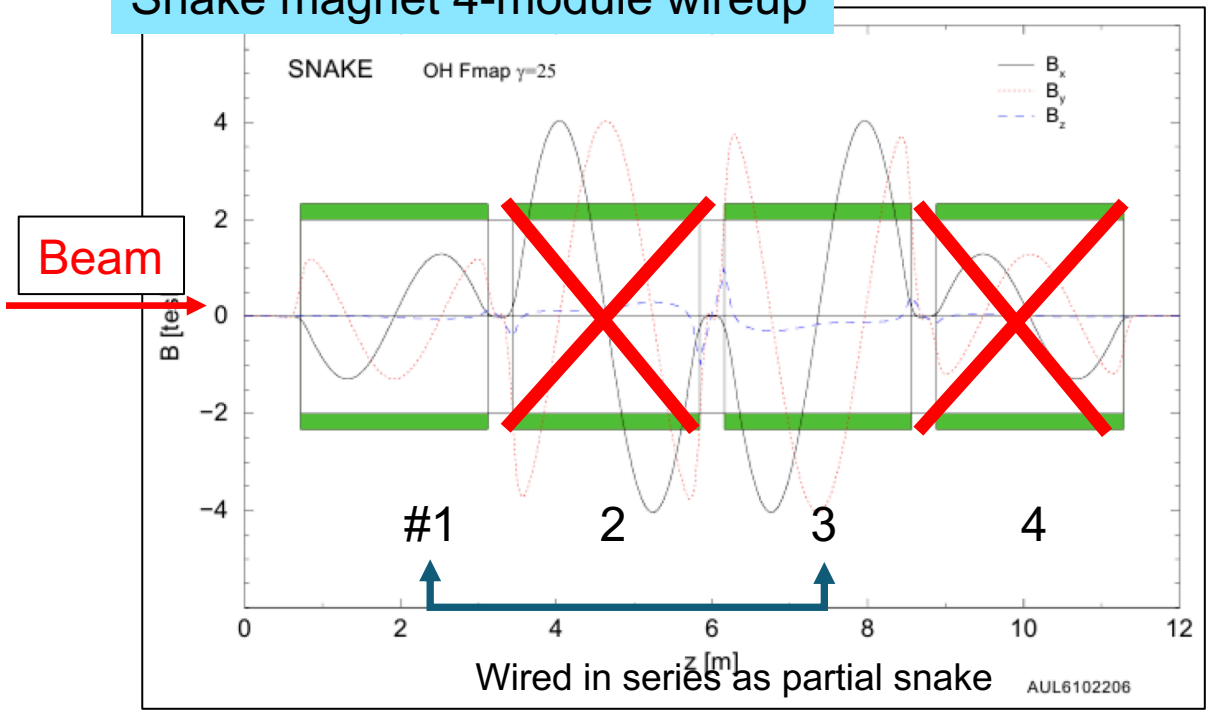


RHIC magnet: single helix

RHIC Snake magnet failure

- 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
  - Blue 9 o'clock snake will not ramp to current
- Dec 6
  - Resistance across coil #2 of BI9 snake is verified (developed an open)
  - 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 outer coils 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 in series outside cryostat to function as a partial snake

Snake magnet 4-module wireup



RHIC magnet: single helix

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

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

Produces imperfection resonances and shift in spin tune

Good news: The AGS uses partial snakes (on purpose!) in normal operation, plenty of expertise

Bad news:

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+

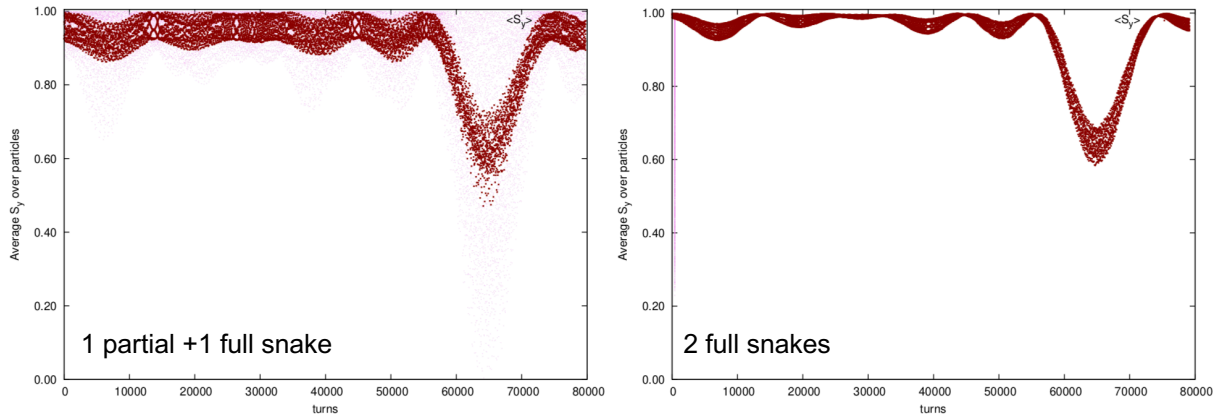
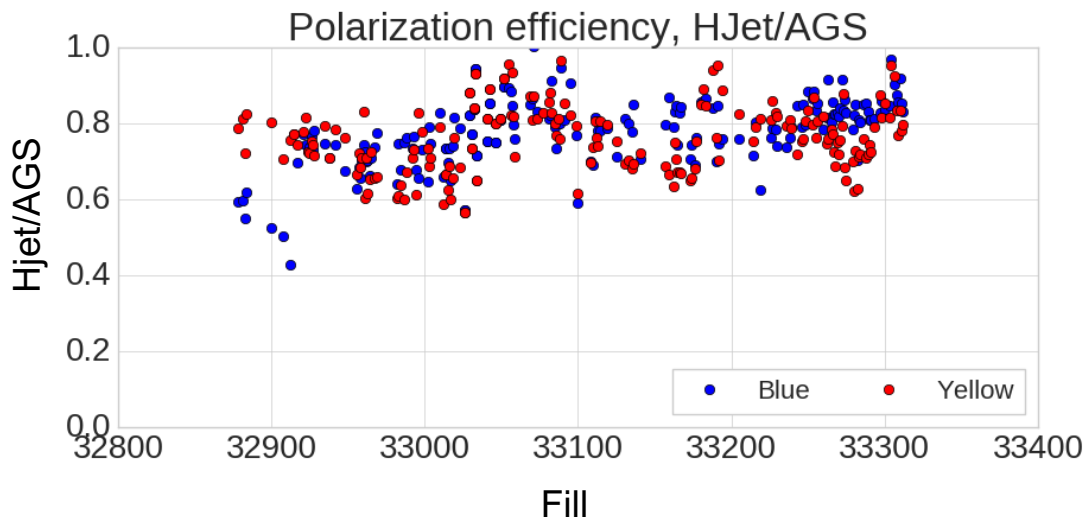


Figure 25: Crossing of 393+Qy. Case of 9 O'clock snake 88% (left), for comparison with Fig. 24, and case with both snakes full (right). Red curve: turn-by-turn $\langle S_Z \rangle$, an average over the 3 particles tracked. Blue: the 3 individual particles.



