Polarized Proton Performance at RHIC Some Recent Improvements

Vincent Schoefer (for many)

E. C. Aschenauer, G. Atoian, M. Bai,M. Blaskiewicz, K. Brown, D. Bruno, R. Connolly, T. D'Ottavio, K. Dress, Y. Dutheil, W. Fischer, C. Gardner, X.Gu, T. Hayes, H. Huang, J. Laster, C. Liu, Y. Luo, Y. Makdisi, G.Marr, A. Marusic, F. Meot, K. Mernick, R.Michnoff, M. Minty, C. Montag, J. Morris, G. Narayan, S. Nemesure, P. Pile, A.Poblaguev, V. Ranjbar, G. Robert-Demolaize, T. Roser, W.B.Schmidke, F.Severino, T.Shrey, K.Smith, D.Steski, S.Tepikian, D.Trbojevic,, N.Tsoupas, J. Tuozzolo, G.Wang, S.White, K.Yip, A. Zaltsman, A.Zelenski, K.Zeno, S.Y.Zhang

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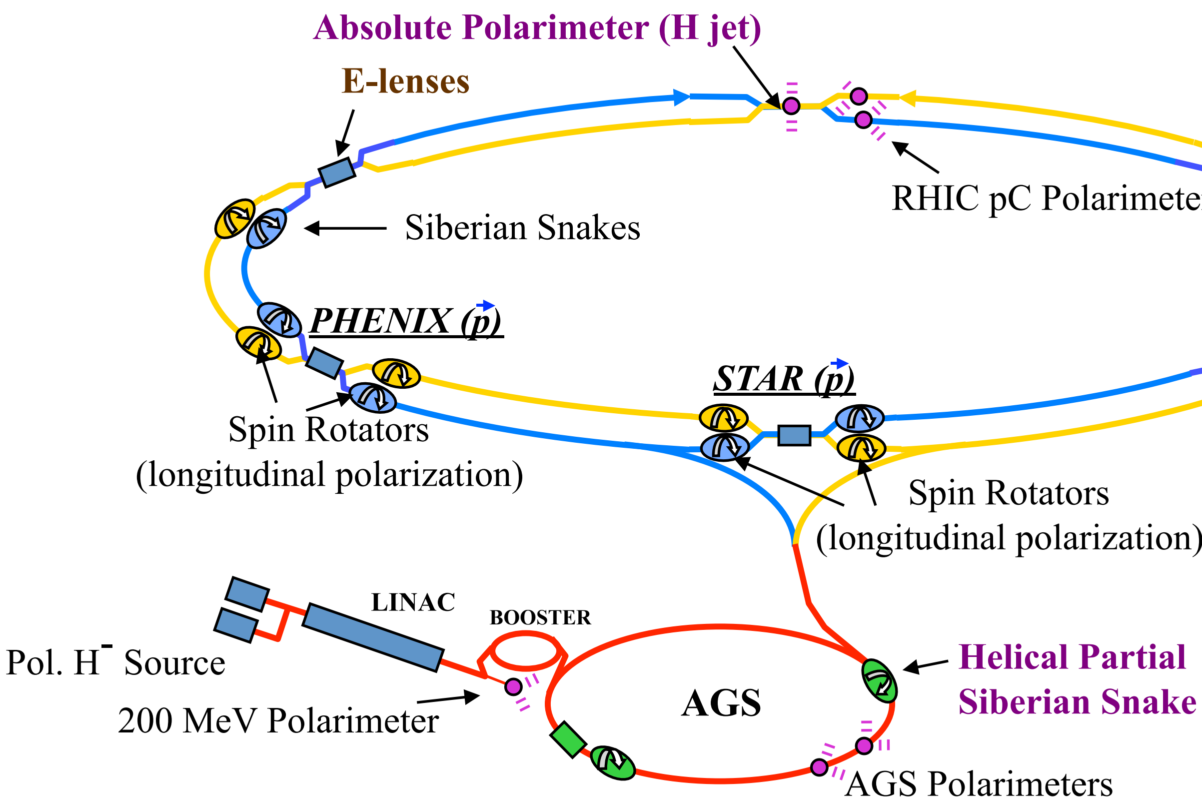
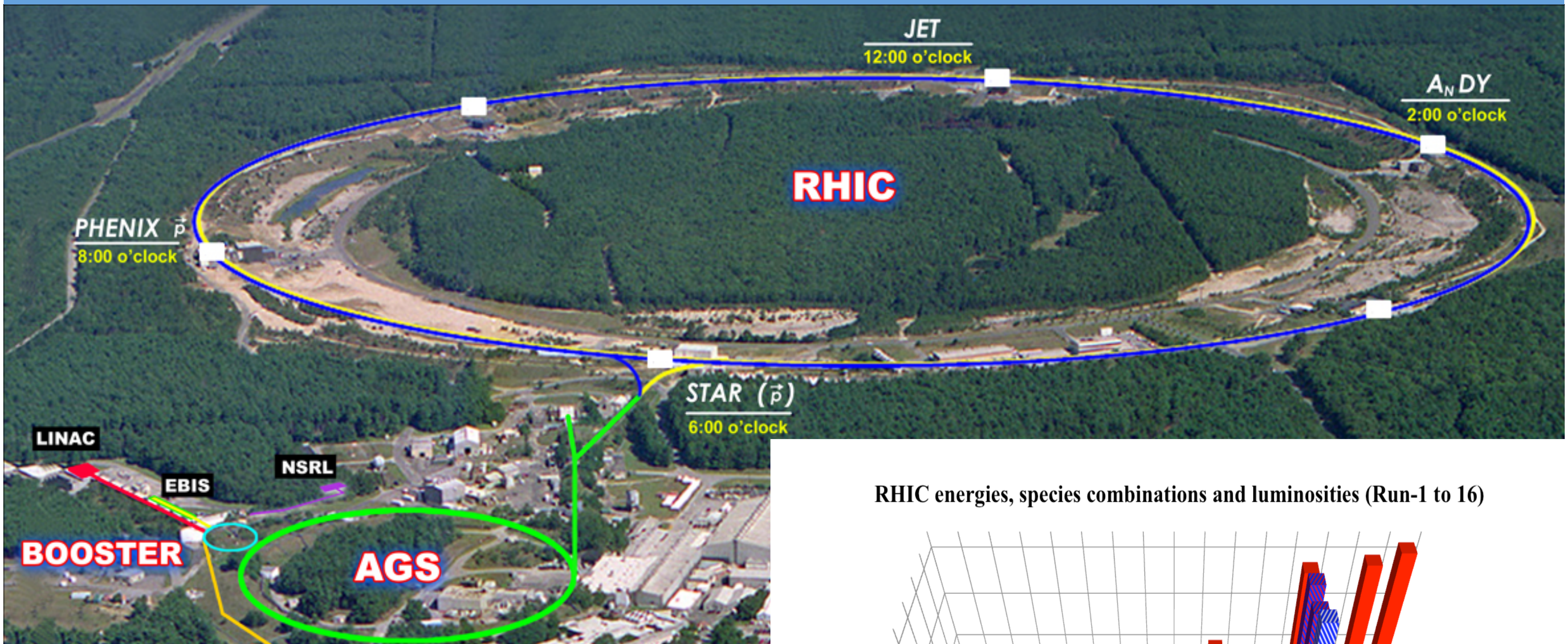
RHIC as Polarized Proton Collider

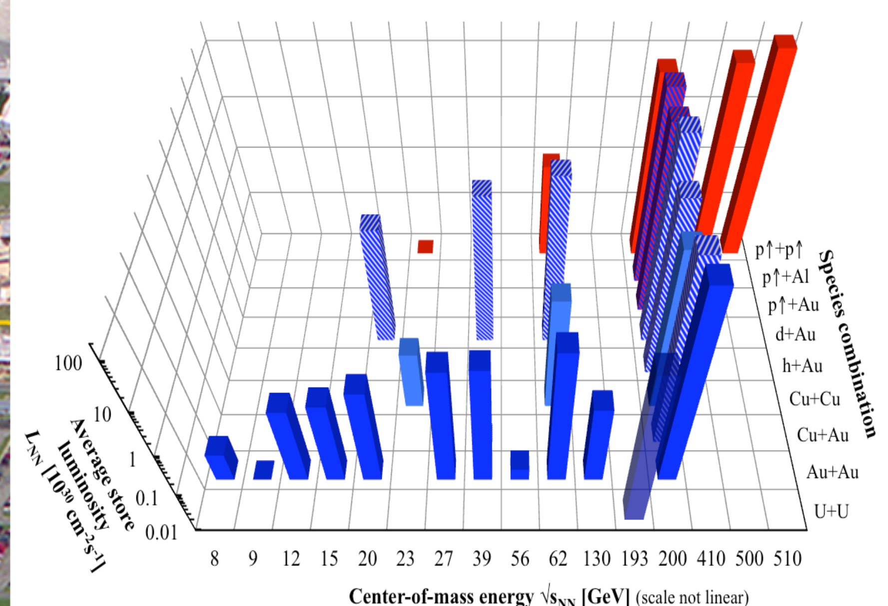


- ➢ Recent operations
- ➢ Highlights of performance improvements
- ➢ Some plans for Run 17

