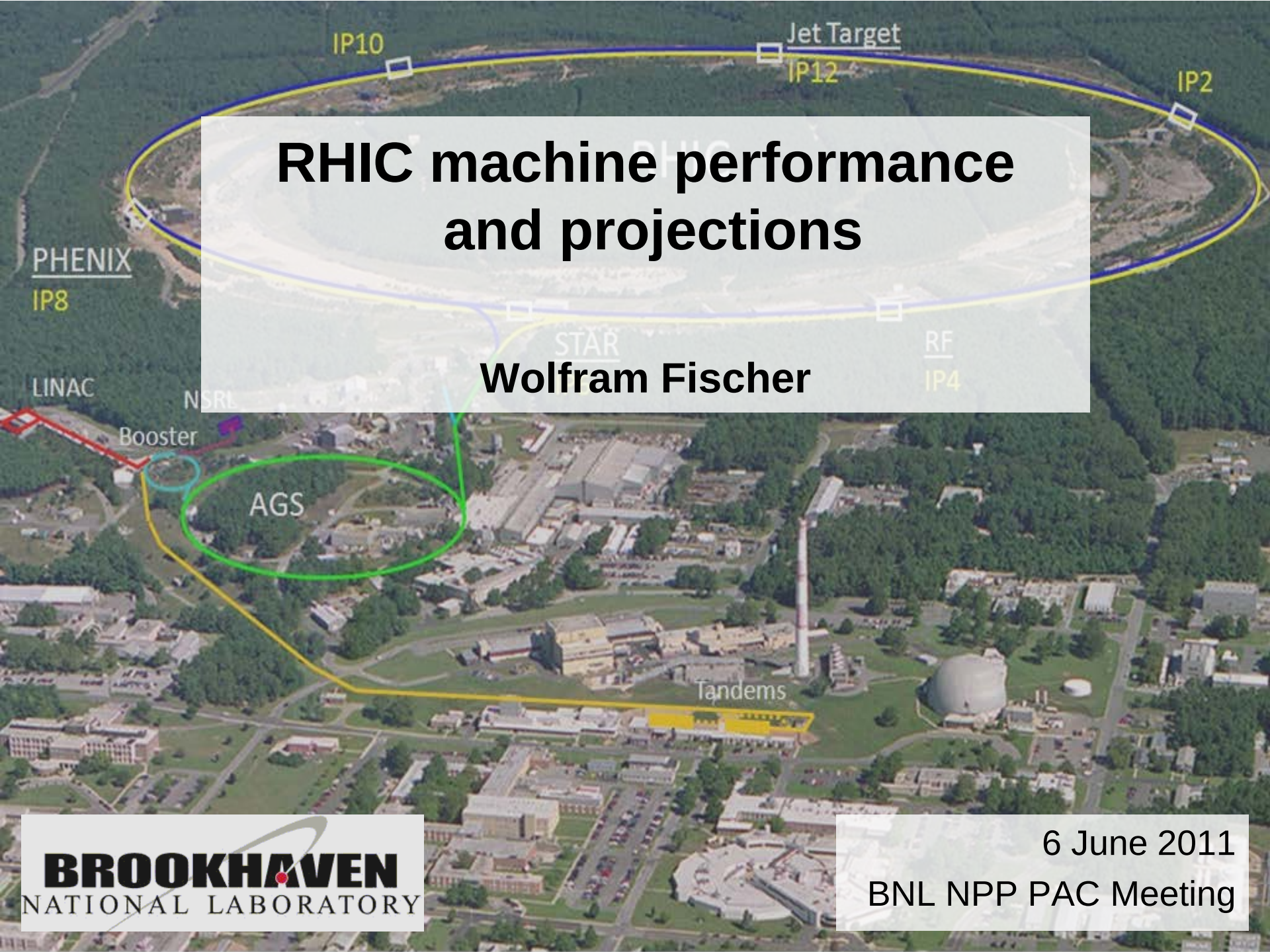