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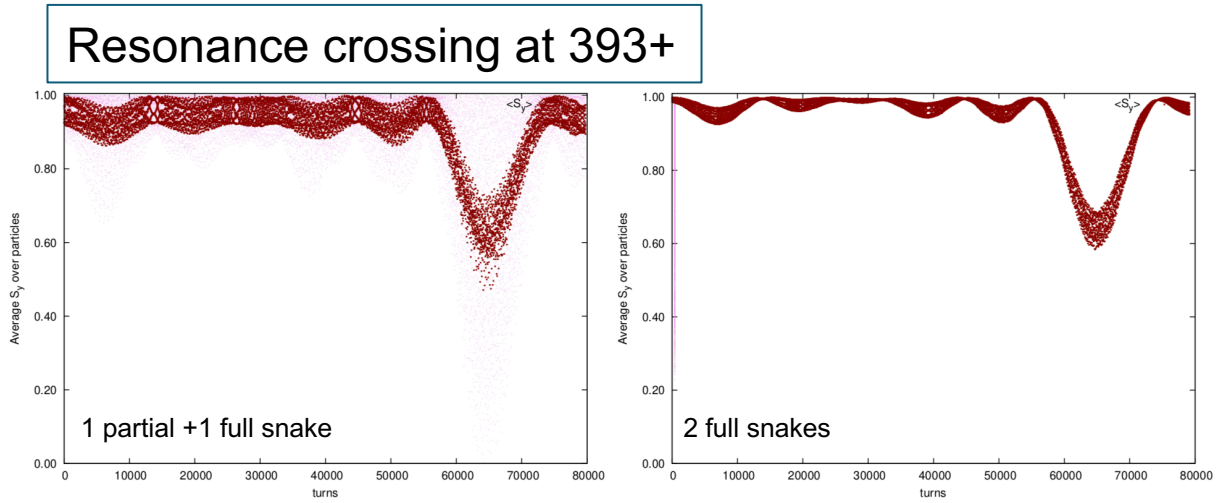

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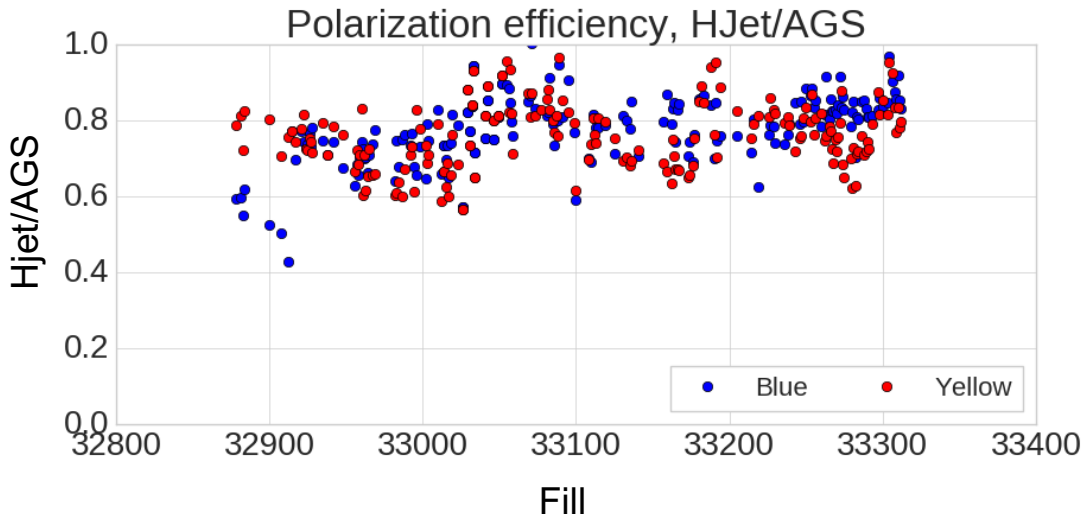
Side note: The low Run 22 yellow transmission, in a ring with working snakes,is not yet well-understood, plans to investigate over shutdown