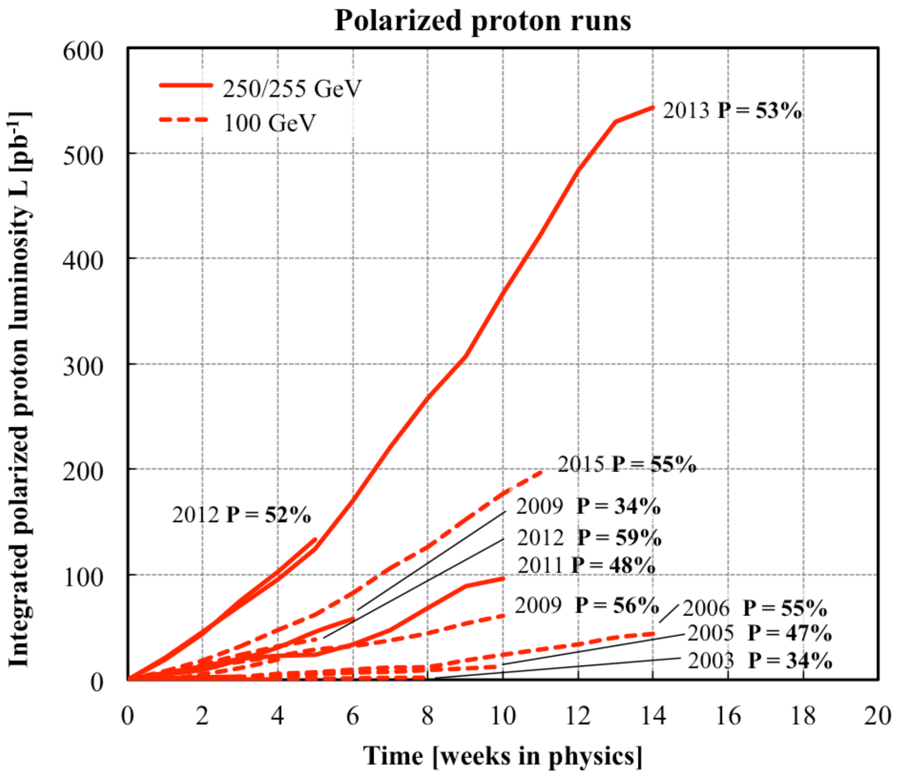
Polarized Proton Operations

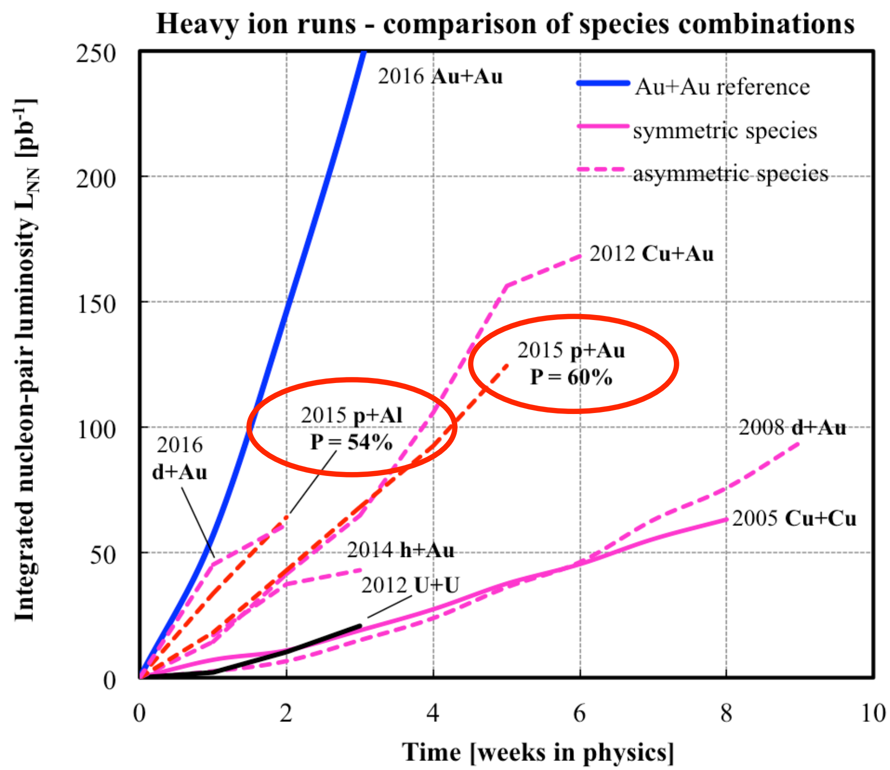


Run	Species	Beam E [GeV]	Length [wks]
2012	p^-p^	100	4.5
		255	5
2013	p^-p^	255	13
2015	p^-p^	100	11
	p^-Al	100	5
	p^-Au	100	2
2017	p^-p^	255	planned



Operating modes





- Record luminosities for p-p collisions
- Doubled peak and average luminosity for 100 GeV collisions (2012 –> 2015)
- First polarized proton on ion collisions
  - Operationally challenging: IP orbits, Injector mode-switching, p-Au injection plateau

Operating a Polarized Collider at *High Luminosity*

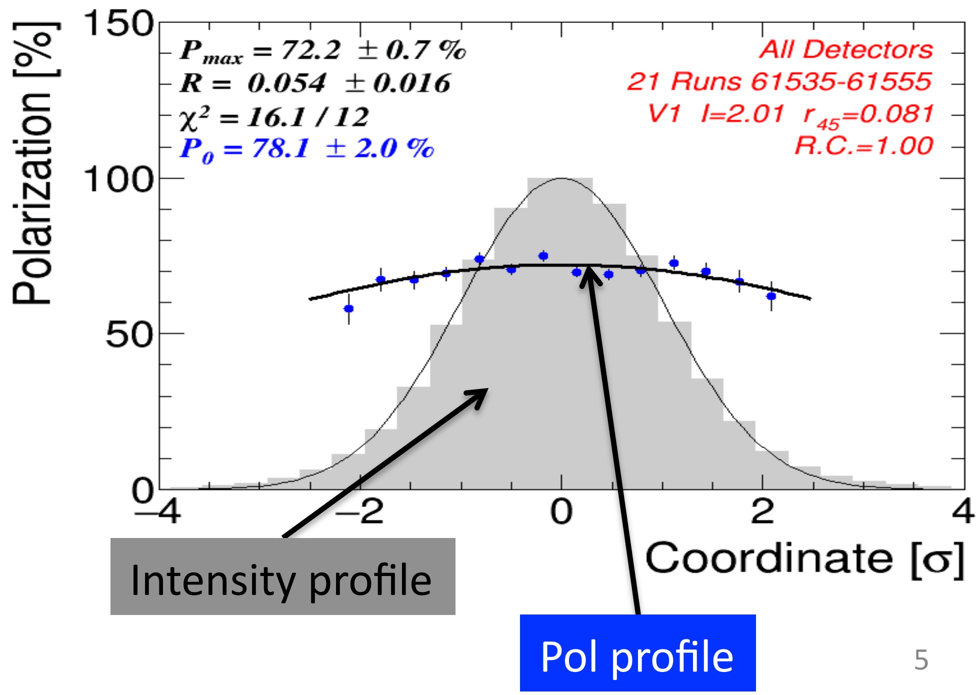
Figure of merit =
- $L \times P^2$ — Single spin, transverse
- $L \times P^4$ — Double spin,longitudinal

Luminosity $L \propto \dfrac{N^2}{\varepsilon}$

For single spin, bunch intensity N as important as polarization P
Double spin, polarization dominates

But emittance, ε also factors into polarization

Amplitude dependent ("intrinsic") resonances dominate polarization loss for AGS and RHIC



Operating a Polarized Collider at *High Luminosity*

- Two pronged approach
  - Directly address depolarizing resonances
    - Snakes, AC dipoles, spin matching, *resonance jumping*
  - Increase the luminosity with the smallest possible emittance
    - Injectors: Dealing with *space charge*
    - Collider: *Beam-beam limitations*

Spin resonance jumping in the AGS

A Siberian snake rotates the spin of the proton by an angle χ in one pass through the device

‘full’ snakes: X = 180° → ν_s = ½, n_{co} = vertical → Not enough room in the AGS!

‘partial’ snakes: X < 180° → ν_s energy dependent, n_{co} NOT vertical → AGS has two partial snakes (helical dipoles) X = 6°, 10°

$\nu_s \neq n$

No imperfection resonance!