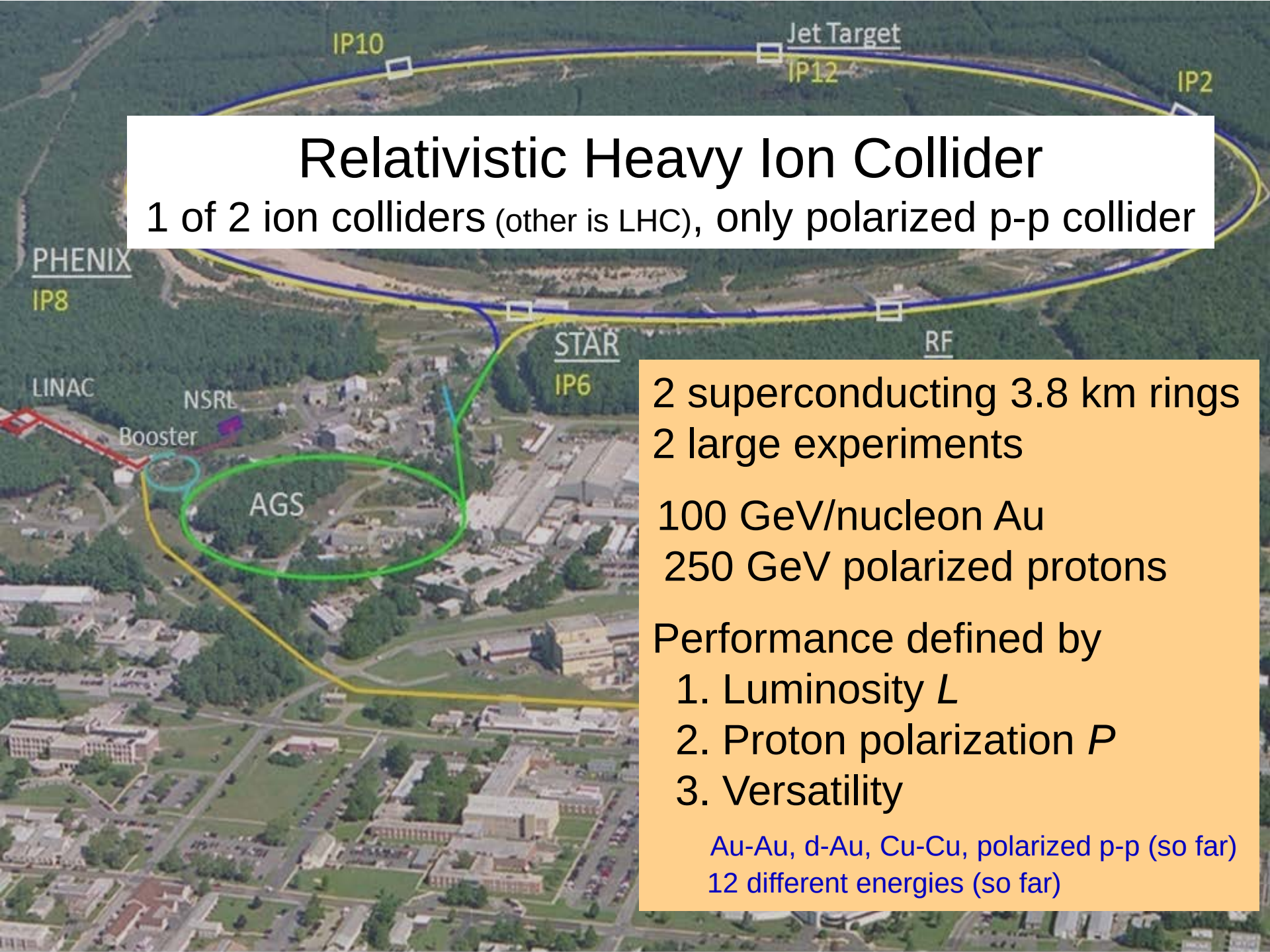
RHIC machine performance and projections

