

# RHIC Operational Modes Enabled by Enhanced Beam Control

V. Schoefer for the RHIC Team

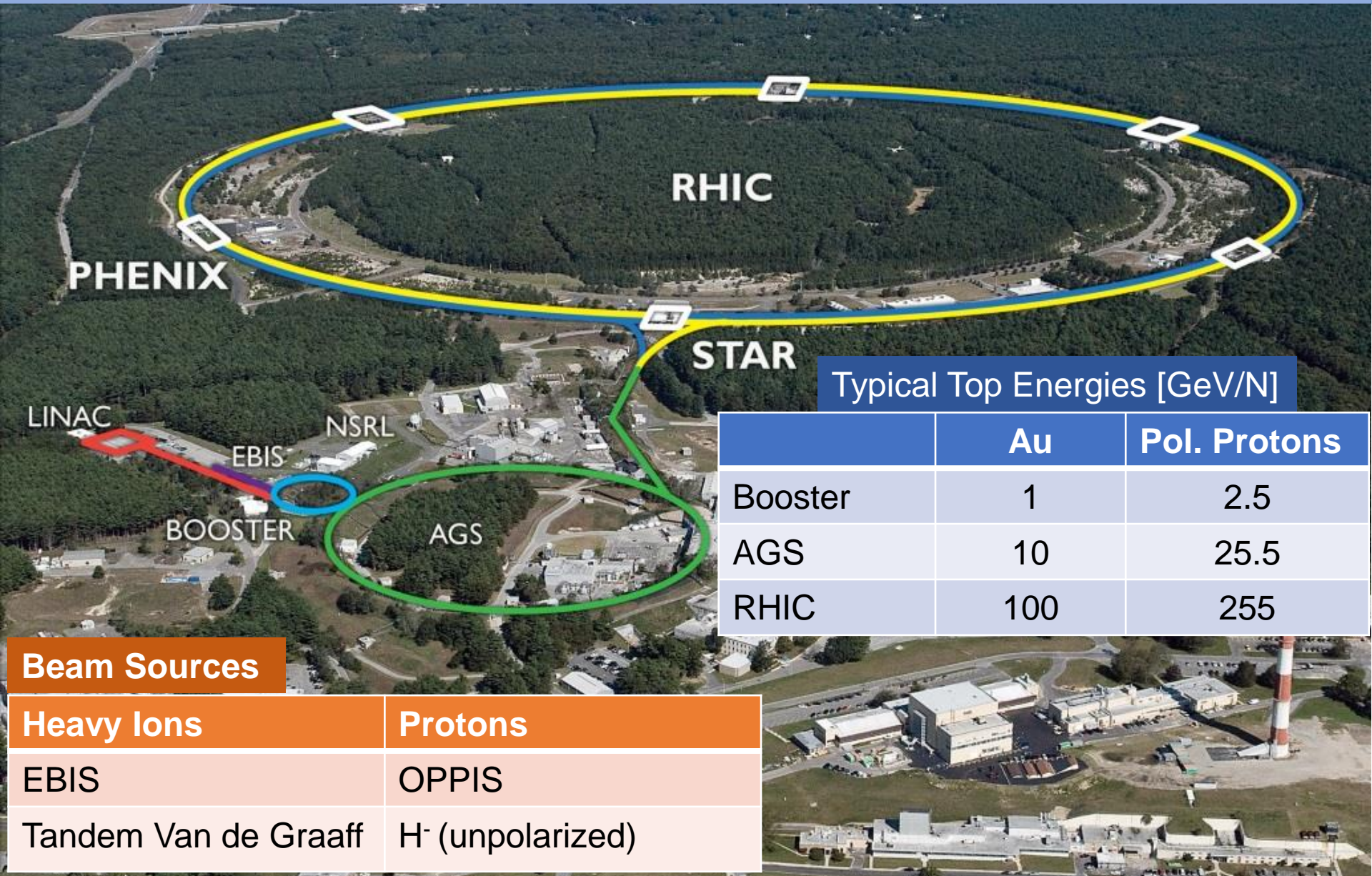
Special thanks to W. Fischer, A. Marusic, M. Minty, T. Shrey  
and G. Marr for input on this talk