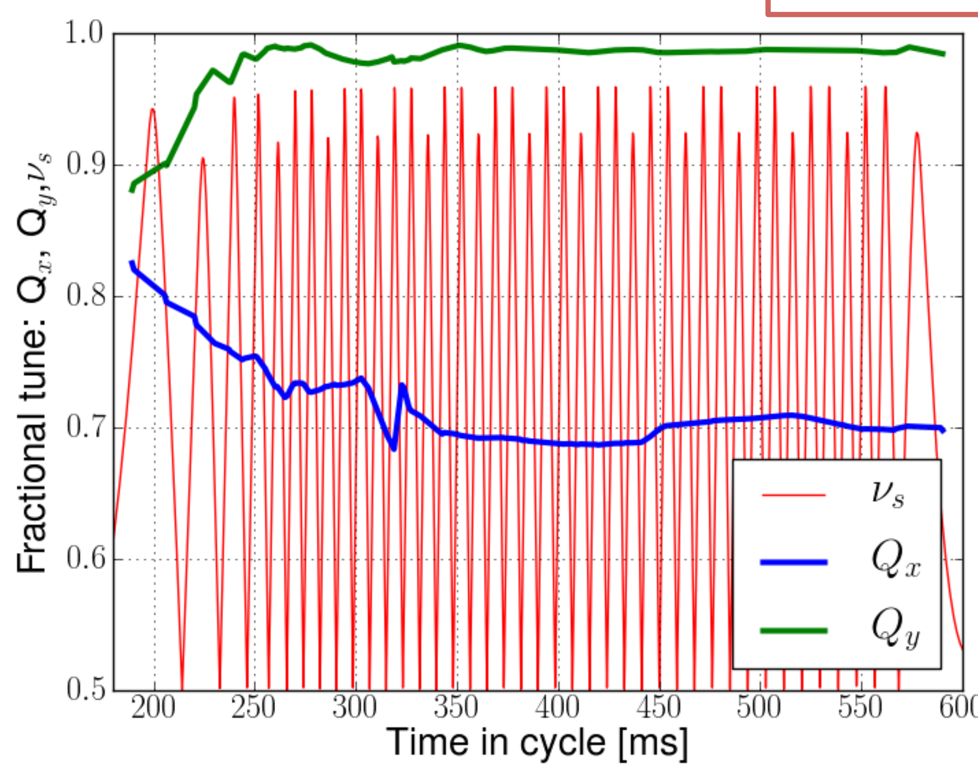
If Q_y near integer

$\nu_s \neq nP +/- Q_y$

No vertical intrinsic resonance!

BUT:
The stable spin vector has a horizontal component
Excites horizontal resonances

$\nu_s = n +/- Q_x$



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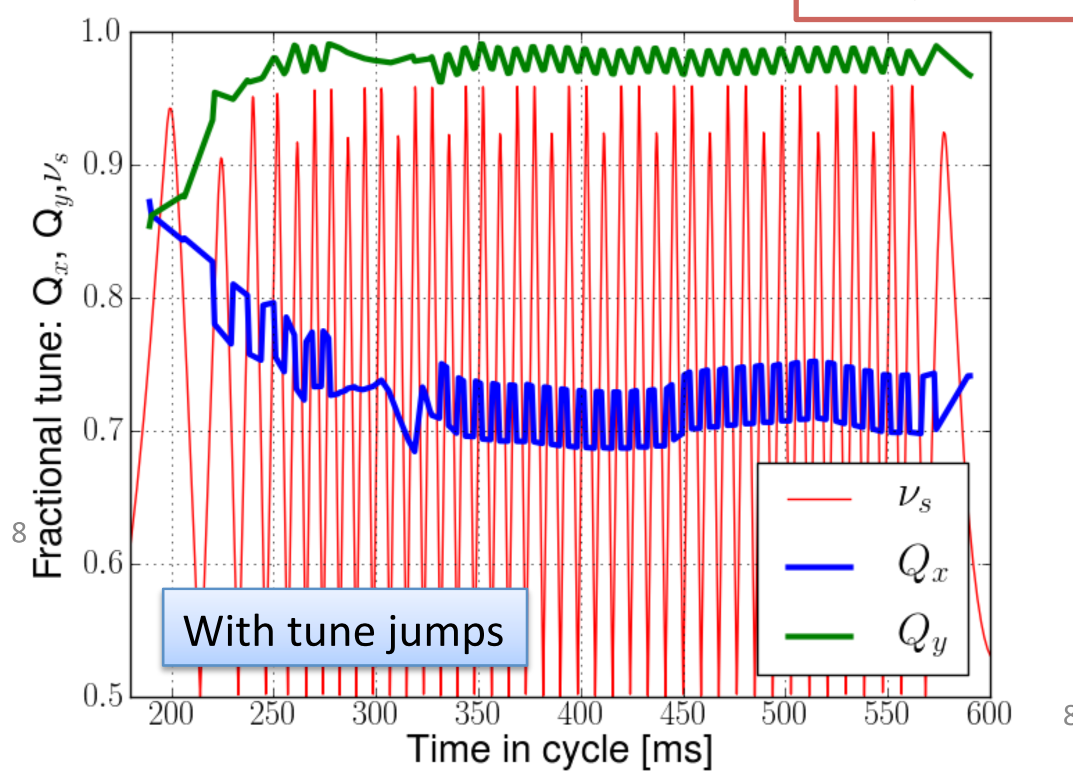
$$\frac{P_f}{P_i} = 2\exp\left[-\frac{\pi|\varepsilon|^2}{2\alpha}\right] - 1$$

Froissart-Stora

P_i, P_f = initial and final polarization

α = crossing rate

ε = resonance strength



Spin resonance jumping in the AGS

Jump quads provide +10% (relative) increase in polarization

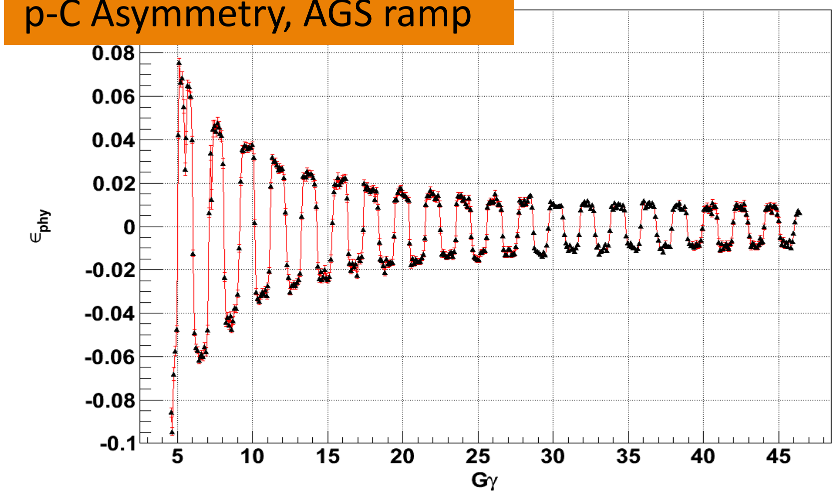
Determination of jump times needs energy measurements to +/- 5 MeV (+/- 100 us)

Energy measured via:

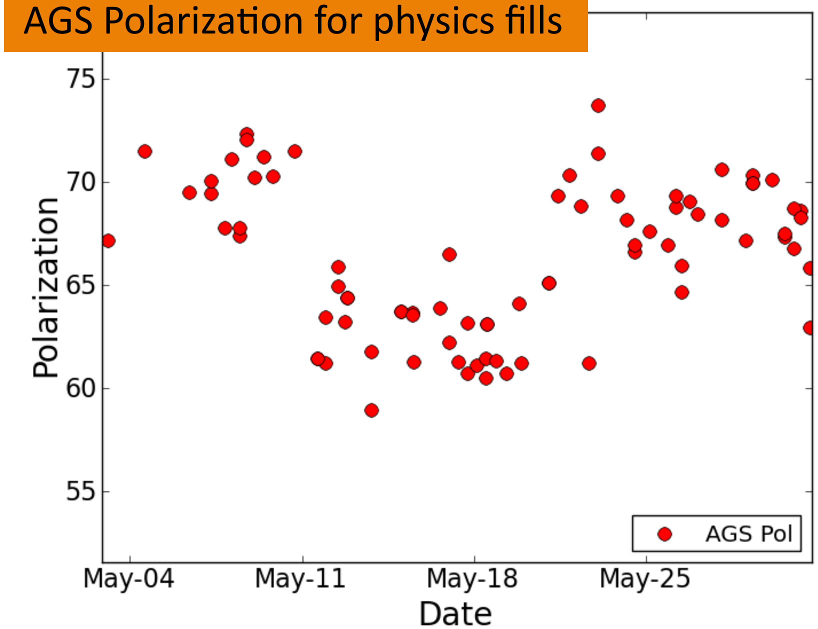
- Main bend field
- Revolution frequency
- Spin flips