Wolfram Fischer

BROOKHAVEN NATIONAL LABORATORY

6 June 2011

BNL NPP PAC Meeting



Relativistic Heavy Ion Collider

1 of 2 ion colliders (other is LHC), only polarized p-p collider

2 superconducting 3.8 km rings
2 large experiments

100 GeV/nucleon Au
250 GeV polarized protons

Performance defined by

1. Luminosity *L*
2. Proton polarization *P*
3. Versatility

Au-Au, d-Au, Cu-Cu, polarized p-p (so far)
12 different energies (so far)

Contents

Improvements for polarized protons in Run-11

AGS

- Magnets surveyed and adjusted horizontally (*P*+)
- Horizontal tune jump quads operational (reduced *P* profiles, *P* +5%)
- Access Control System rebuild after fire on 11/09/11

RHIC

- Magnets surveyed and adjusted vertically (*P*+)
- New auto-transformer in Blue to reduce flattop-to-ramp MMPS transients (needed for 9 MHz rf, had done Yellow previously) (*P*+)
- Yellow snake installed in sector 9 after repair
- Inserts installed in beam dump (19 pieces, 12.7 cm long), allowed for higher intensity, at limit in Run-9 (Q4 quench without) (*L*+)
- 2 common storage cavities moved to sector 3, 2 more cavities installed => allows for permanent 9 MHz cavity (*L*+)

Main improvements for polarized protons in Run-11

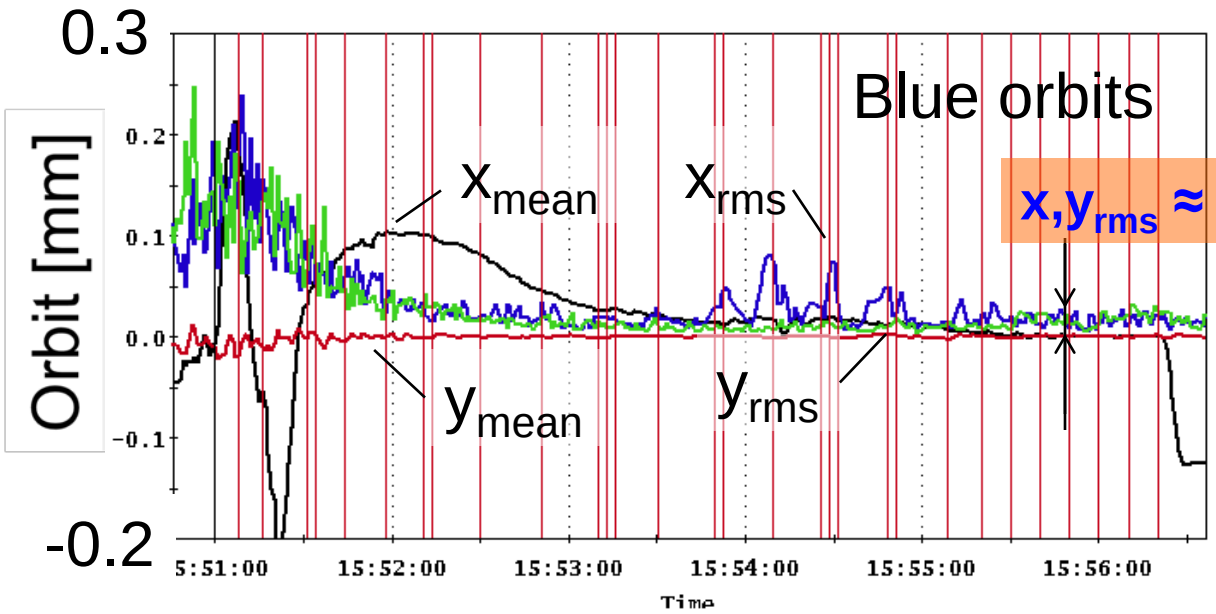
RHIC

- 2 storage cavities permanently converted to 9 MHz,
  1 bouncer cavity install in each ring (9 MHz) (*P*+, *L*+)
- Current limit for tq increased from 100 A to 140A IR6 to IR8 (*L*+)
- Collimation on ramp with continuous set point changes (*L*+)
- RHIC CNI polarimeters with new electronics (mitigates rate dependence)
- First H-jet polarization measurement at injection