*APEC Workshop Dec. 2018*

**BROOKHAVEN**  
NATIONAL LABORATORY



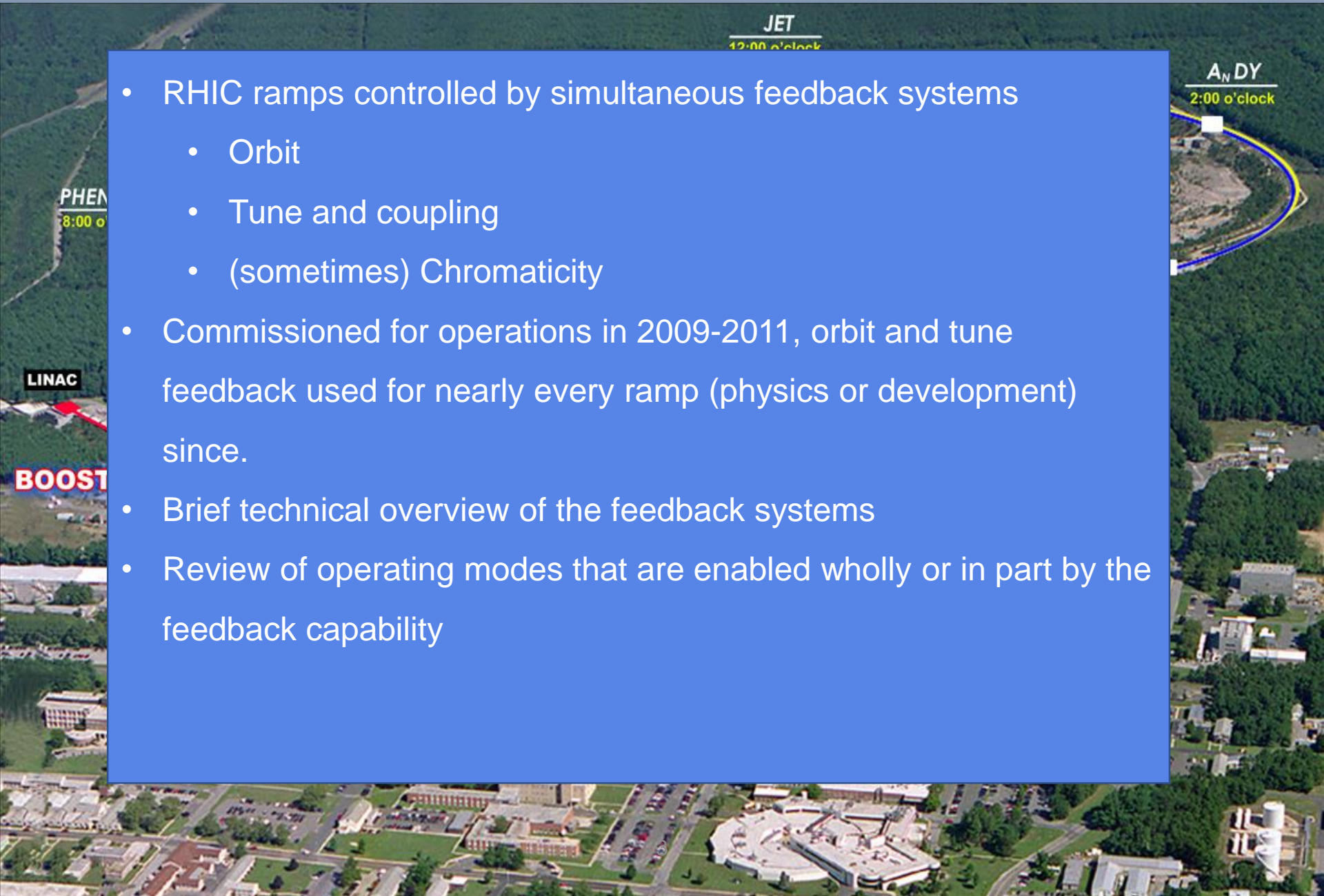
# RHIC Accelerator Complex





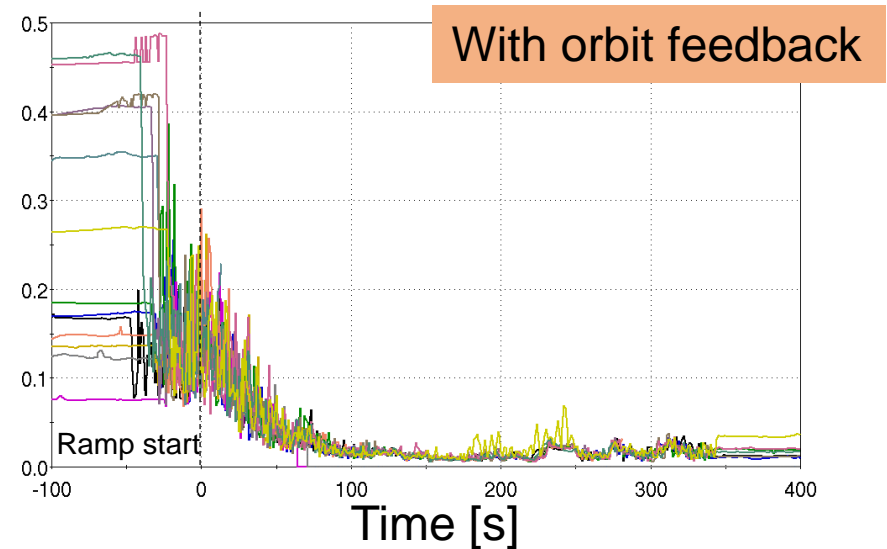
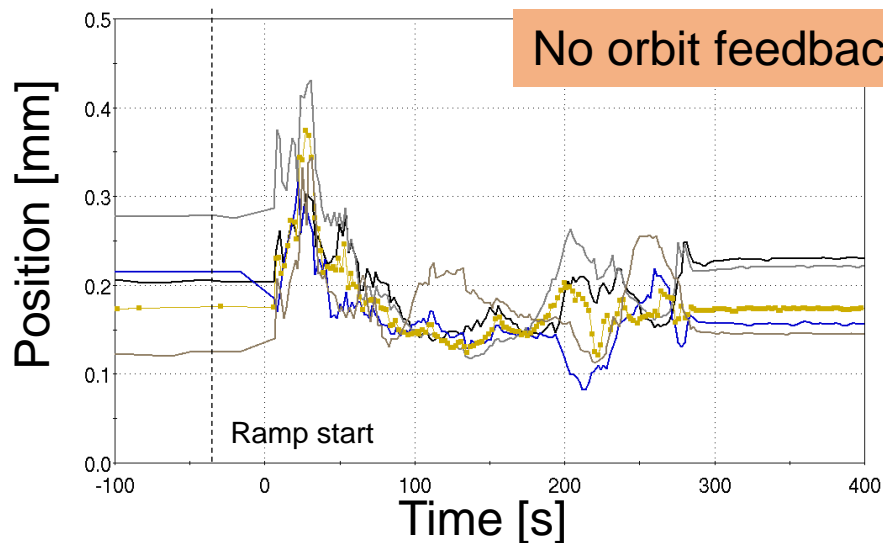
# Outline

- RHIC ramps controlled by simultaneous feedback systems
  - Orbit
  - Tune and coupling
  - (sometimes) Chromaticity
- Commissioned for operations in 2009-2011, orbit and tune feedback used for nearly every ramp (physics or development) since.
- Brief technical overview of the feedback systems
- Review of operating modes that are enabled wholly or in part by the feedback capability



# RHIC Feedback Systems: Orbit (Slow)

## Orbit RMS During Several Ramps



- 1 second avg orbit measurement
- Standard lattice orbit correctors
- Correction matrices pre-calc'd based on model, updated at 1Hz on ramp
- Iterated SVD corrections also at 1Hz
- **BPM Filtering and model improvements**
- **Push-button for operations**

# RHIC Feedback Systems: Tune, Coupling : Measurement during the ramp

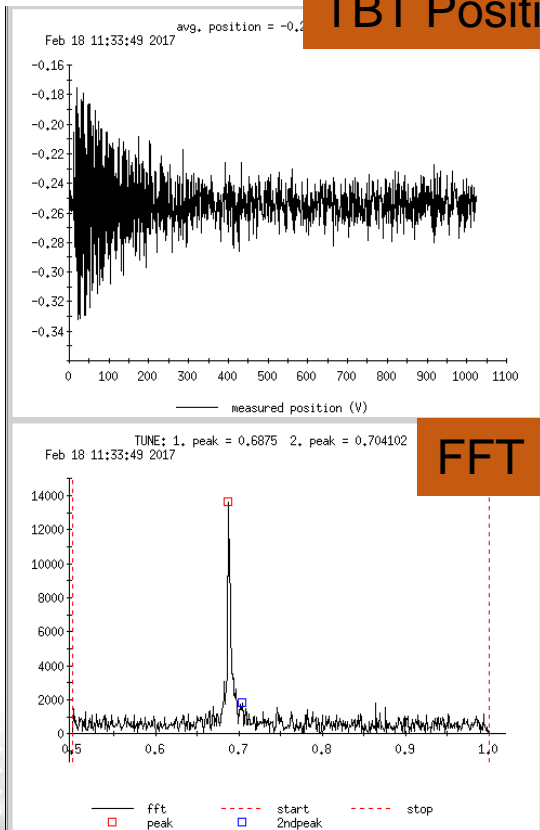
Pre-2006:

Large single turn kick

FFT of free oscillation

No feedback on measurement

TBT Position



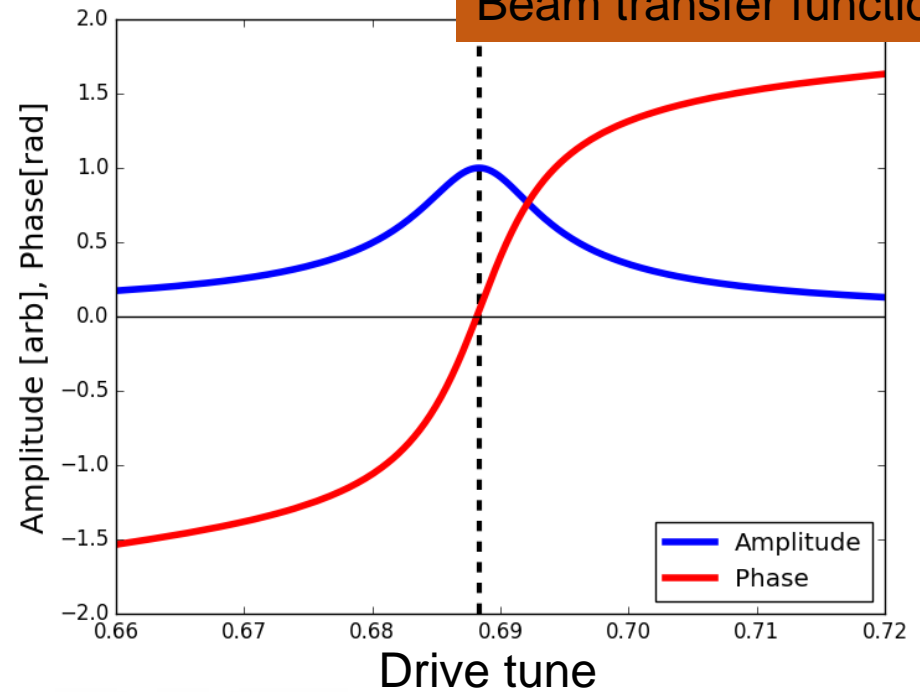
Post 2006:

Continuous driven oscillation

Zero phase determines resonance

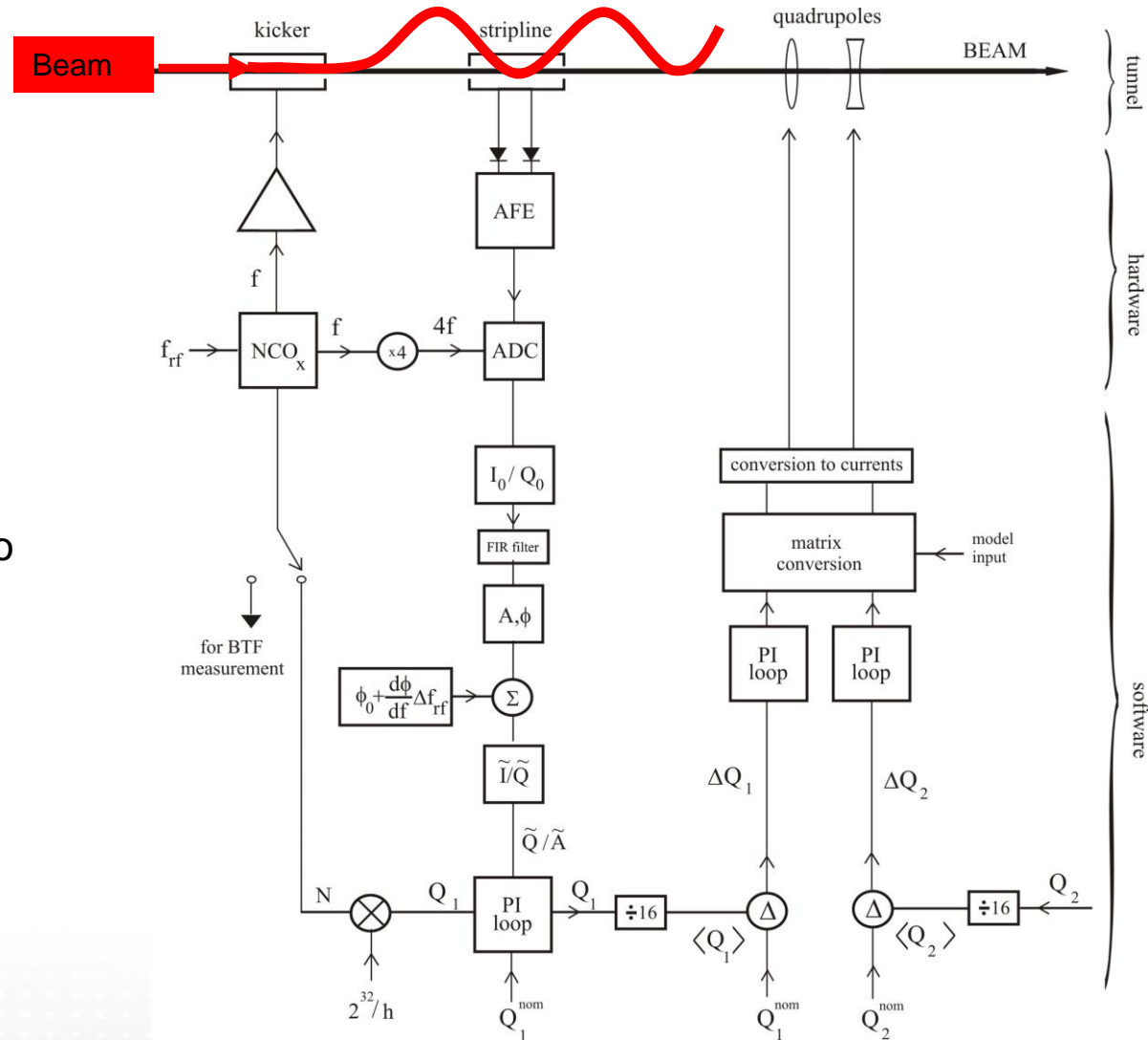
Feedback possible

Beam transfer function



Phase =  $\Delta\phi$  between kick and measurement

# RHIC Feedback Systems: Tune, Coupling



- Sensitivity
  - Direct diode detection
  - Allows determination of tune with *very small* ( $10\text{-}30 \mu\text{m}$ ) excitation
  - No emittance growth
- Precision
  - Phase-locked loop
  - Locks drive frequency to resonance
  - Tune determined to  $10^{-5}\text{-}10^{-6}$
- Control
  - Feedback to magnets
  - Model inputs

# Beam Stability

Control of orbit, tune and coupling **improve by factor of 10-100** over open loop operation

Coupling control critical to tune control (Hor, Ver PLLs have to be able to clearly distinguish eigenmodes)

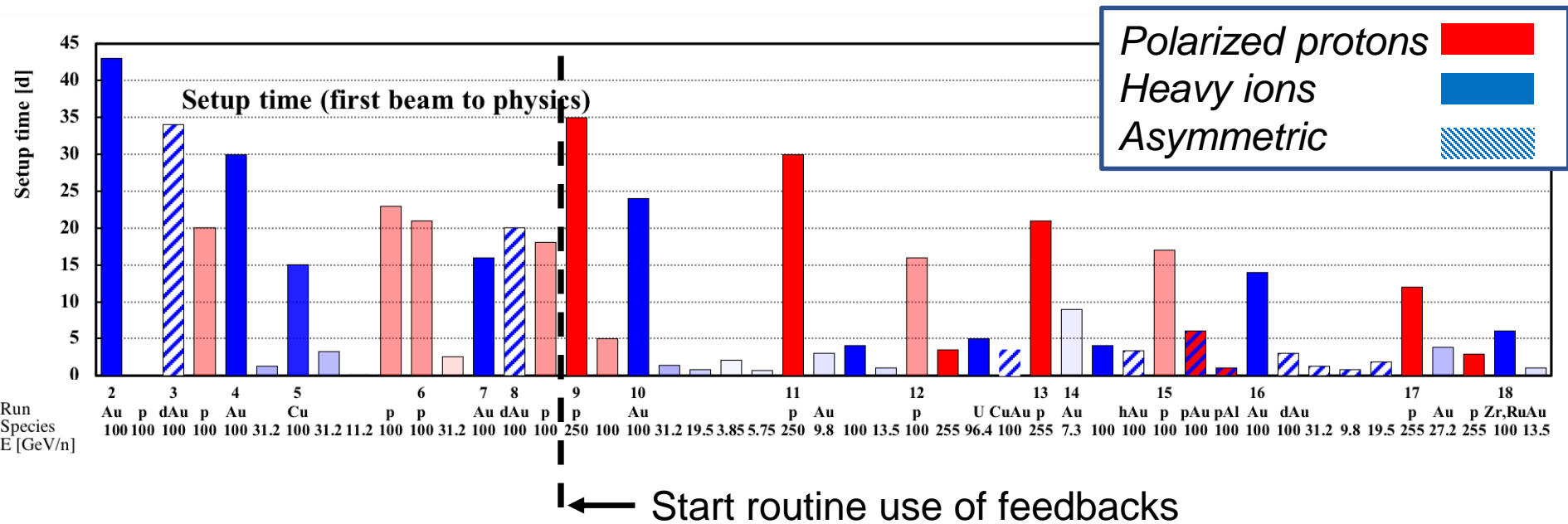
## Parameter Stability Over Course of RHIC Ramp