Run 15: unidentified 'drift' makes the jump quads ineffective

p-C Asymmetry, AGS ramp



AGS Polarization for physics fills



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Run 15: unidentified ‘drift’ makes the jump quads ineffective

Investigation of possible systematic errors

- Power supply triggering delays
- Contribution of orbit correctors to main bend
- Orbit driven spin tune shifts (too small)
- Measurement time synchronization errors

Additional diagnostics

- Online jump quad field measurements
- Monitoring of main magnet cooling water temperature
- Improved climate control for reference magnet instrumentation (source of field measurement)

Space charge effect in the injectors

Space charge tune shifts

$$\Delta Q_{sc} \propto \left(\frac{N}{\varepsilon}\right)\left(\frac{1}{\beta^2\gamma^3}\right)\left(\frac{I_{peak}}{I_{avg}}\right)$$

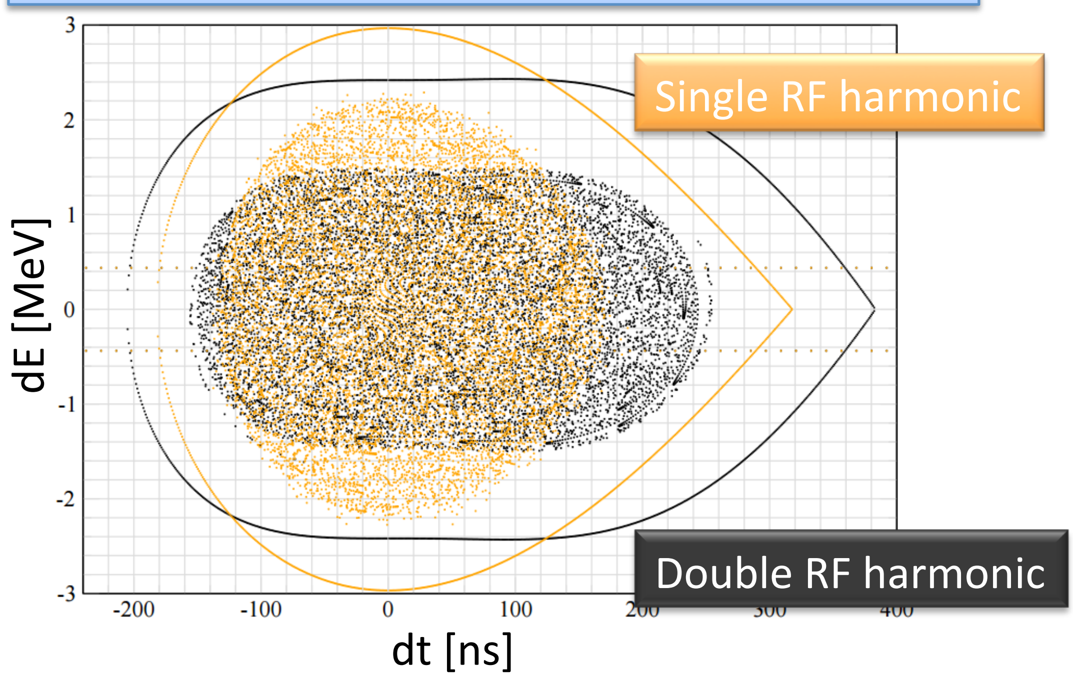
β,γ = relativistic factors
I = peak and average beam current
N,ε = intensity, emittance

RUN 13 Source Upgrade
N = 5×10^{11} → 1×10^{12} /pulse from source

Protons at Booster injection
200 MeV, N=9×10^{11}
$\Delta Q_{sc} > 0.2$

Defocusing the bunch longitudinally reduces the space charge 'bunching factor'

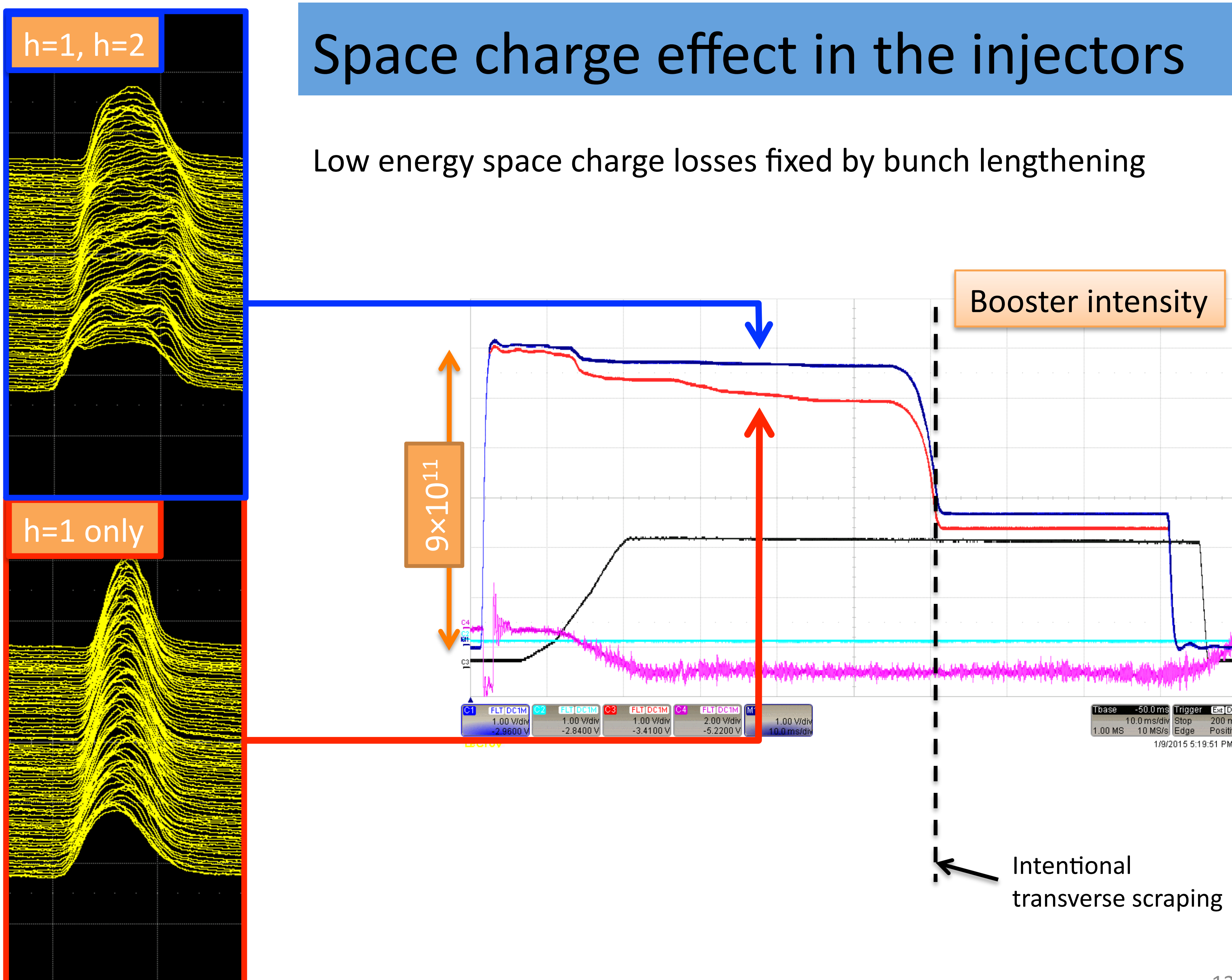
Longitudinal Phase Space (Booster acceleration)



Plot courtesy C. Gardner

Space charge effect in the injectors

Low energy space charge losses fixed by bunch lengthening



Beam-beam Limitations

Oncoming proton beam acts as a nonlinear defocusing force.