RHIC beam and optics control

- All ramps with orbit, tune, and coupling feedback (*P*+, *L*+)
- Ramps Q_v = 0.673 (near low order resonance) (*P*+)
- Radial loop control via all BPMs (previously only 2) (*P*+, *L*+)
- Octupoles on ramp to suppress instabilities (*L*+)
- Operational use of 10 Hz orbit feedback in store (*L*+)
- First use of beta-beat correction in operation (*L*+)

Beam control improvement – feedbacks on ramp

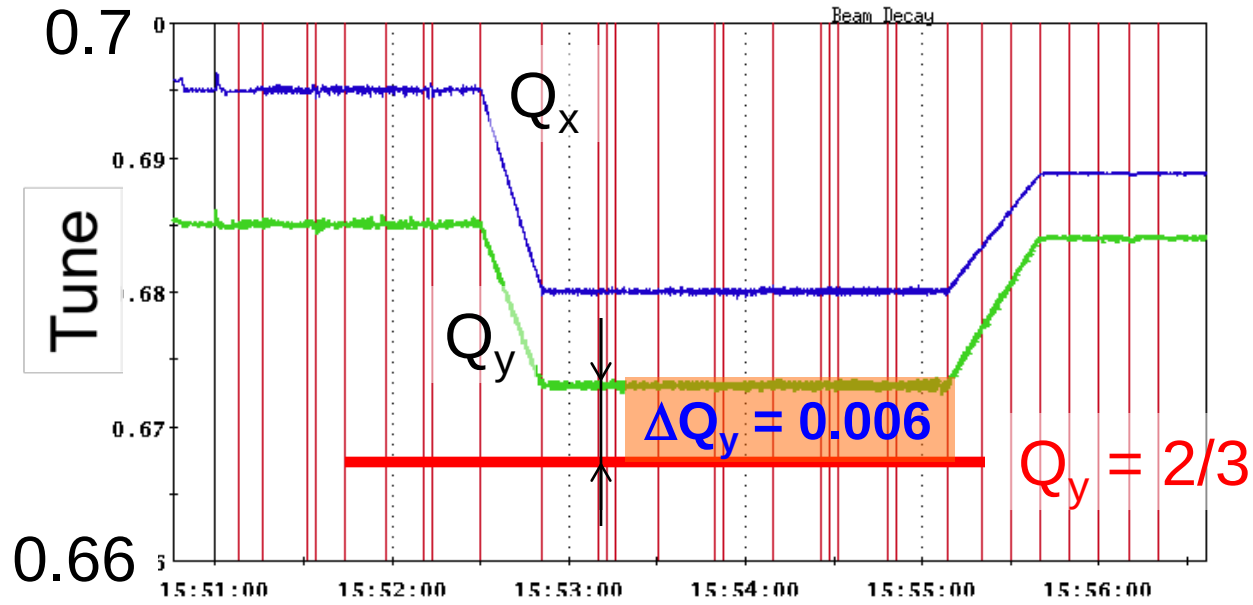


M. Minty,
A. Marusic et al.

$x,y_{rms} \approx 20$ μm (!)

Orbit feedback on every ramp allows for

- Smaller y_{rms} (smaller imperfection resonance strength)
- Ramp reproducibility (have 24 h orbit variation)