	No feedbacks	With feedbacks
Orbit ( $x_{rms}, y_{rms}$ )	$\sim 500 \mu\text{m}$	$\sim 20 \mu\text{m}$
Tune ( $Q_x, Q_y$ )	$\sim 0.1$	$< 0.001$
Coupling $ C $	$\sim 0.1$	$< 0.01$

Includes fast events like transition, snapback

*But what can we DO with it?*

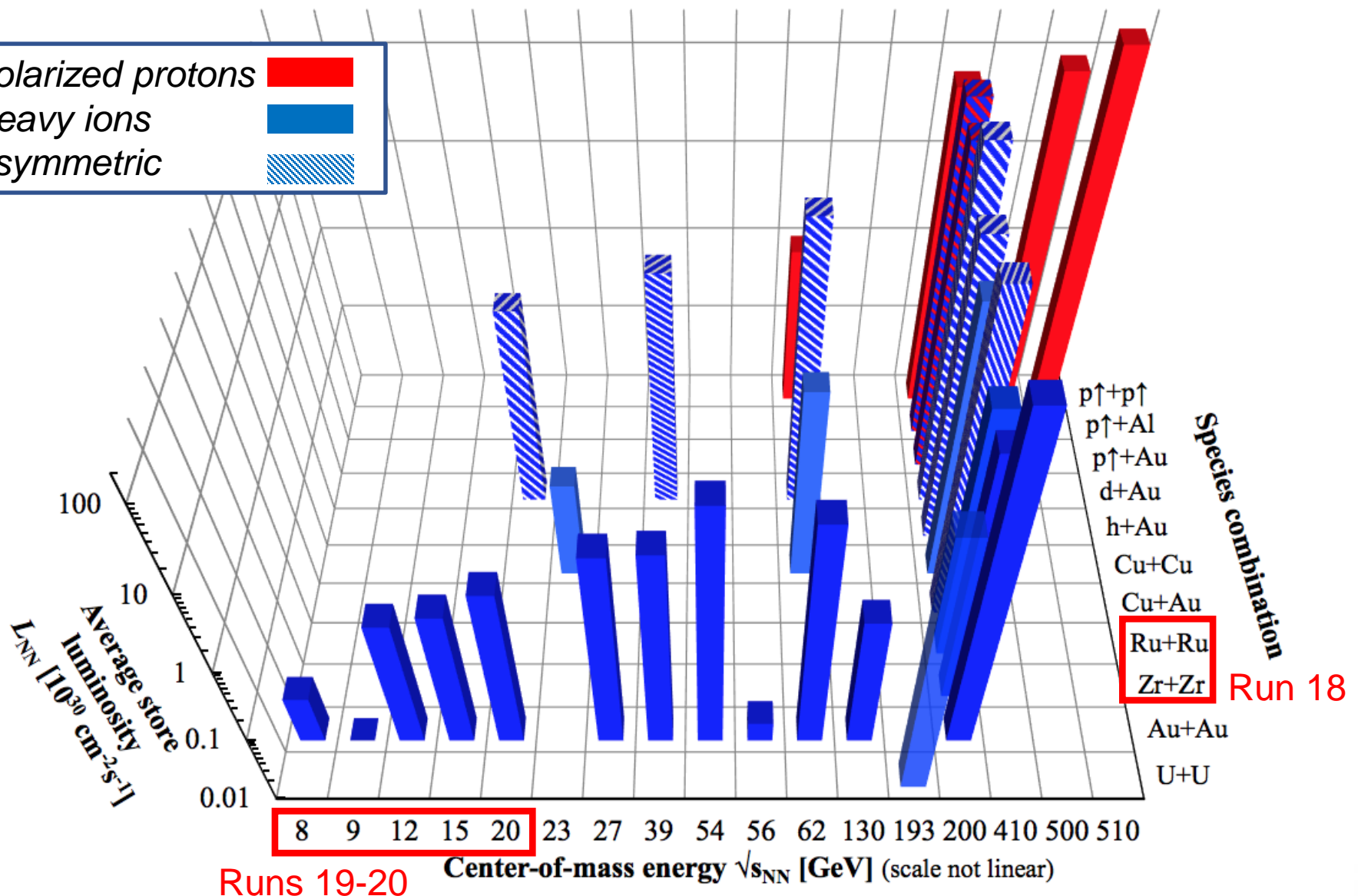
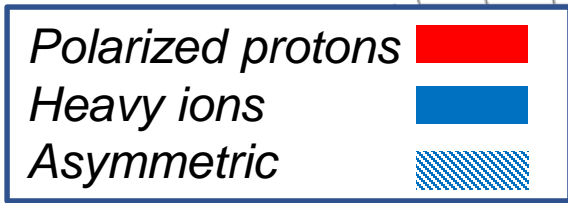
# Startup Time Improvement



- Initial startup times drop from ~ 2-3 weeks, converging to <1 week
- First few days are often one shift/day of beam
- Beam to flattop often on first ramp
- Startups now often include setting up *all* the ramps we plan to use for the run at once



# RHIC energies, species combinations and luminosities (Run-1 to 18)



# More modes, then more, then more...

*Faster setups means more setups....*

1. Only one mode at a time
  1. All experiments and development done with the physics ramp
2. Single day ramp setups are possible
  1. Often ions and polarized proton physics in alternating years, this allows polarized proton trials and experiments *during ion runs*, beneficial for prep ahead of time
3. Asymmetric collisions become *much* easier
  1. Polarized protons colliding with Au,Al in 2015
  2. p-Au required proton pre-acceleration: setup and maintain 3 ramps
4. *Culminates in the "Isobar Run" in Run 18*
  1. *Daily switching of accelerated species in the collider for the first time*

# Isobars in Run 18

Ru-96  
Zr-96

IUPAC Periodic Table of the Elements

IUPAC Periodic Table of the Elements																																			
1 H hydrogen 1.008																	2 He helium 4.0026																		
3 Li lithium 6.941	4 Be beryllium 9.0122	atomic number name conventional atomic weight standard atomic weight																10 Ne neon 20.180																	
11 Na sodium 22.990	12 Mg magnesium 24.305	13 Al aluminum 26.982	14 Si silicon 28.086	15 P phosphorus 30.974	16 S sulfur 32.06	17 Cl chlorine 35.45	18 Ar argon 39.948	19 K potassium 39.098	20 Ca calcium 40.078	21 Sc scandium 44.956	22 Ti titanium 47.88	23 V vanadium 50.942	24 Cr chromium 51.996	25 Mn manganese 54.938	26 Fe iron 55.845	27 Co cobalt 58.933	28 Ni nickel 58.693	29 Cu copper 63.546	30 Zn zinc 65.38	31 Ga gallium 69.723	32 Ge germanium 72.630	33 As arsenic 74.922	34 Se selenium 78.971	35 Br bromine 79.904	36 Kr krypton 83.796										
37 Rb rubidium 85.468	38 Sr strontium 87.62	39 Y yttrium 88.906	40 Zr zirconium 91.224	41 Nb niobium 92.906	42 Mo molybdenum 95.94	43 Tc technetium 98	44 Ru ruthenium 101.07	45 Rh rhodium 102.91	46 Pd palladium 106.42	47 Ag silver 107.87	48 Cd cadmium 112.41	49 In indium 114.82	50 Sn tin 118.71	51 Sb antimony 121.76	52 Te tellurium 127.60	53 I iodine 126.90	54 Xe xenon 131.29	55 Cs caesium 132.91	56 Ba barium 137.33	57-71 lanthanoids	72 Hf hafnium 178.49	73 Ta tantalum 180.95	74 W tungsten 183.84	75 Re rhenium 186.21	76 Os osmium 190.23	77 Ir iridium 192.22	78 Pt platinum 195.08	79 Au gold 196.97	80 Hg mercury 200.59	81 Tl thallium 204.38	82 Pb lead 207.2	83 Bi bismuth 208.98	84 Po polonium [209]	85 At astatine [210]	86 Rn radon [222]
87 Fr francium [223]	88 Ra radium [226]	89-103 actinoids	104 Rf rutherfordium [261]	105 Db dubnium [262]	106 Sg seaborgium [263]	107 Bh bohrium [264]	108 Hs hassium [265]	109 Mt meitnerium [266]	110 Ds darmstadtium [267]	111 Rg roentgenium [268]	112 Cn copernicium [269]	113 Nh nihonium [270]	114 Fl flerovium [271]	115 Mc moscovium [272]	116 Lv livermorium [273]	117 Ts tennessine [274]	118 Og oganeson [276]																		