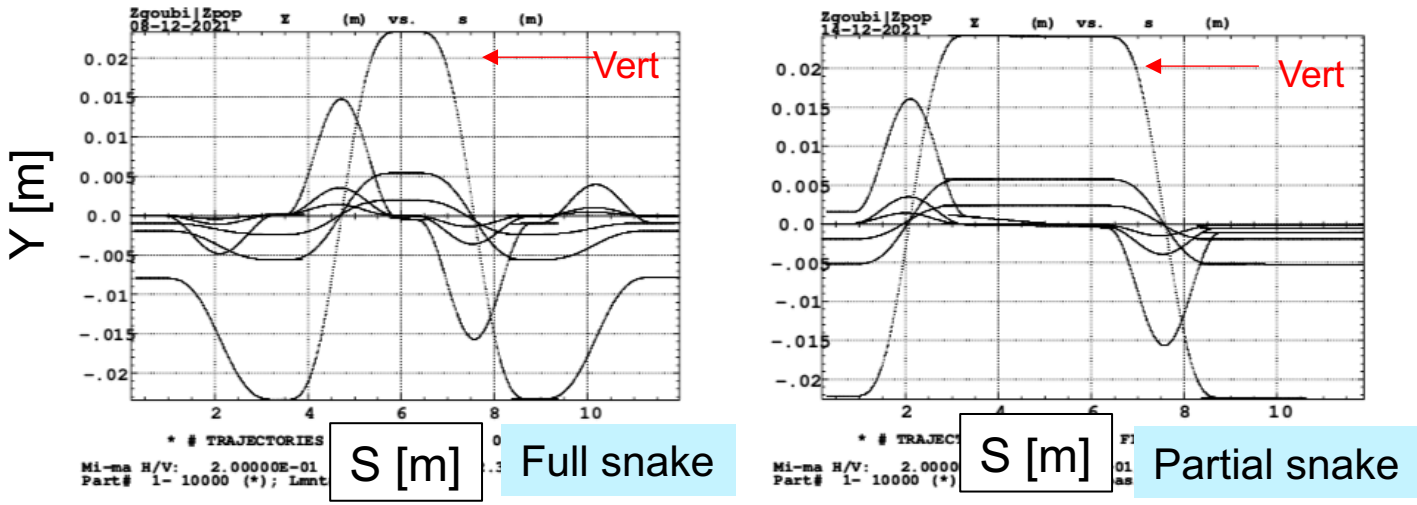


Partial snake configuration: Aperture

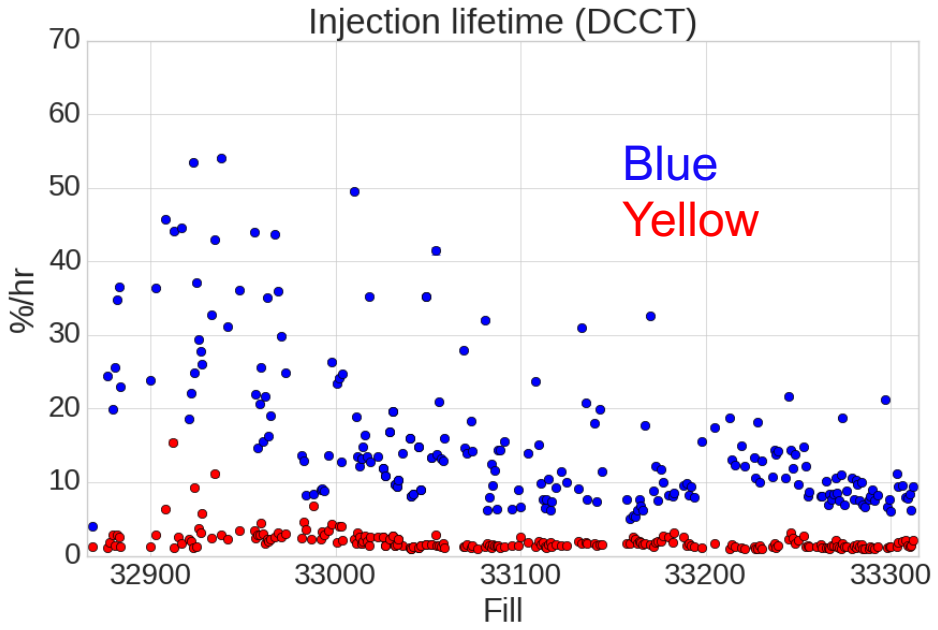
Operations with partial snake put beam very close to aperture

- Tight steering tolerances (sub-millimeter)
- Many snake BLM permit pulls
  - Particularly late in a blue fill: injection loss + injection kicker reflection loss
- Continuous lifetime tuning necessary at injection energy

Trajectories inside snake



Continuous work on blue beam lifetime through the run
Unusually sensitive to emittance



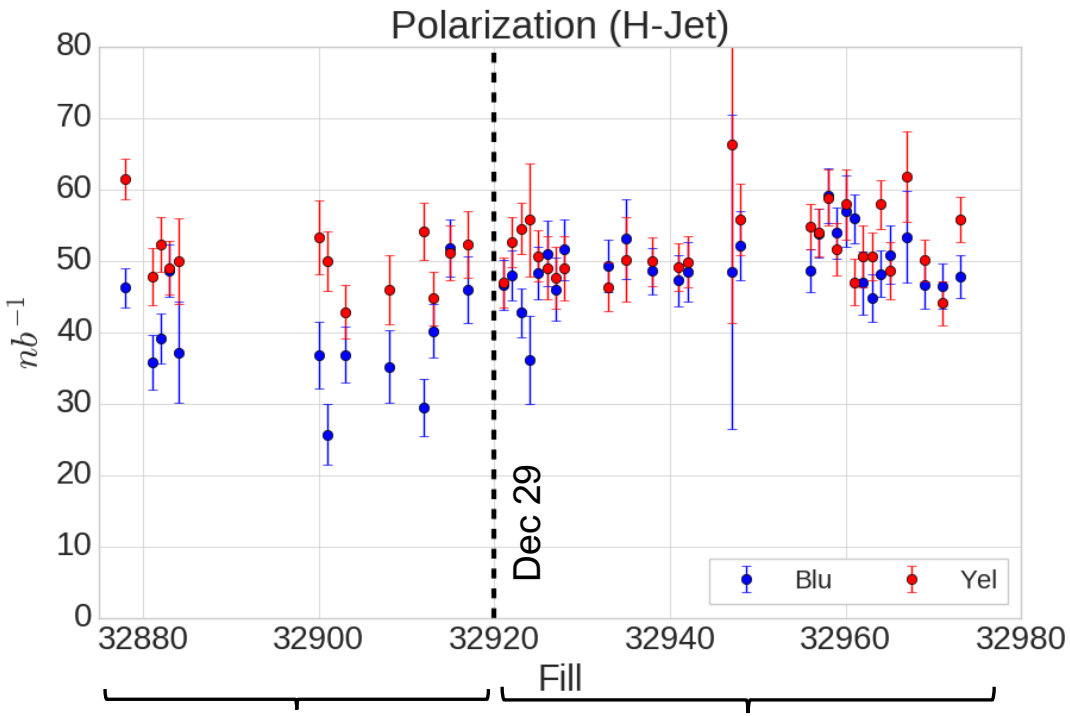
Partial snake configuration: Stable spin direction (INJECTION)

Non-vertical stable spin at injection due to partial snake causes polarization loss from mismatch to incoming beam

Re-calculation of the 3 o'clock snake parameters, allowed re-matching the new injection conditions

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

Not quite target 55%, but first time the run looked possible!