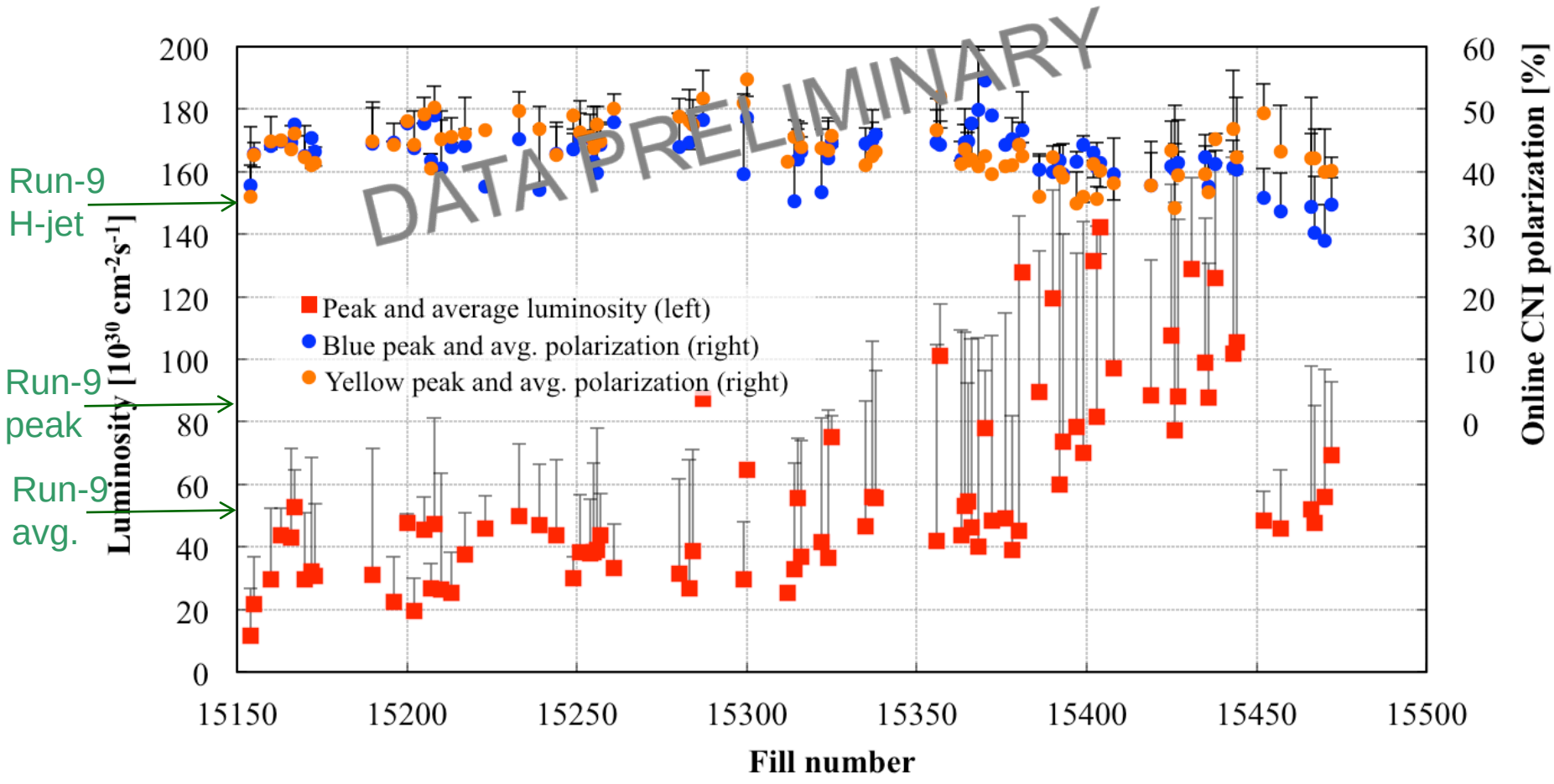


Tune/coupling feedback on every ramp allows for

- Acceleration near $Q_y = 2/3$ (better P transmission compared to higher tune)