Same number of *nucleons*  
Different number of *protons*

Same *QGP matter*  
Different *magnetic field*



57 La lanthanum 138.91	58 Ce cerium 140.12	59 Pr praseodymium 140.91	60 Nd neodymium 144.24	61 Pm promethium [145]	62 Sm samarium 150.36	63 Eu europium 151.96	64 Gd gadolinium 157.25	65 Tb terbium 158.93	66 Dy dysprosium 162.50	67 Ho holmium 164.93	68 Er erbium 167.26	69 Tm thulium 168.93	70 Yb ytterbium 173.05	71 Lu lutetium 174.97
89 Ac actinium [227]	90 Th thorium 232.04	91 Pa protactinium 231.04	92 U uranium 238.03	93 Np neptunium [237]	94 Pu plutonium [244]	95 Am americium [243]	96 Cm curium [247]	97 Bk berkelium [247]	98 Cf californium [251]	99 Es einsteinium [252]	100 Fm fermium [257]	101 Md mendelevium [258]	102 No nobelium [259]	103 Lr lawrencium [260]

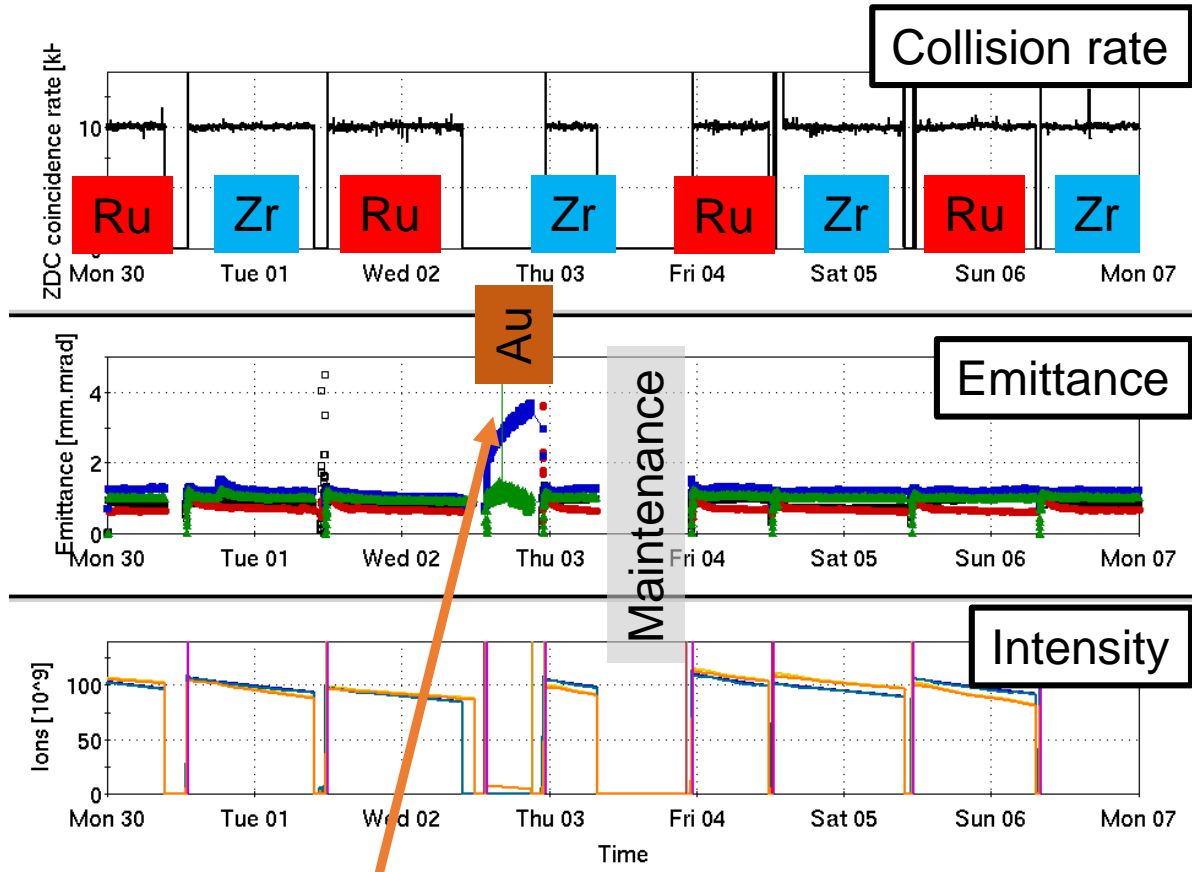
For notes and updates to this table, see [www.iupac.org](http://www.iupac.org). This version is dated 28 November 2016. Copyright © 2016 IUPAC, the International Union of Pure and Applied Chemistry.

- Experimental requirement
  - Ru-Ru collisions and Zr-Zr collisions
  - Systematic error from instantaneous luminosity means luminosity leveling
  - Systematic error from **detector aging over days and weeks**

*Third requirement rules out long run of Ru-Ru followed by long Zr-Zr run  
Daily switching of species in the collider! (Never tried before!)*

# Ru-Ru and Zr-Zr

- Lumi leveling
  - Steering
  - 3D Stochastic cooling
- RHIC/switching reliability
  - **Feedbacks!**
  - **Flexible sequencer app!**
- Complex reliability
  - 20+ hour stores
  - Injector maintenance during physics!
  - Record 91% availability for Run 18