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

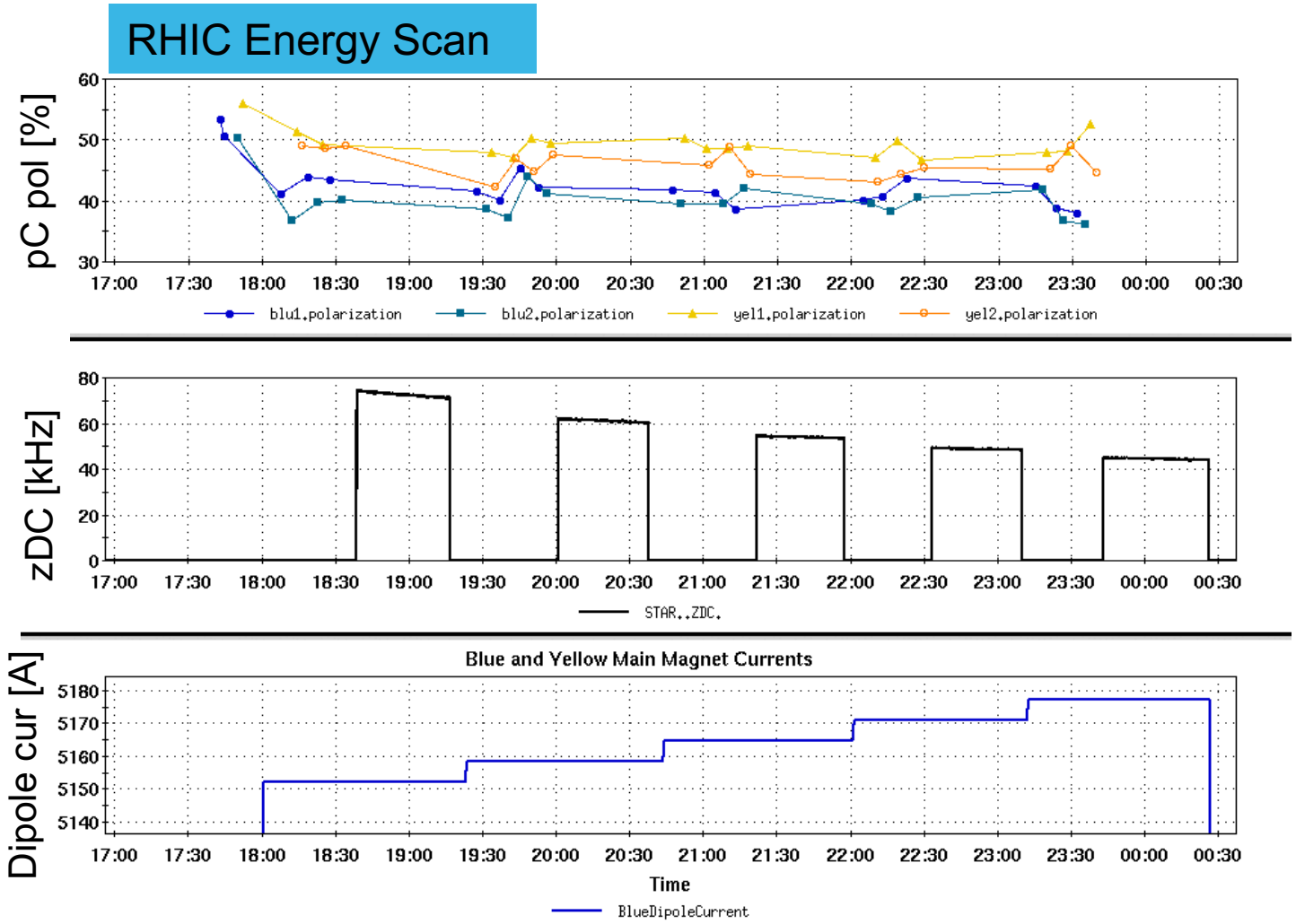
BO3 snake: 'nominal' full snake

BI9 partial snake: constant 320 A

BO3 snake modified to compensate

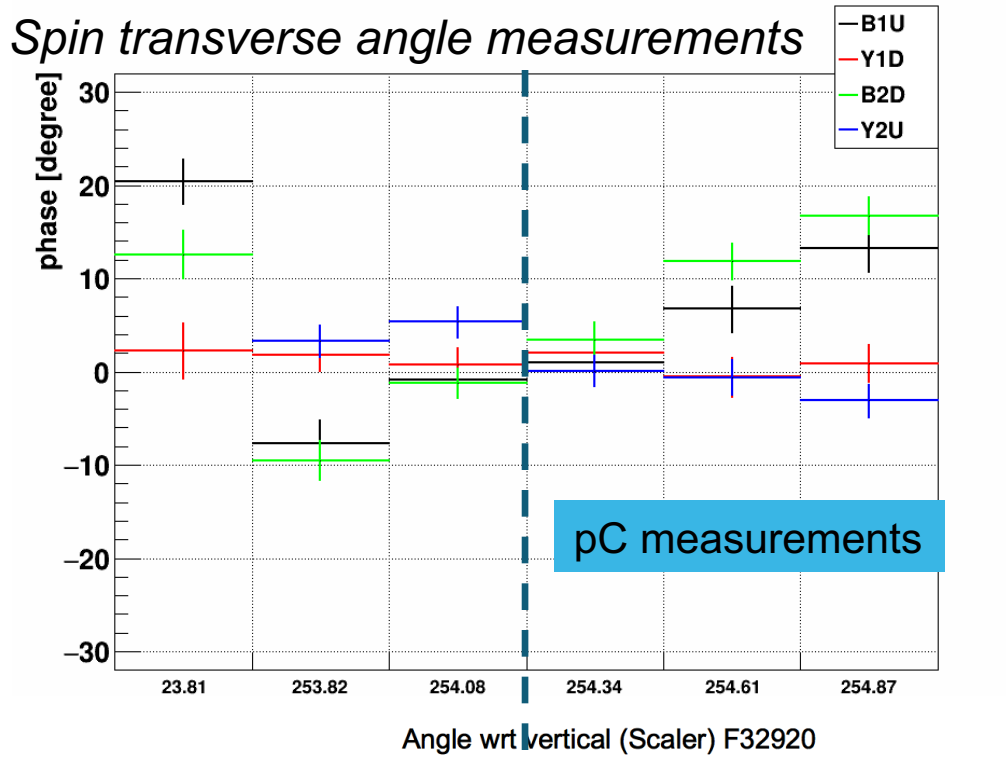
Partial snake configuration: Store energy scan

- 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)

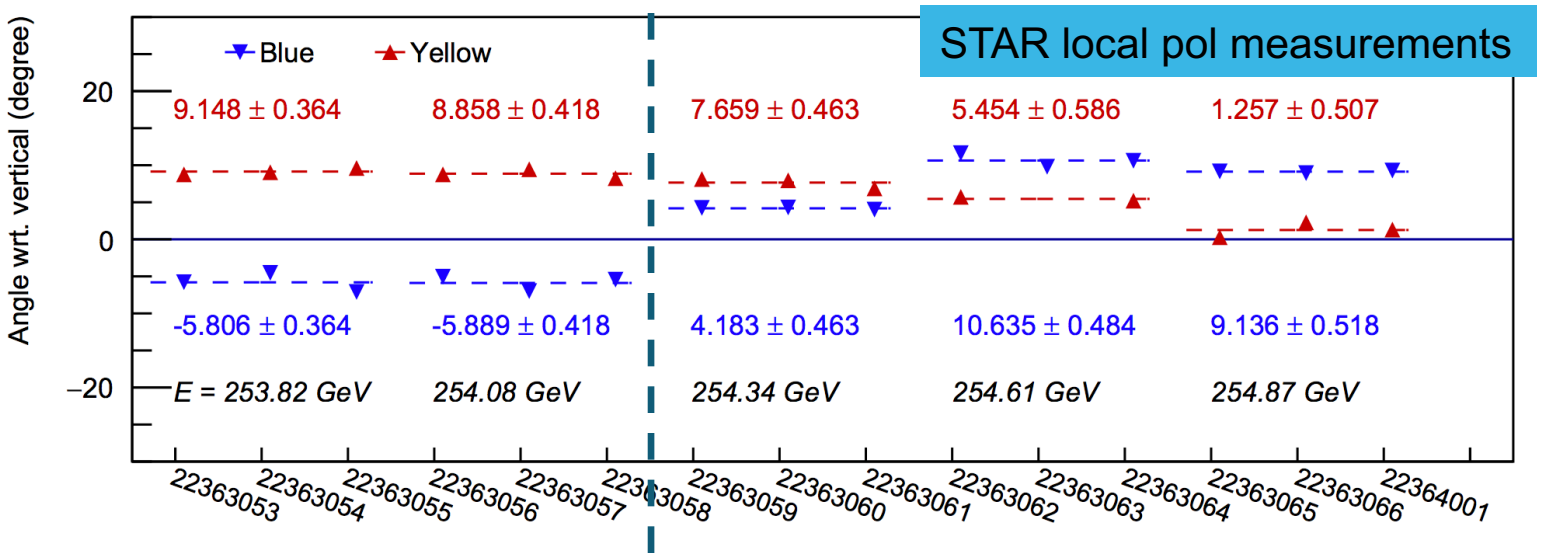


Partial snake configuration: Store energy scan

- 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



Looking forward…

Blue snake questions you may have

- Shouldn't the snakes be able to survive a power outage? Yes
- Haven't they before? (and didn't the other three this time?) Yes
- Is there something special about this snake? Radiation exposure? Well, it's near the dump and sees blue injections first…..
- Are any others in similar condition? Maybe. Yellow 9 o'clock sees dumped beam also, but it was inspected/repaired in 2009.