Defocusing strength parameterized by the 'beam-beam tune shift', scales like:

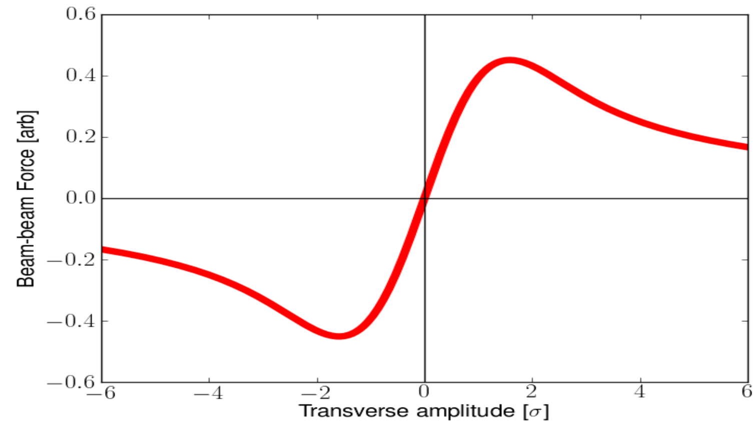
$$\Delta Q_{bb} \propto \left(\frac{N}{\varepsilon}\right)$$

Nonlinearity produces both a shift in tune and a tune spread

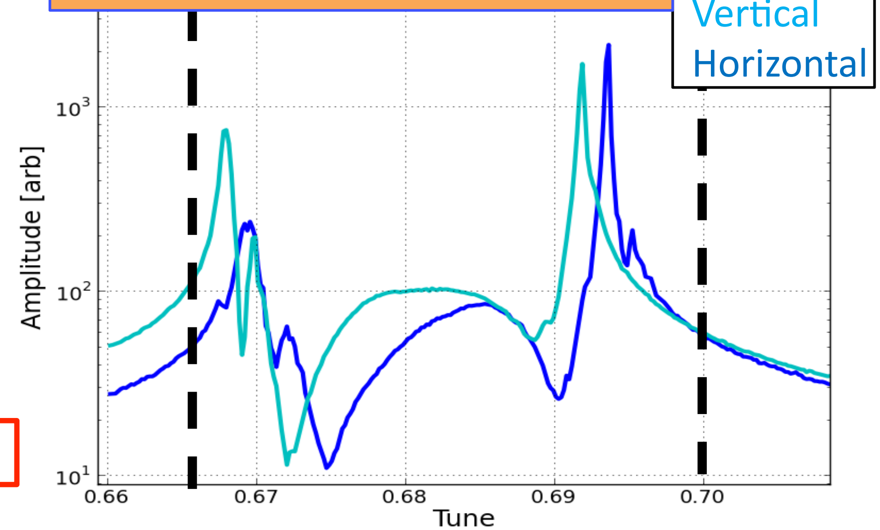
Tune spread in collision fills the space between damaging resonances

$$Q_{x,y} \begin{cases} 2/3 \rightarrow \text{Emittance blowup} \\ 7/10 \rightarrow \text{Depolarizing 'snake resonance'} \end{cases}$$

Shape of beam-beam force for Gaussian beams



Transverse Beam Transfer Functions



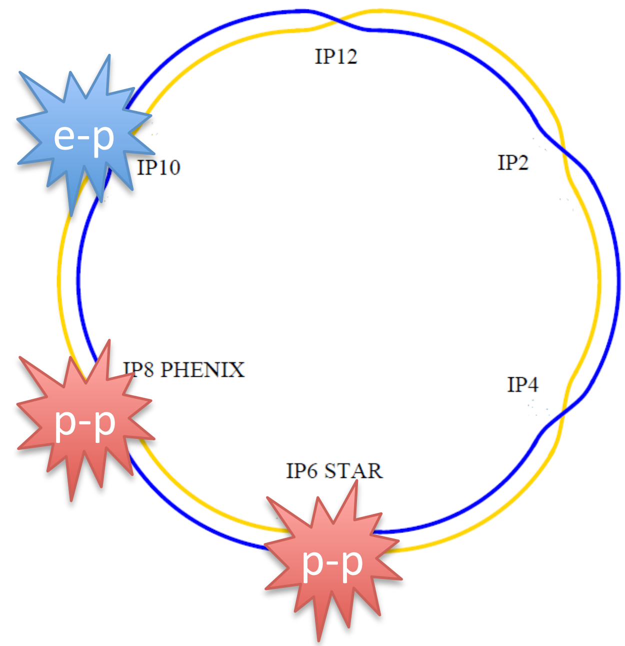
Beam-Beam Compensation with electron lenses

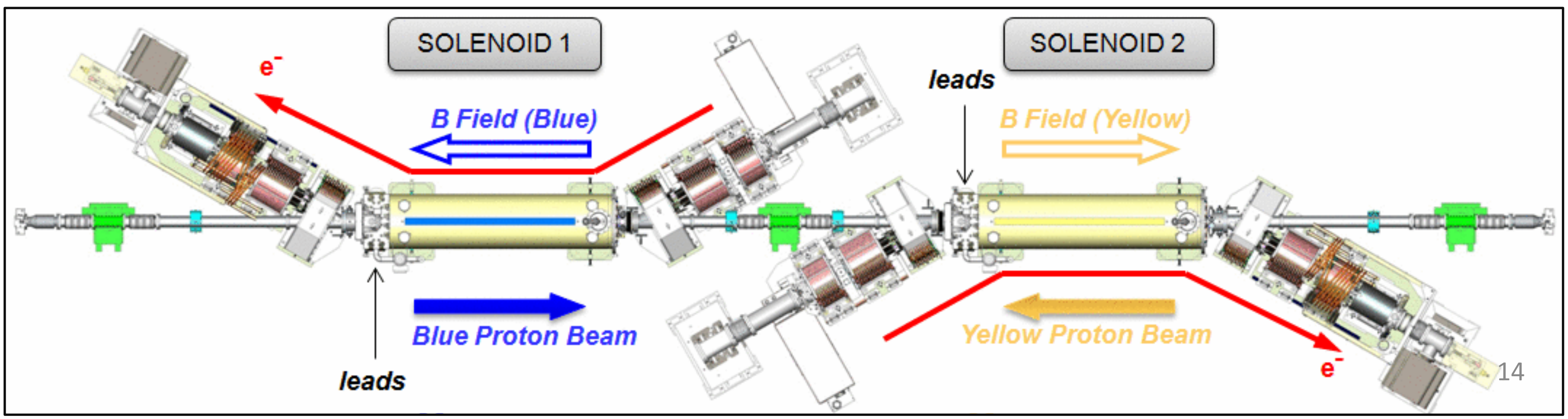
Equal and opposite force supplied by colliding head on with 10 keV electron beam: cancels one p-p interaction

E-beam size matched to proton beam size at location of lens

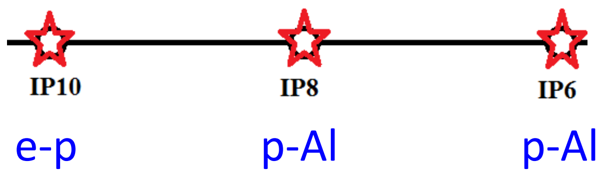
6 T solenoid fields avoid e-beam driven stability