Gold ramp for Coherent Electron Cooling  
Proof-of-principle experiment work

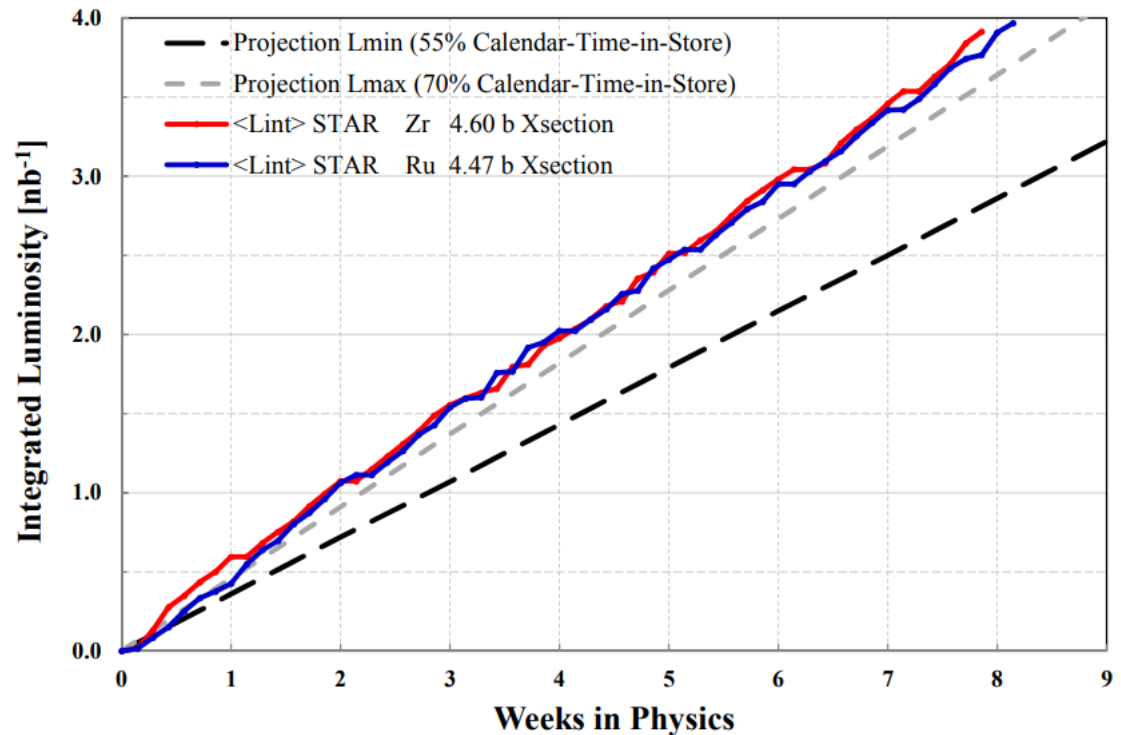


# Ru-Ru and Zr-Zr

- Lumi leveling
  - Steering
  - 3D Stochastic cooling
- RHIC/switching reliability
  - **Feedbacks!**
  - **Flexible sequencer app!**
- Complex reliability
  - 20+ hour stores
  - Injector maintenance during physics!
  - Record 91% availability for Run 18

## Run18 Delivered Luminosity

$^{96}\text{Zr}^{40+}$  on  $^{96}\text{Zr}^{40+}$   $^{96}\text{Ru}^{44+}$  on  $^{96}\text{Ru}^{44+}$   $\sqrt{s}=200$  GeV



**Of the weird things I did to the beam, I especially like things I did for polarization people.**

-- Al, our local feedback guru

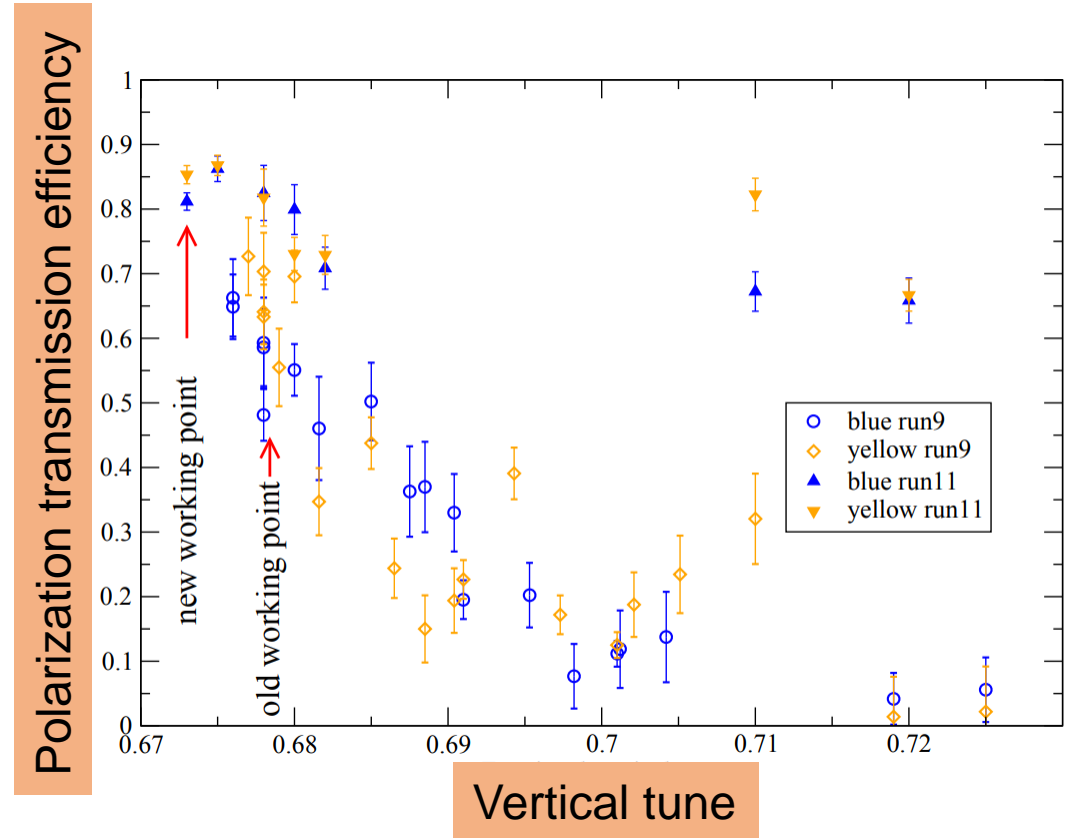
# Acceleration Near 2/3 Resonance

Polarization transmission through RHIC acceleration is sensitive to the vertical tune

Snake resonance at : 7/10  
Betatron resonance at : 2/3

Figure of merit for double-spin experiments:

$$\text{FOM} = (\text{lumi}) * (\text{polarization})^4$$



# Acceleration Near 2/3 Resonance

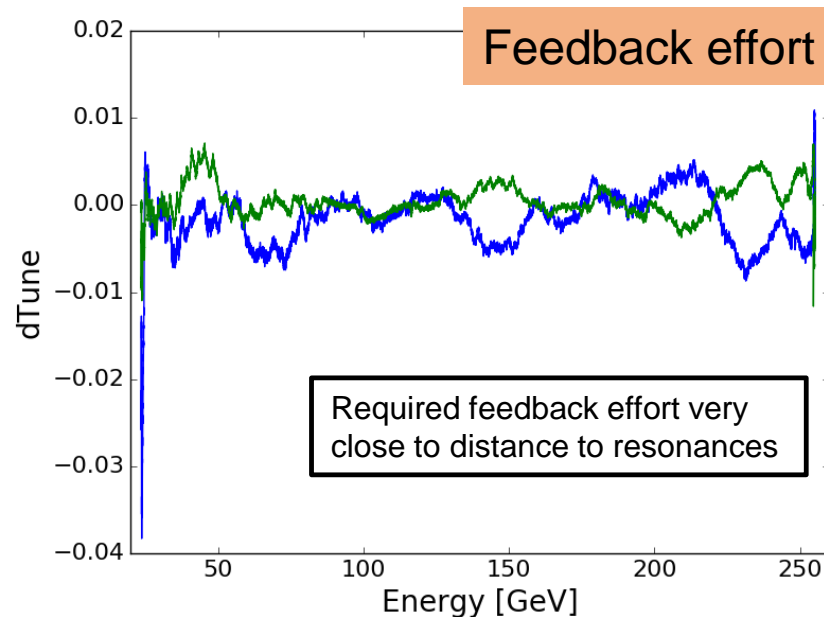
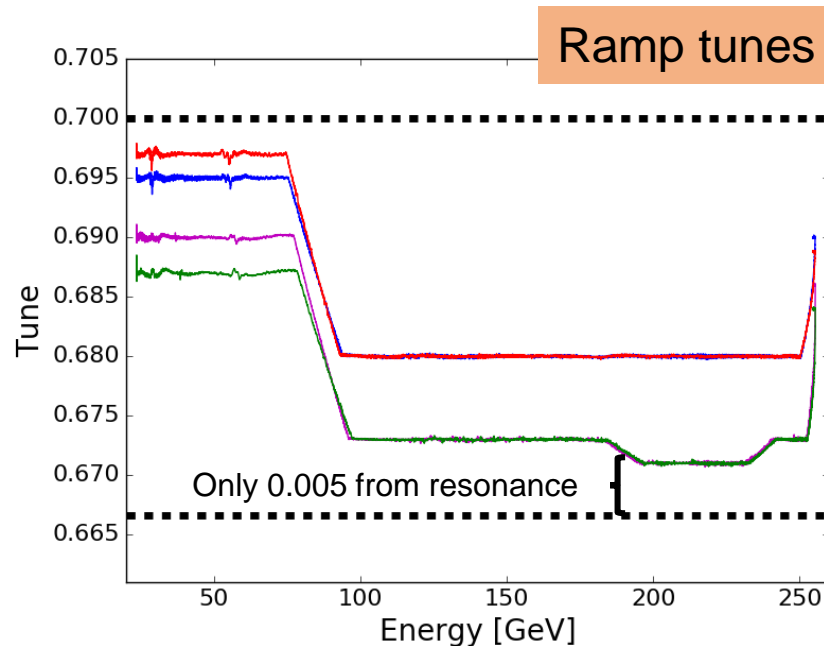
Polarization transmission through RHIC acceleration is sensitive to the vertical tune