To do:
-- Damaged snake already removed and delivered to Superconducting Magnet Division
-- Aim to repair and replace snake in the ring *this* shutdown
-- Dummy section to be installed by early July to complete cryo loop for sPHENIX tests and in case needed for Run 23

-- Inspection will hopefully yield clues about the failure mode

-- Analysis of snake radiation exposure/quench history


RHIC alcove 9C, 12/18/21

Siemens vs Westinghouse

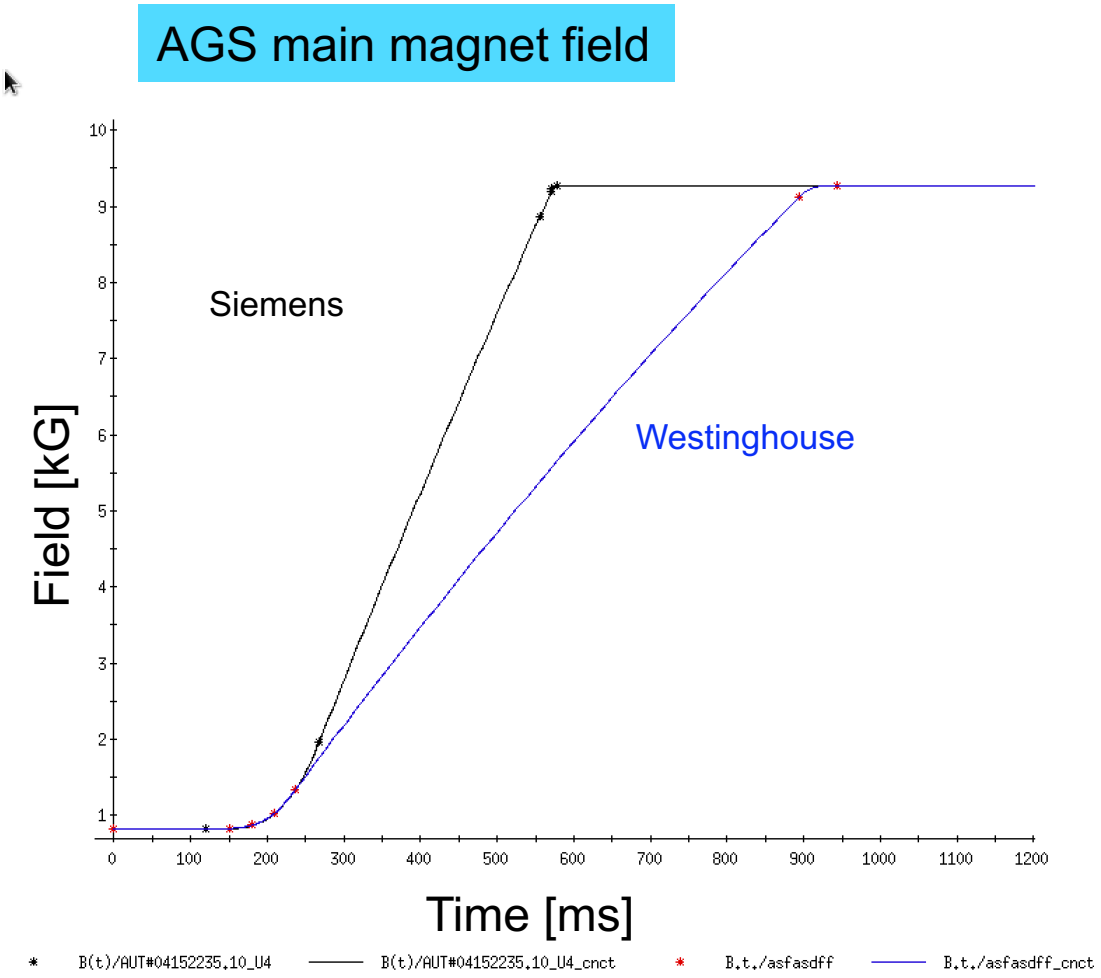
Jan 12th: Siemens AGS main magnet motor generator fails in the evening due to overheating brush rings