Requires lattice modification to prevent driving resonances

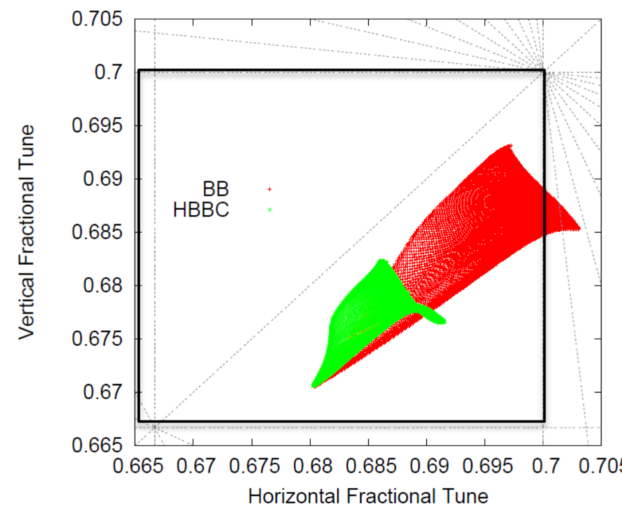


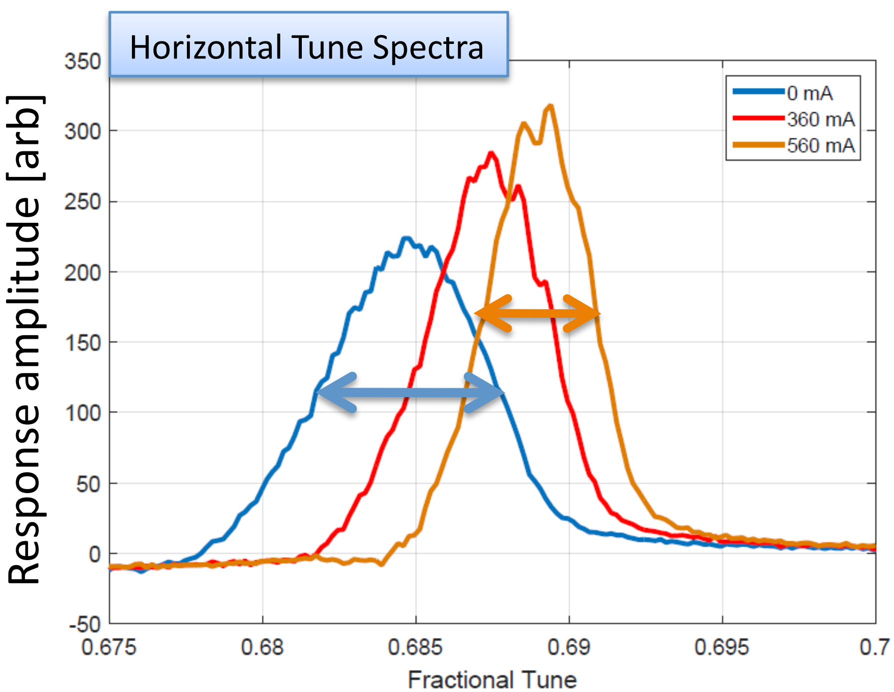


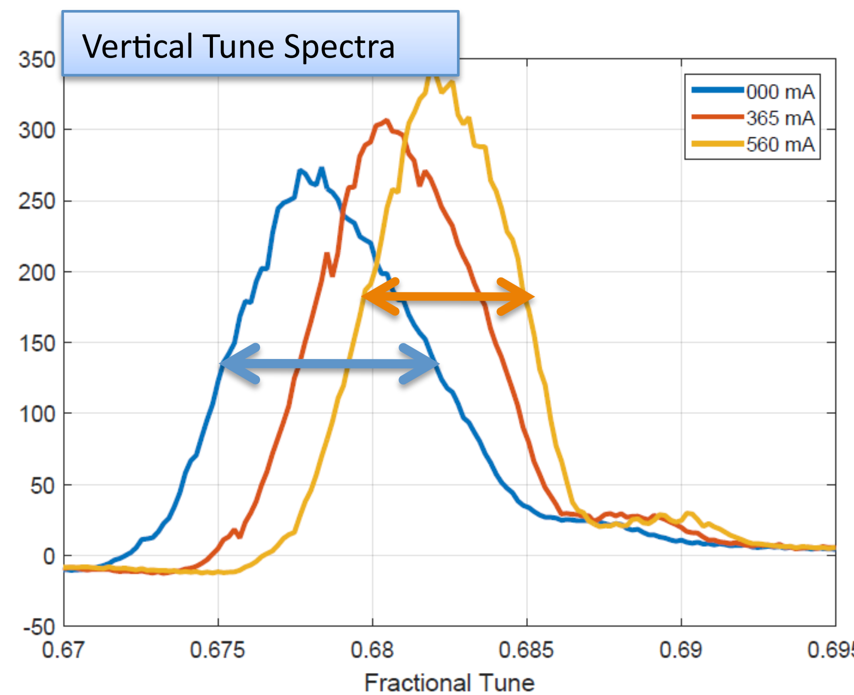
Tune spread compensation with p-Al



Beam-beam induced tune spread from Al beam compensated by the e-lens





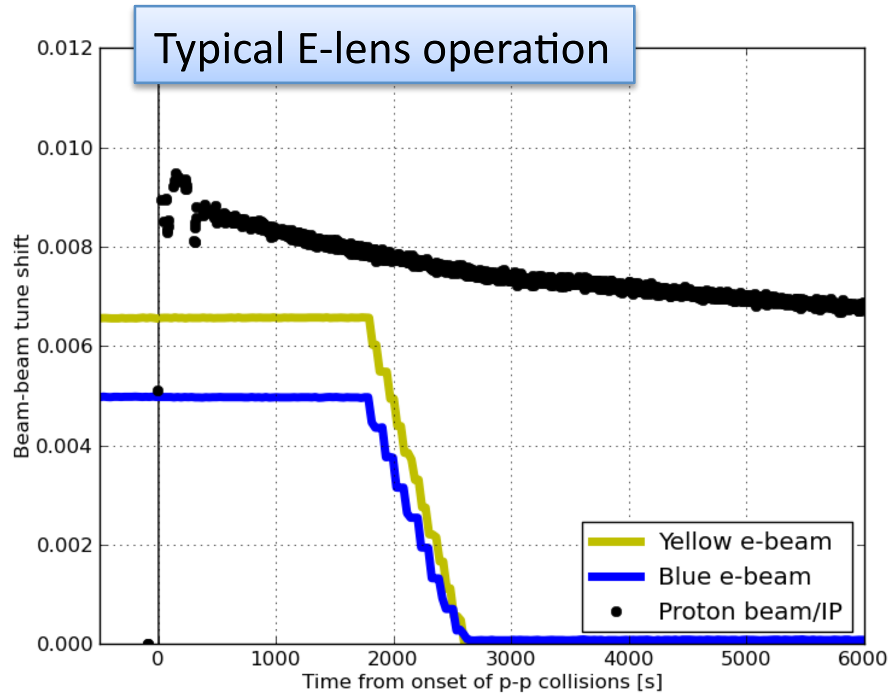


Plots courtesy X.Gu

Beam-beam compensation

Run	ΔQ_{bb}/IP*
Run 12	0.006
Run 15 (no e-lens)	0.008
Run 15 (w/ e-lens)	0.010

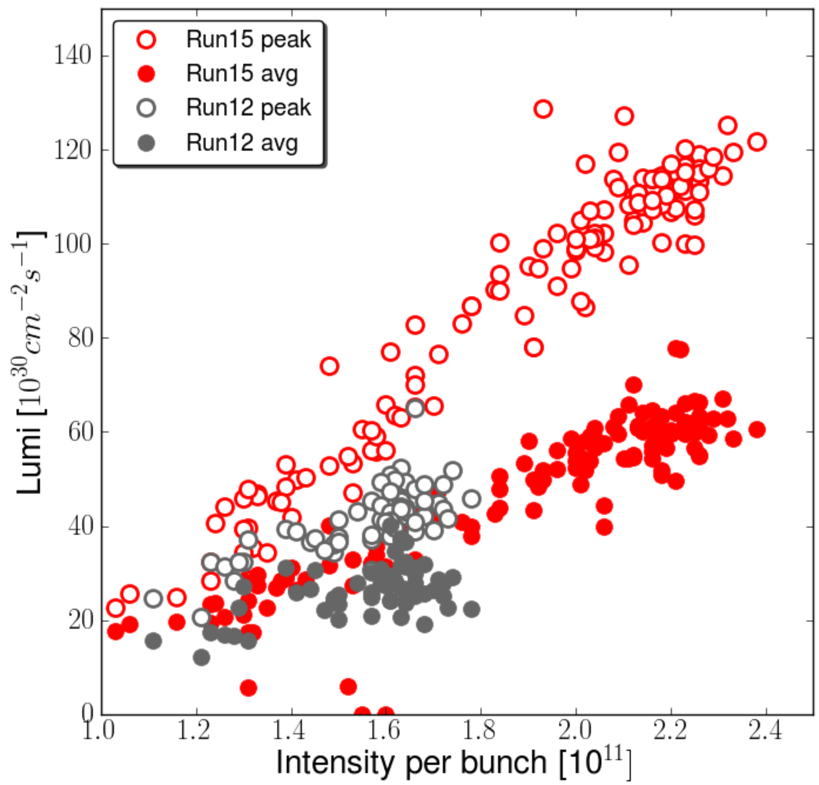
* Max achieved without emittance blowup



Improvement without e-lens due to improvements in lattice design, particularly for off-momentum particles.

Luminosity with beam-beam compensation

Run	Luminosity (avg, relative to Run 12)
12	
15 (no e-lens)	+66%
15 (w/ e-lens)	+91%