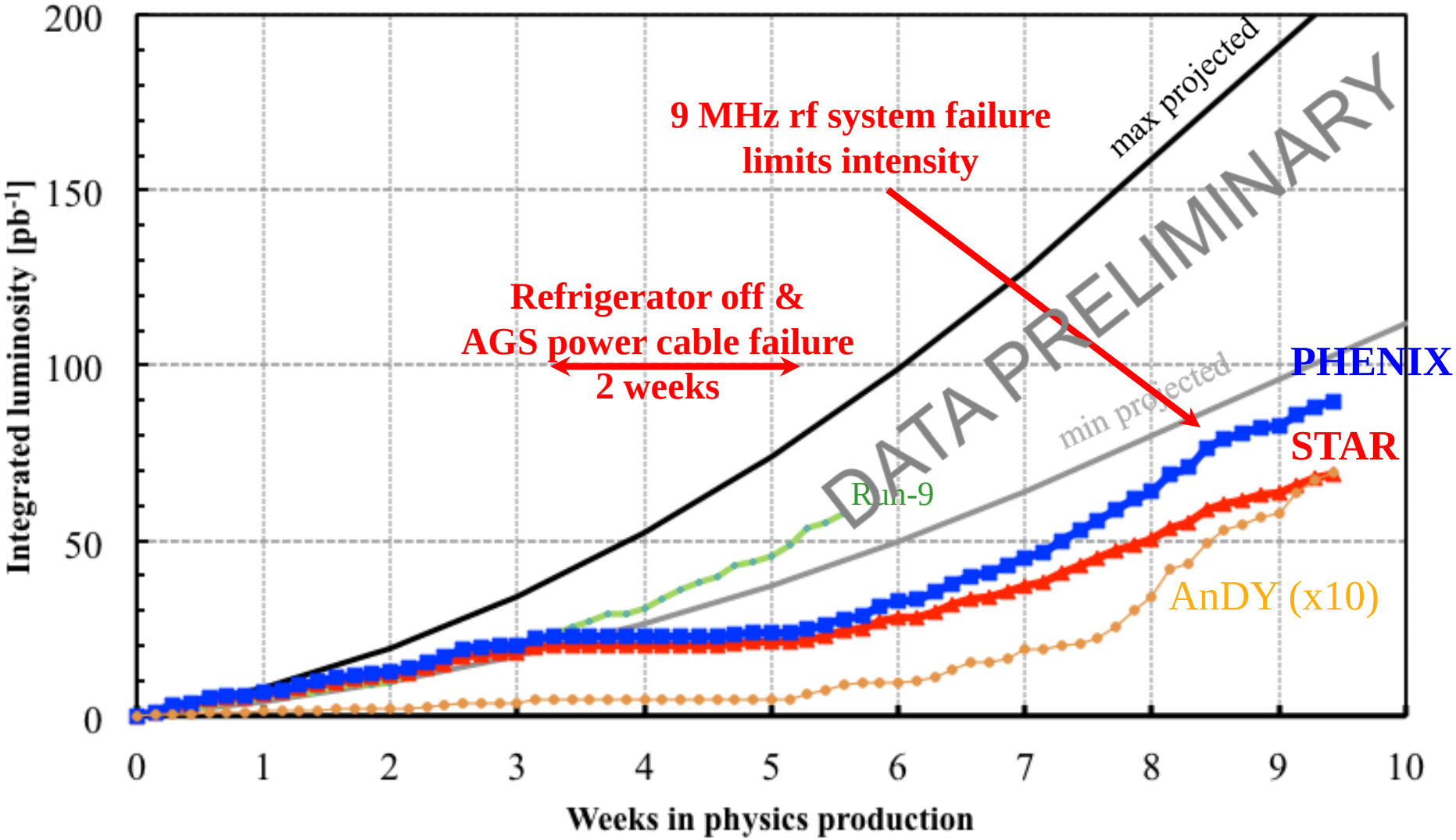
Run-11 250 GeV store overview – polarization and luminosity