Jan 14th: Westinghouse brought on as backup

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



Siemens vs Westinghouse: Field Stability

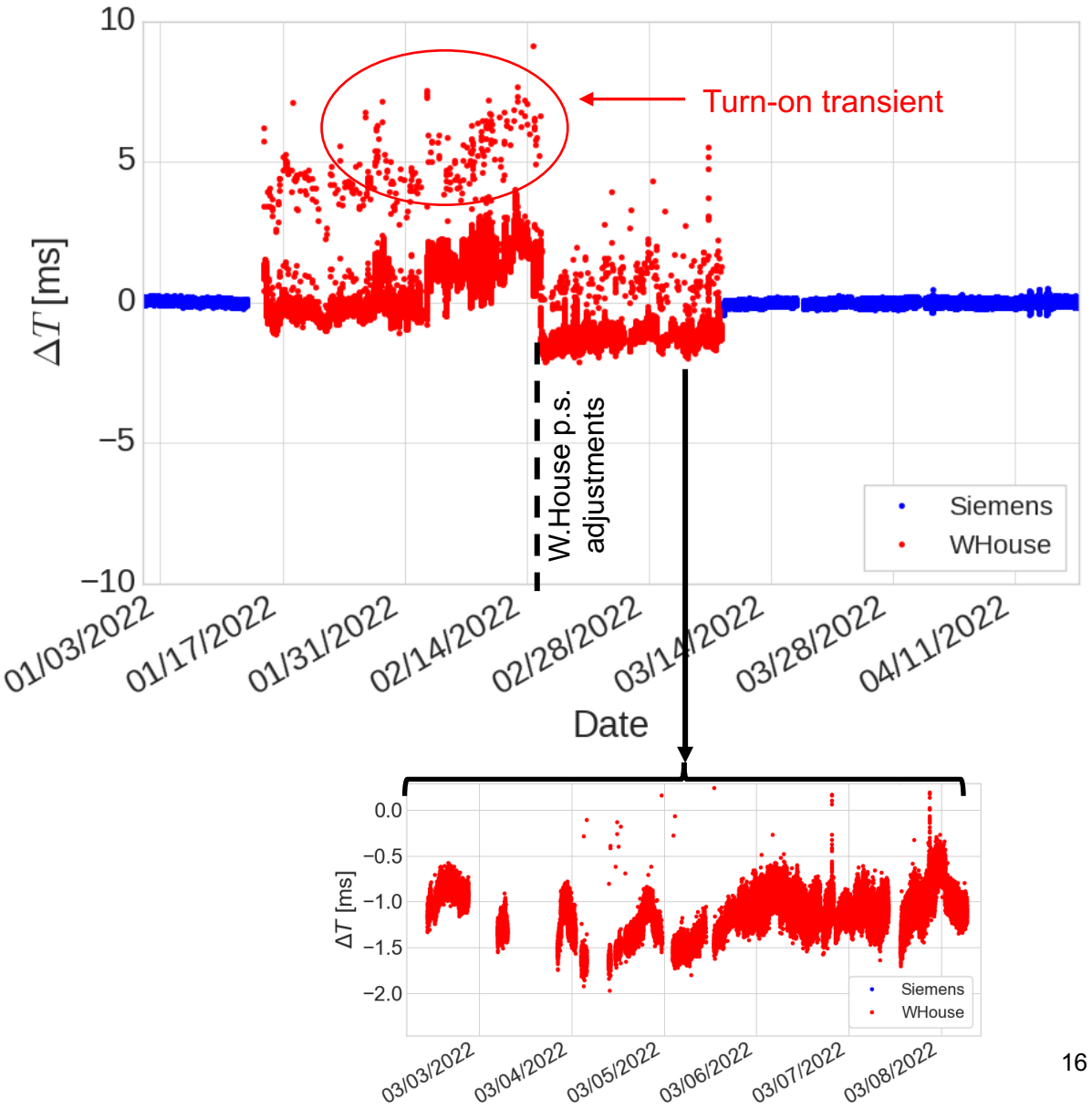
Long term stability

- 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

- Cost of Westinghouse operation:
  - ~8% (relative) drop in polarization
  - ~15% drop in figure of merit
  - Over 7.5 weeks, that's the equivalent of 1 lost week of physics operation

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



Anatomy of a Difficult Run

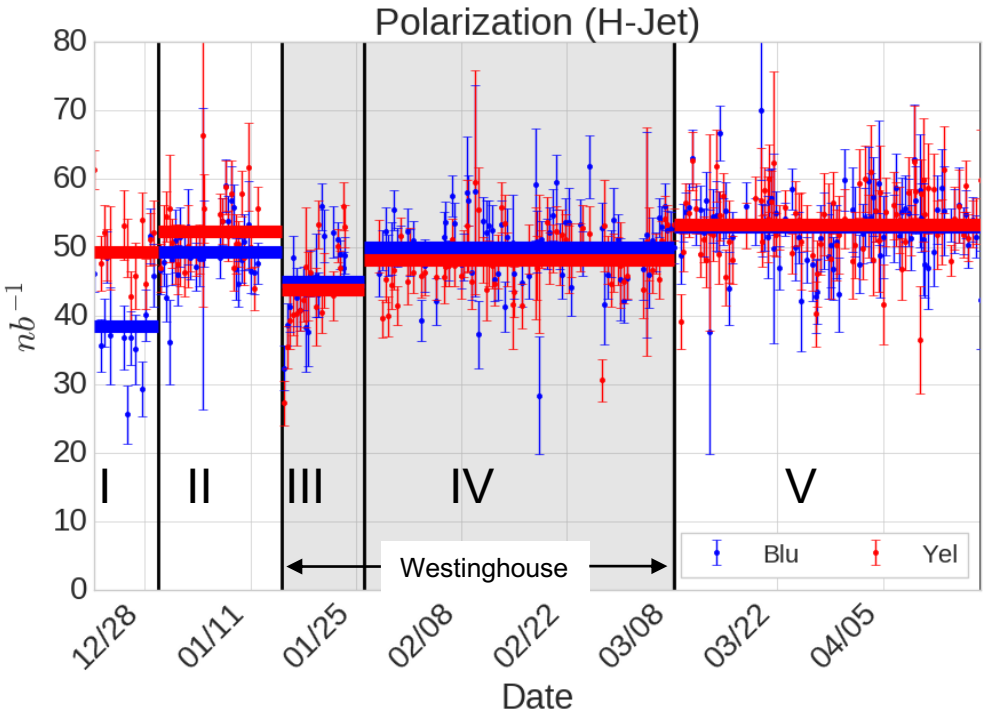
(I) Initial setup using Siemens, non optimal partial snake configuration, low blue polarization and *lots* of setup time

(II) Operation with Siemens, close to Run 17 performance

(III) Switch to Westinghouse, ~1 week of supply work and injector re-setup

(IV) Steady state Westinghouse operations, lower 8% (rel.) lower polarization)

(V) March 8th switch back to steady state Siemens through end of run. Close to Run 17 performance (53% polarization vs 55% in Run 17)



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***

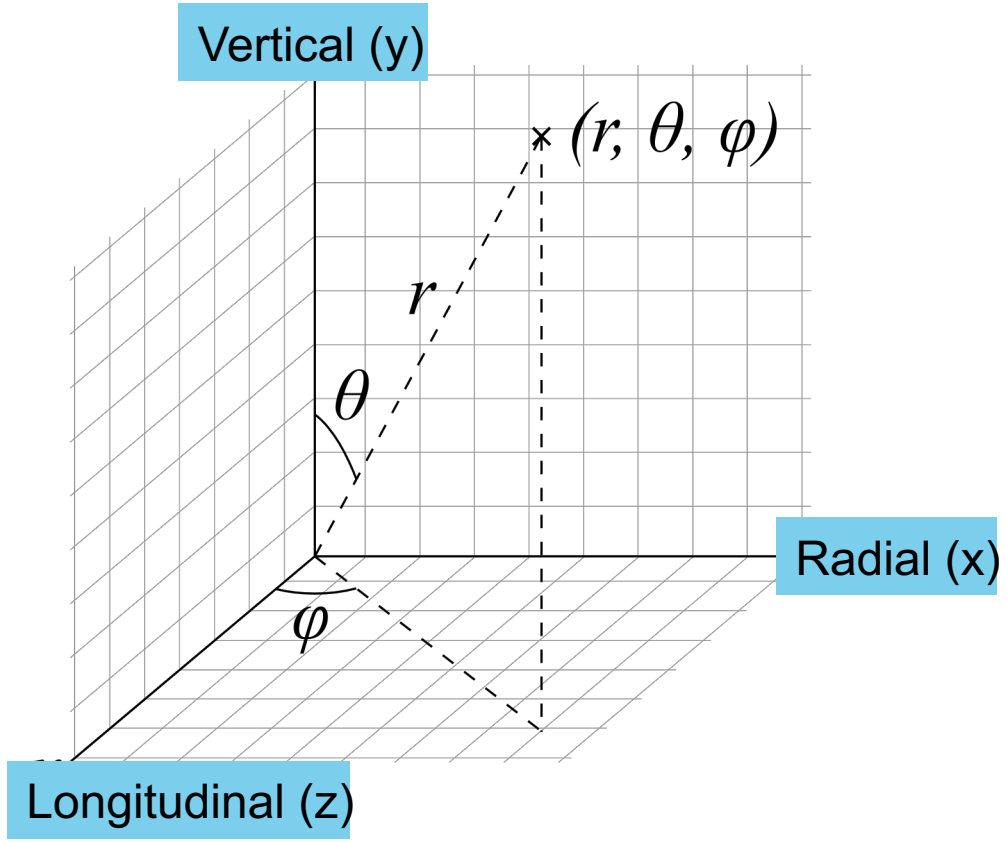
Spin direction measurements

Measurement of full 3D stable spin vector is necessary for physics data and polarimeter calibration

STAR local polarimeter and IP12 pC polarimetery are blind to longitudinal component

Have to effect a known, local rotation to get some or all of the longitudinal into the transverse