Snake resonance at : 7/10

Betatron resonance at : 2/3

Figure of merit for double-spin experiments:

$$\text{FOM} = (\text{lumi}) * (\text{polarization})^4$$



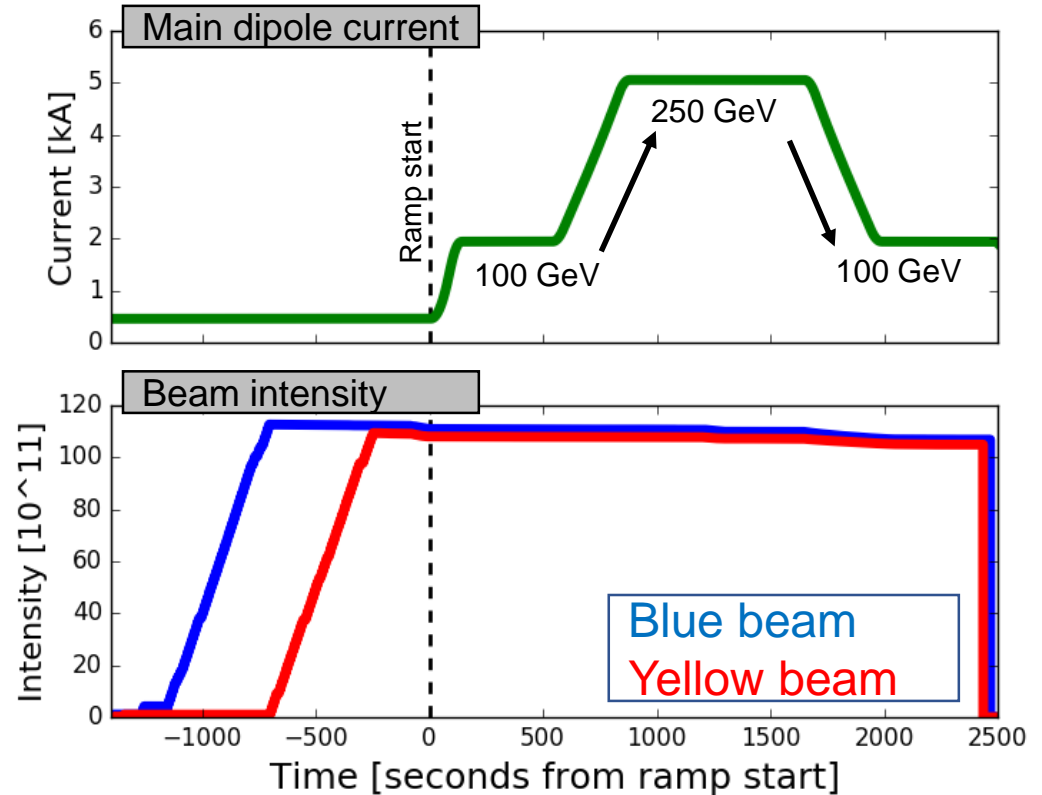


# 100-250-100 GeV ramp

Polarimeter analyzing power is energy dependent

Useful calibration is to accelerate-decelerate to an energy plateau and compare polarization

- Model uncertainty on down ramp
- Chromaticity feedback
  - RF freq modulated at 0.5 Hz
  - Tune feedback effort deviations over each modulation cycle used to calculate a chrom
  - Update sent to the sextupoles



Chrom feedback effort during the down ramp was up to **40 units!**  
Successful measurement completed in one shift with feedback  
Would have taken days without it => Would never have been done

# Stable Spin Direction

Run 12,15: Observed tilt of stable spin direction away from vertical (ideal)

Spin closed orbit a function of energy and orbit

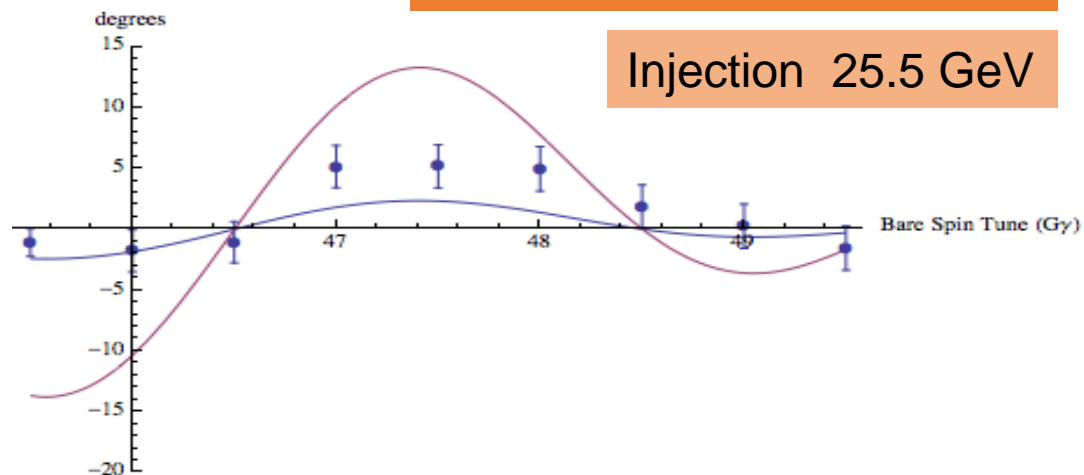
Depolarizing resonances a function of betatron tune and energy

Scan energy: don't hit a resonance, don't change the orbit

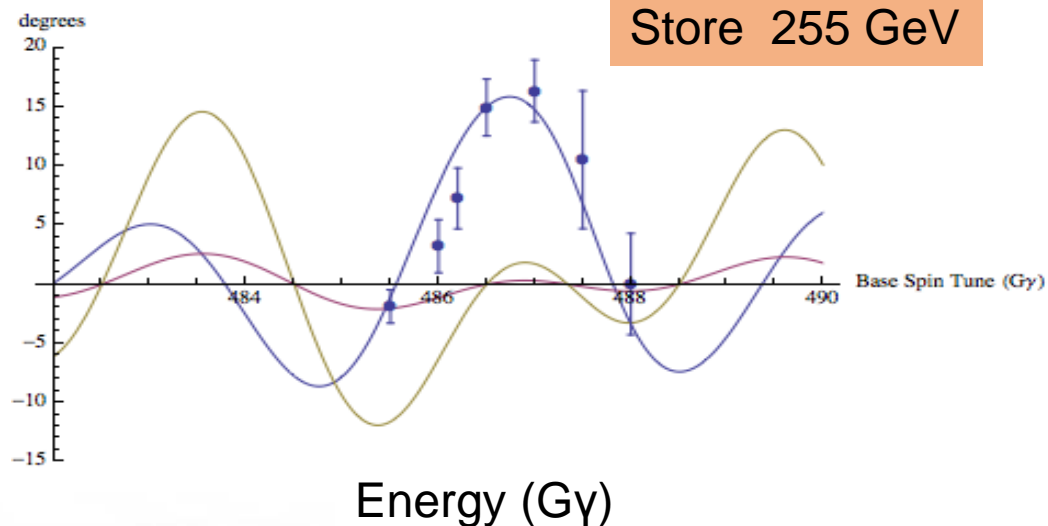
Hysteresis in mains -> corrections can change during repeated scans