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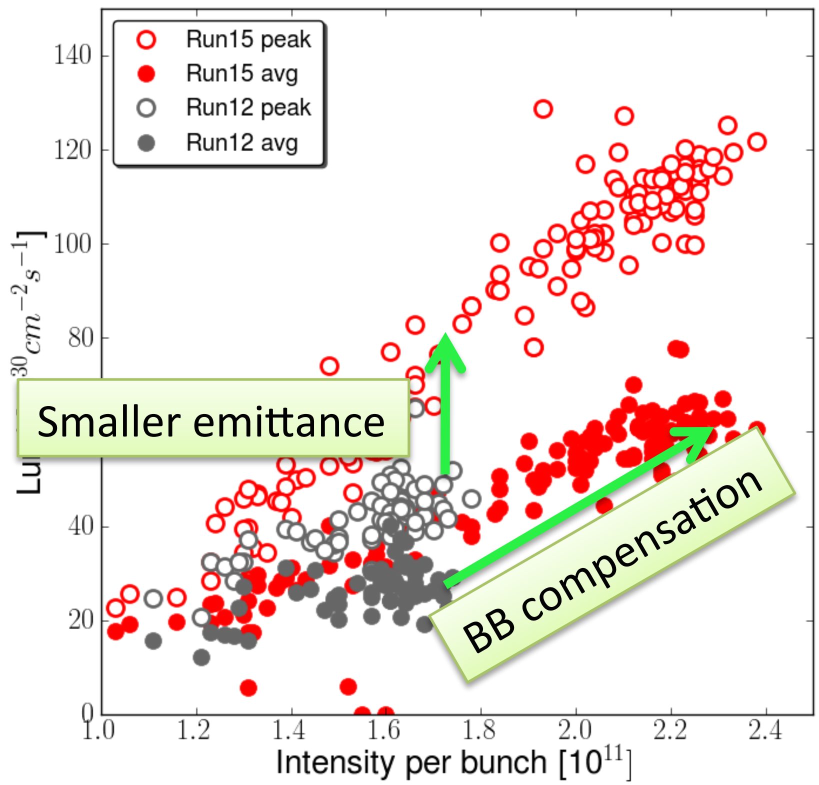
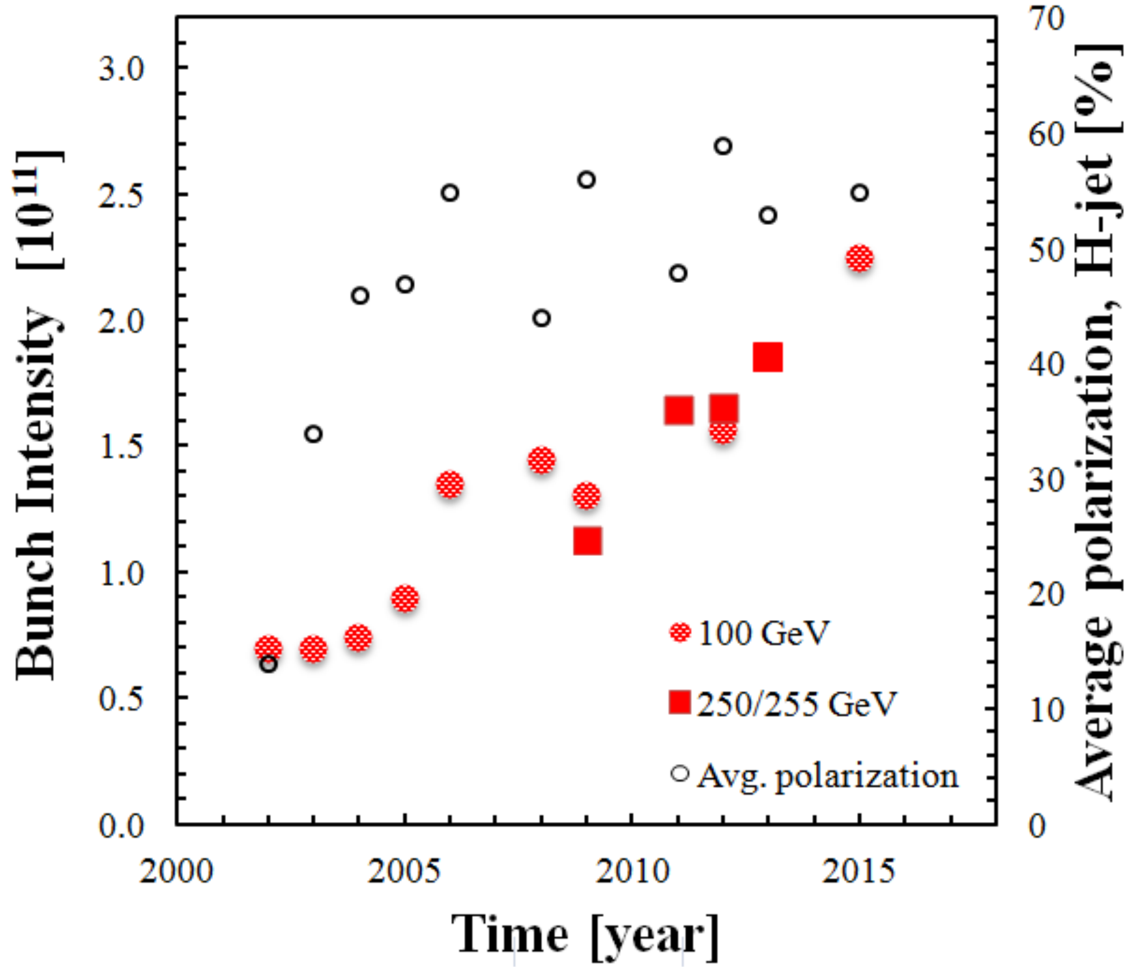


Overall RHIC Performance

Recent collider performance increases largely from increase in luminosity at fixed polarization.

2011-2013 improvements moderate

Intensity jump in 2015 when electron lens allows RHIC to accept the brighter injector beam



W. Fischer et al. Phys. Rev. Lett. **115, 264801**

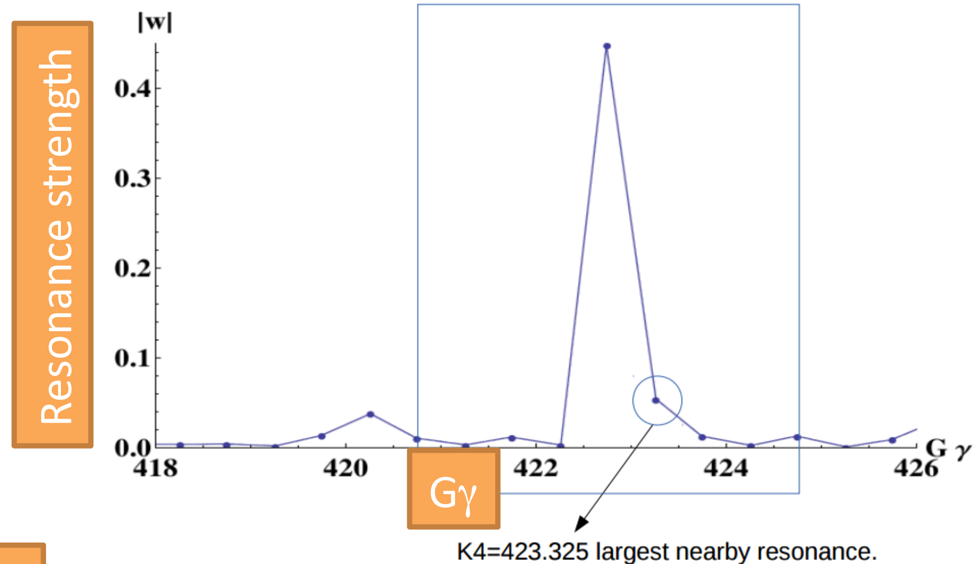
Plans for Run 17
Spin resonance compensation in RHIC

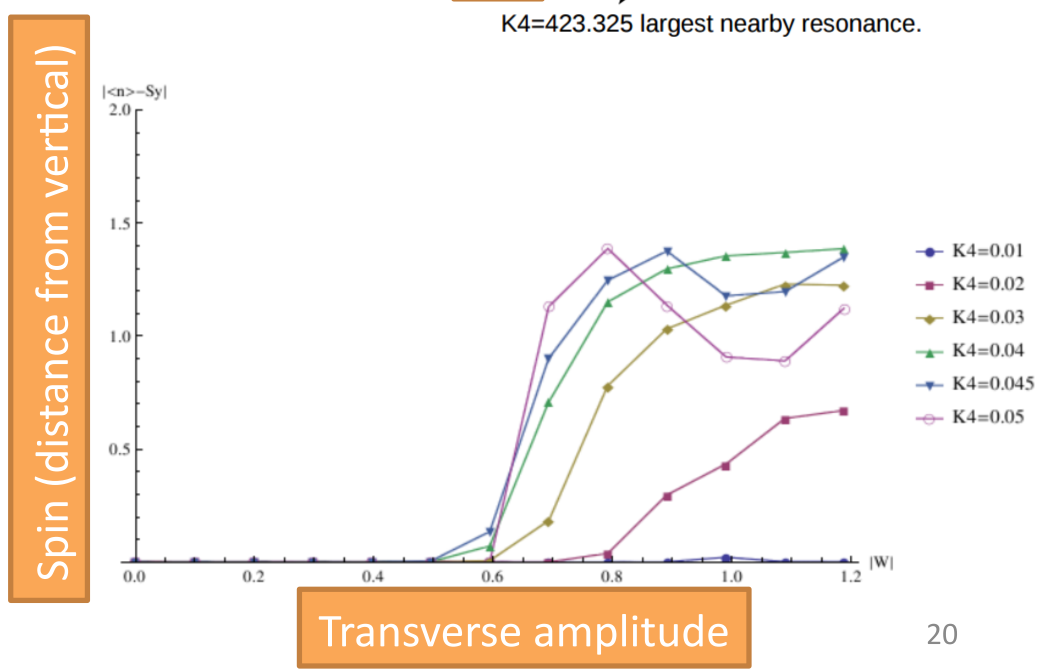
Lose 15-20% polarization during acceleration from 100 to 255 GeV

Three major intrinsic resonances are too strong to be compensated directly
Single resonance model says two snakes is enough

Resonance overlap (parametric resonance) is a possible source of depolarization.