- At STAR, use spin rotators
- At pC polarimetry, use precession from horizontal orbit angle scan



Spin direction at STAR

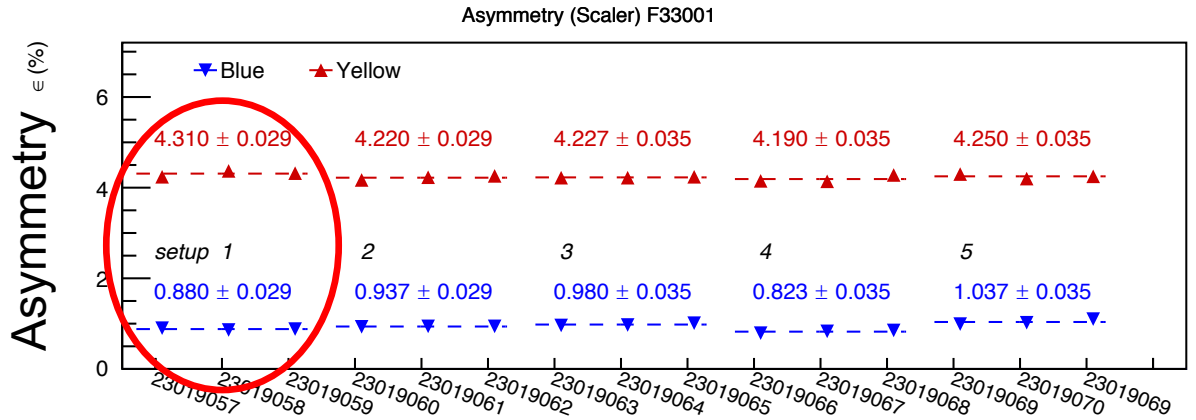
Rotator experiments showed small residual longitudinal component in blue and almost none in yellow (not shown)

‘Small’ means <0.1 (for |S| =1), preliminary

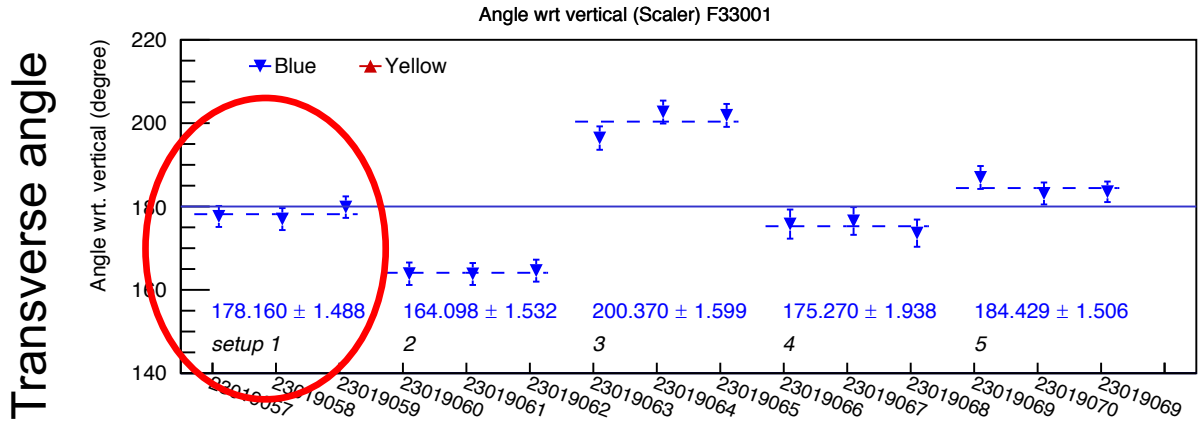
Analysis during the run done with ‘legacy’ algorithms designed to aid and tune actual longitudinal running – not ideal for analyzing this situation

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

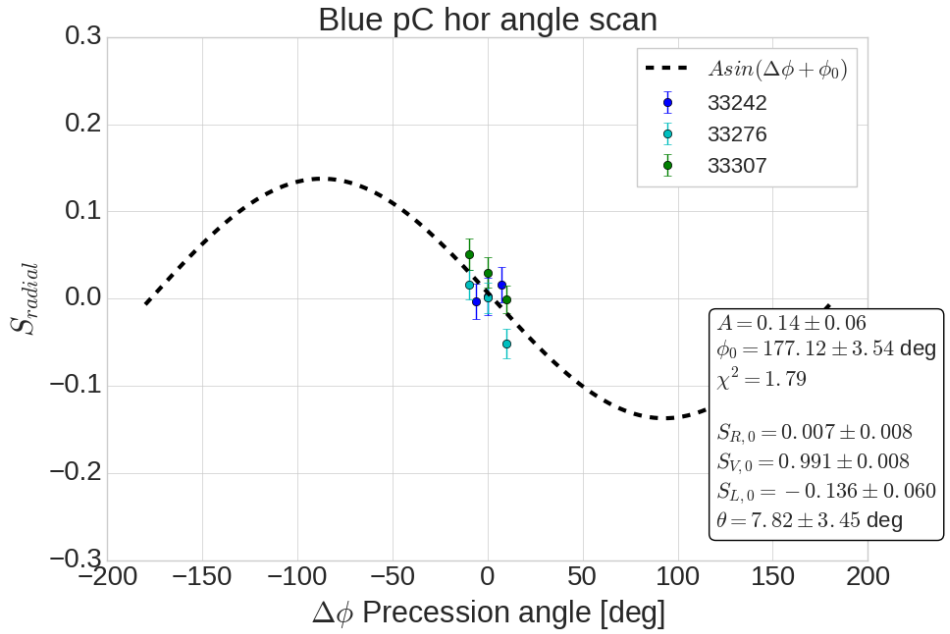
Achievable orbit angle +/- 350 μrad
Achievable spin precession +/- 9 degrees

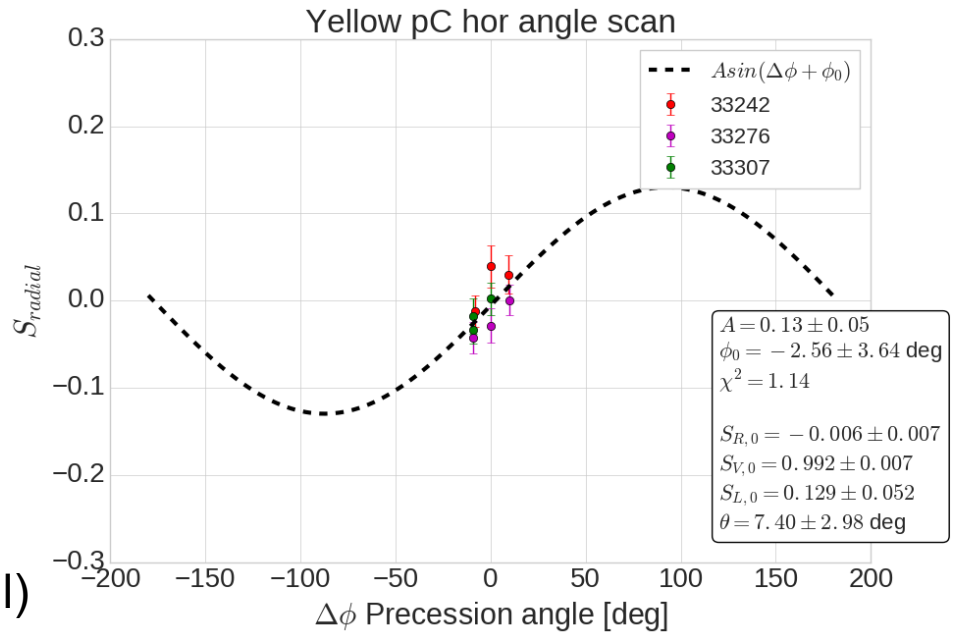
Results required: ~100 pC measurements over 3 sessions