Spin projection onto H plane

Injection 25.5 GeV



Store 255 GeV



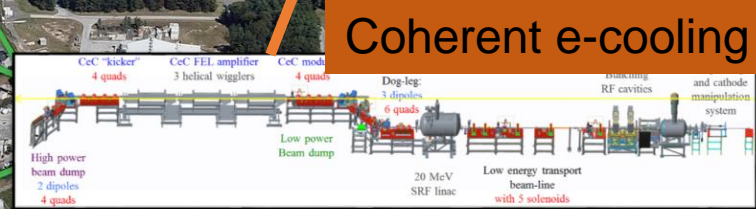
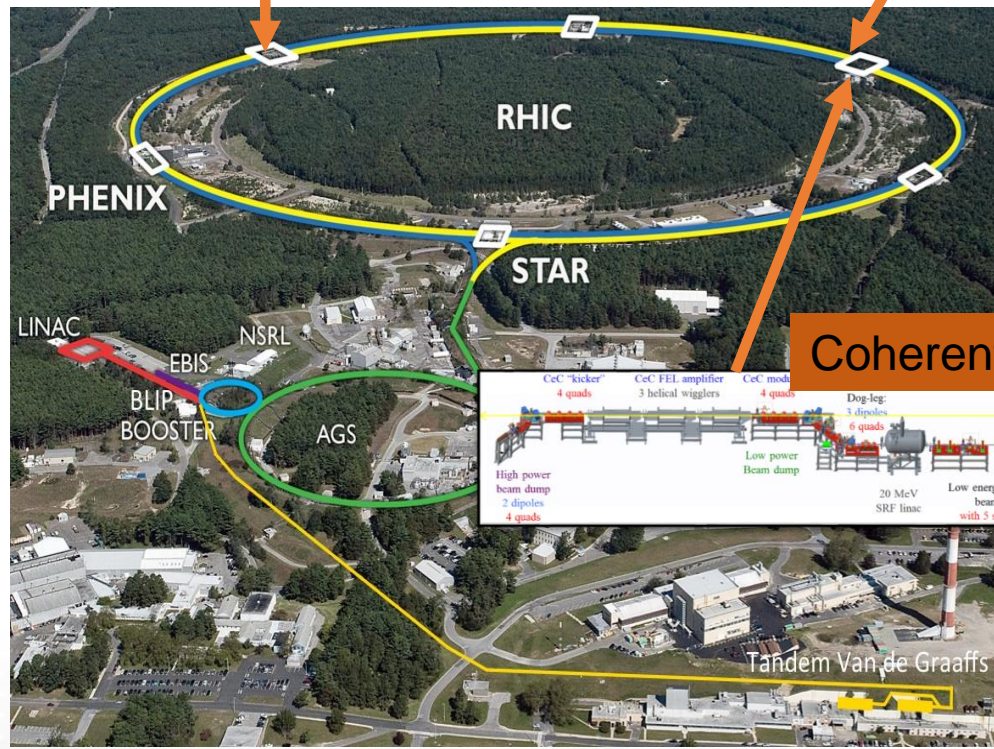
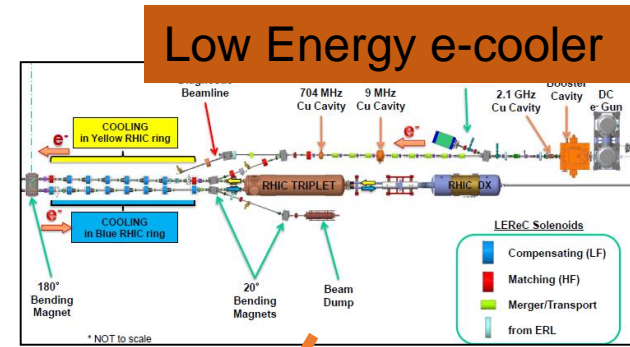
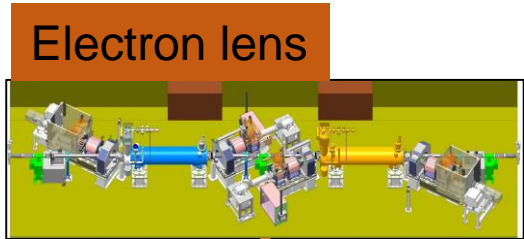
# Introduction of New Facilities

New facilities added

- Fringe fields
- Common elements with ion beam
  - Strong solenoids
  - Merge dipoles
- Changing fields during RHIC injection and stores

“Feedback will handle it”

-- people who previously would have spent several shifts incorporating the new facilities into RHIC.



# Summary

- Enhanced beam control led to drastic reduction in setup times
  - Enabled new kinds of physics operation and experiment, notably recent daily changes of species in the collider
- RHIC's most demanding program is polarized protons but the feedback 'lessons learned' are widely applicable to other facilities
  - Near resonance operation: Enlarging the possible configuration space (**near integer for space charge**)
  - Acceleration-Deceleration: Experiments with configurations well outside the model assumptions (**magnets in saturation, large momentum offset...**)
  - Stable spin direction: "Delicate" experiments (for us polarization, for a **high intensity** facility, feedback might allow experiments that would otherwise be unacceptably risky)
- Enhanced beam control has operational impacts in reliability and flexibility that go beyond the immediate improvement in precision



# References

- Tune/coupling feedback
  - Direct diode detection
    - M. Gasior, R. Jones, [The Principle and First Results of Betatron Tune Measurement by Direct Diode Detection](#), *LHC Project Report 853*, 2005
  - Phase locked loop tune measurement
    - R. Jones, P. Cameron, Y. Luo, [Towards a Robust Phase Locked Loop Tune Feedback System](#), C-A/AP Note/#204, 2005
  - Tune/Coupling feedback
    - Y. Luo, et al., Phys Rev ST AB, 9, 124001, 2006, [Continuous measurement of global difference coupling using a phase-locked-loop tune meter in the Relativistic Heavy Ion Collider](#)
    - P. Cameron et al, [Simultaneous tune and coupling feedback in the Relativistic Heavy Ion Collider, and possible implications for the Large Hadron Collider commissioning](#), Phys Rev ST AB, 9, 122801, 2006
  - Chromaticity Feedback
    - A. Marusic et al, [Chromaticity Feedback at RHIC](#), IPAC10, Kyoto, Japan

# References

- Orbit feedback
  - Fast 10 Hz feedback
    - R. Michnoff et al, [RHIC 10 Hz Global Orbit Feedback System](#), PAC 11, New York City, 2011
  - Global slow orbit feedback
    - M. Minty et al, [Global Orbit Feedback at RHIC](#), IPAC10, Kyoto, Japan
- Operational experience with simultaneous feedbacks
  - M. Minty et al, [Simultaneous Orbit, Tune, Coupling and Chromaticity Feedback at RHIC](#), PAC 2011
  - M. Minty et al, [Precision Beam Instrumentation and Feedback-based beam Control at RHIC](#), IPAC 2011

# Backup Slides

# RHIC Feedback Systems: Orbit (Fast)

- Triplet vibrations cause  $\sim 10$  Hz horizontal oscillation
  - Fast enough to evade 1 Hz correction
  - Slow enough to affect 1 Hz avg
- 
- 12 dedicated warm air-core magnets (per ring)
  - 36 fast (10kHz) BPMs