Can improve the transmission by compensating neighboring small resonances.



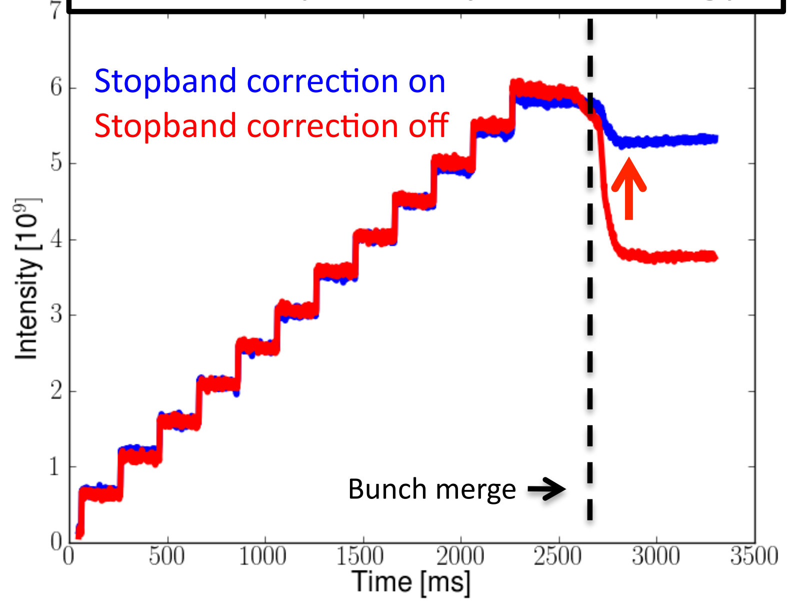


V. Ranjbar, PR-ST AB18, 014001 (2015)

Plans for Run 17
Further emittance improvements in the injectors

- Space charge mitigation in AGS
  - Lower RF harmonic, longer bunches
  - Add Booster-style dual harmonic scheme
  - Nonlinear stop-band correctors (recently installed for Au)
- AGS instrumentation
  - Commissioning RHIC-style ionization profile monitors in AGS
  - AGS base-band tune system
    - Fast tune measurements
    - Spectra of transverse motion to identify/eliminate external excitations

Au Intensity (AGS injection energy)



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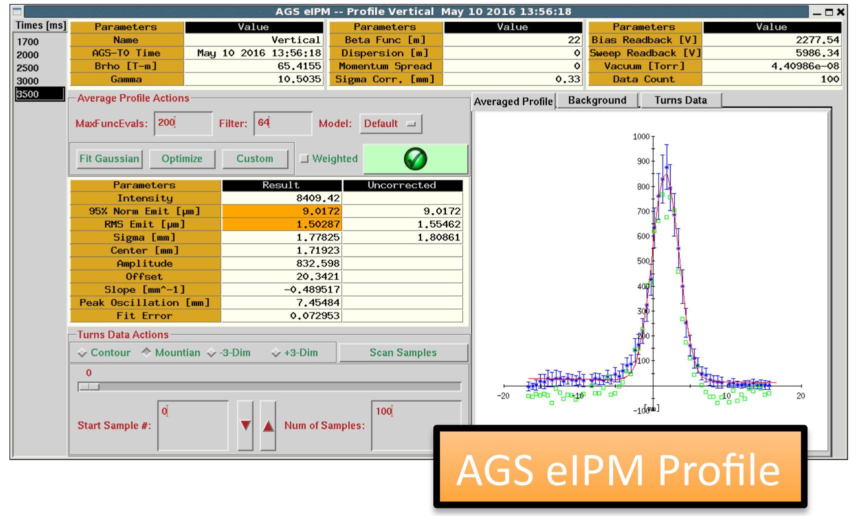
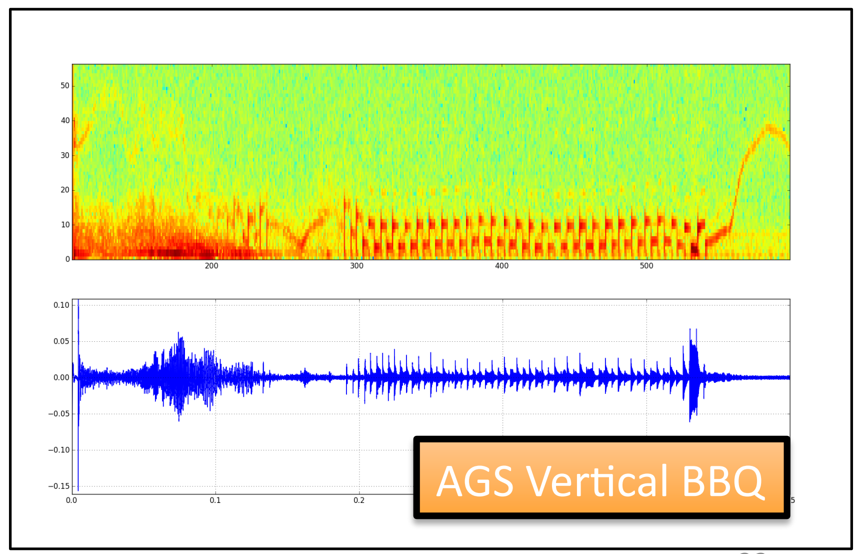




Summary

- Record polarized p-p luminosities have been attained over the last few years
- Improvements over the last few years come from work done all over the complex, source to collision
- First operation with asymmetric polarized proton on ion collisions
- Benefits come from both improved beam dynamics (emittance) and direct efforts to address depolarization
- Run 17 will be the first 255 GeV since 2012, so it will be the first to benefit from the full effects of these upgrades

Backups

Proton-Ion Operations

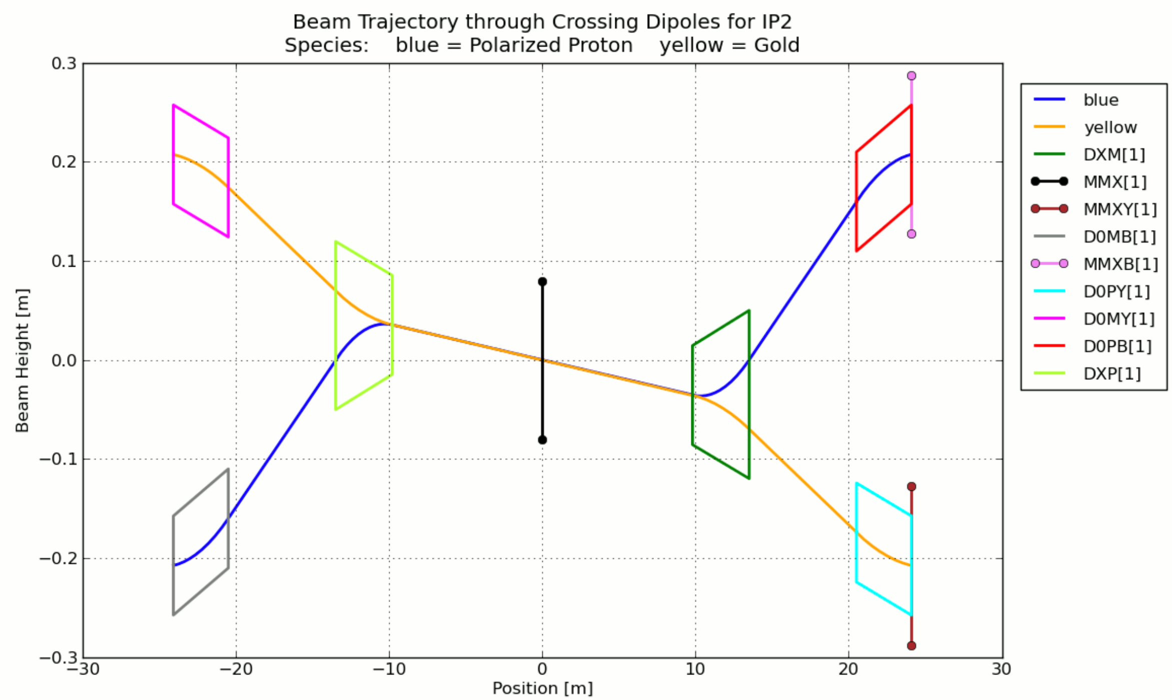
Run Coordinator: Chuyu Liu

p-Au (and p-Al) operation require moving DX magnets to keep beams inside the aperture. A first for RHIC operation.

Several aperture restrictions identified/removed before the switch (ion pumps, STAR pipe)

Physical move took ½ day

Established collisions in ~ 1 week.



(plot courtesy of C. Liu)

Proton-Ion Operations:

Two Ramp Scheme