Spin tilt away from vertical is about 7 +/- 3 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).*

Note: this won’t work well at 100 GeV (spin precession is too small)





Abort kicker pre-fire prevention

Delayed mode relays engaged for all physics fills

- Requires all the upgraded MPS inputs for
  - corrector currents
  - beam coherence
  - both absolute and rate-of-change position measurements
- Pieces commissioned during low-energy operation

With the full system: No pre-fires during Run 22 high energy operation

A few incidents of pre-firing *without* the protection engaged during no beam/ low intensity setup (so we didn't just get lucky!)

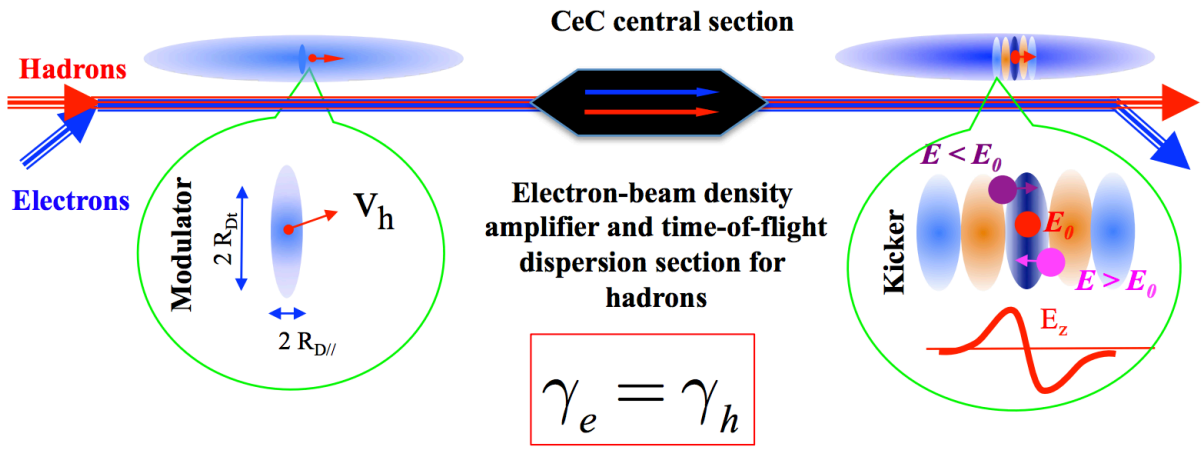
Coherent electron cooling

A difficult run for everyone: ~70% of available operational time lost to failures, prevented full cooling demonstration

- Beam current measurement difficulties
- Cathode exchange failure: mechanical problem with cathode exchange mechanism, contaminated SRF cavity, needed weeks of re-conditioning

Nevertheless, some highlights:

- Solenoid beam-based alignment completed
- Improved source laser stability (timing jitter ~3 ps, sufficient for CeC demonstration)
- Cryo-cooled bolometer commissioned
- Plasma cascade amplification at high gain restored on Apr 17 (one day before run end)



$$\gamma_e = \gamma_h$$

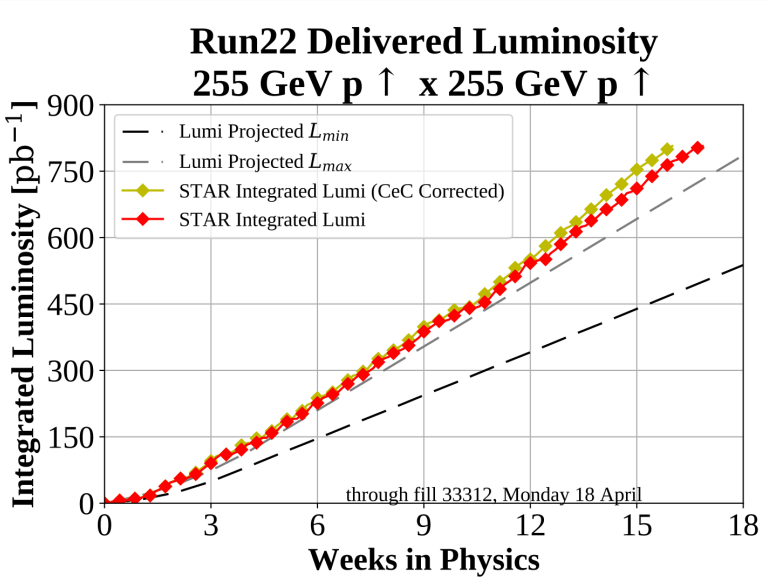
Final Score

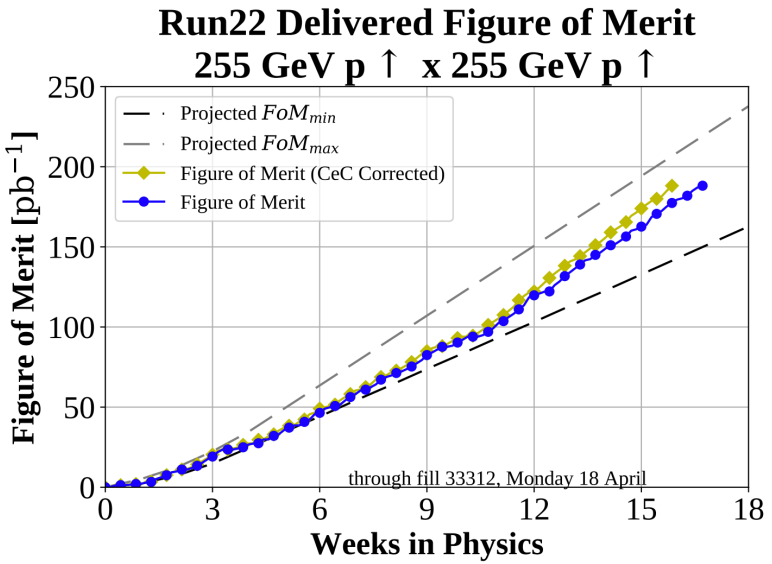
Delivered luminosity and figure of merit were, in the end close or above targets (right)

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%
$L P_b P_y$	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.
  - High marks for inter-department cooperation: super collaboration between C-AD, STAR and Superconducting Magnet Division

- In addition to meeting goals
  - We achieved better characterization of total 3-D spin orientation at STAR and the polarimetry than ever before
  - Commissioned machine protection equipment at high energy, very important for safe sPHENIX operation