Run Coordinator: Haixin Huang

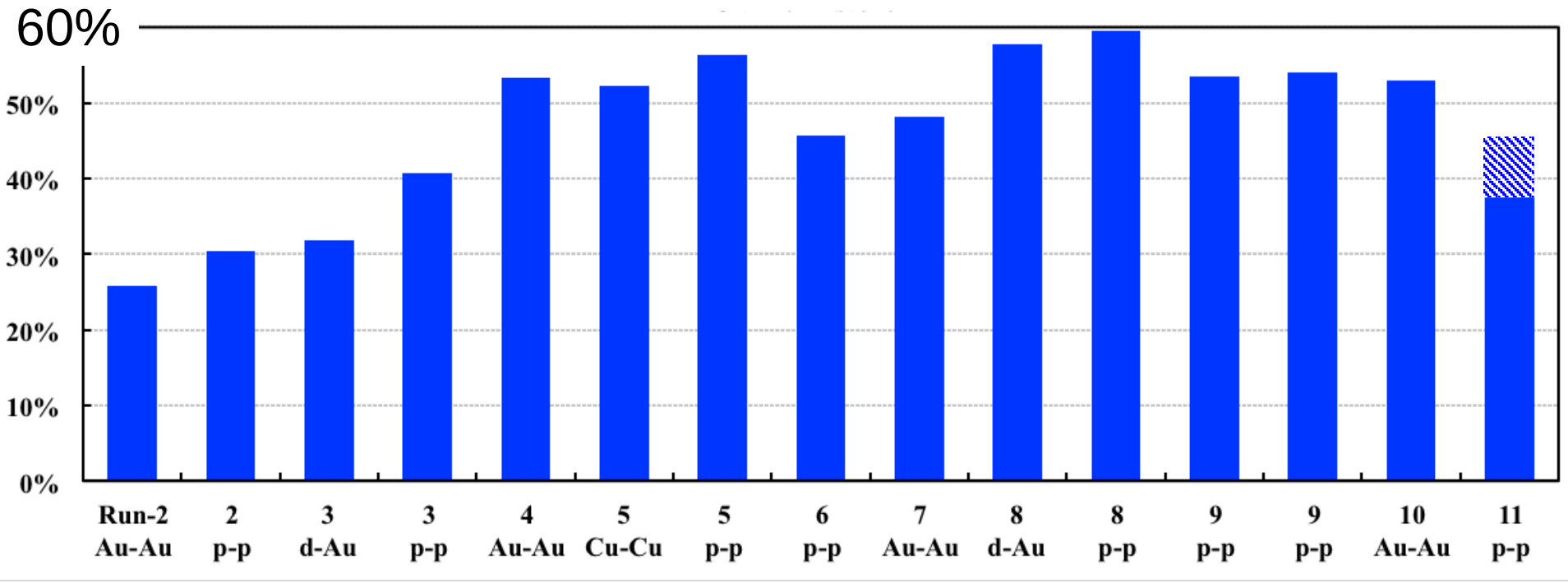


Run-11 polarized proton luminosity √s = 500 GeV

Run Coordinator: Haixin Huang



RHIC time-in-store history (% of calendar time)



Time-in-store lower than in previous runs

- No common reason identified for reduced time-in-store
- Increase in MTTR (Mean Time To Repair), PS overall about the same as Run-9
- 2 largest events (refrigerator off, AGS power cable) account for 9%
- Effect on performance stronger than linear (scheduling difficult, less time for implementation of improvements, more time re-establishing machine)

Unusual events in 250 GeV polarized proton Run-11

- Total of 6 snow days during start-up (>20 h excused time in January), delayed physics by about ½ week
- Fast emittance growth in Blue ring (intermittently observed in 2007 and 2009, tracked down to loose wire in dump kicker thyratron module B), delayed physics by about ½ week
- Breaker trip on 03/07/11 leads to refrigerator shut-off and helium venting in 2:00 and 6:00 service buildings, loss of about 3.5 tons of He, after repair encounter difficulties in purchasing replacement He, operation re-established on 03/17/11 – 219h downtime
- Power cable failure shut-down most of AGS equipment and part of building 911 – 78h downtime
- New 9 MHz RF system breaks 1 week before run end (current shield for bellows failing leading to overheating), luminosity cut in half

Polarization in Run-11 (analysis still ongoing)

Store polarization as measured by H-jet (measures <P>): 46% in Run-10 vs. 35% in Run-9

(polarization has a profile, max. polarization in center is up to 65%)

- AGS horizontal tune jump system operational
  - tested in Run-9, *P* +5% with high intensity
- Acceleration near Q_v = 2/3 in RHIC
  - measured *P* transmission as function of Q_v in Run-9, tested ramp with Au in Run-10, simulated differences between Au and p ramp last summer
- Vertical orbit control on ramp
  - 20 μm measured orbit rms late in ramp – real rms depends on BPM offsets
- First H-jet measurement at injection

Possible incremental improvements for next run

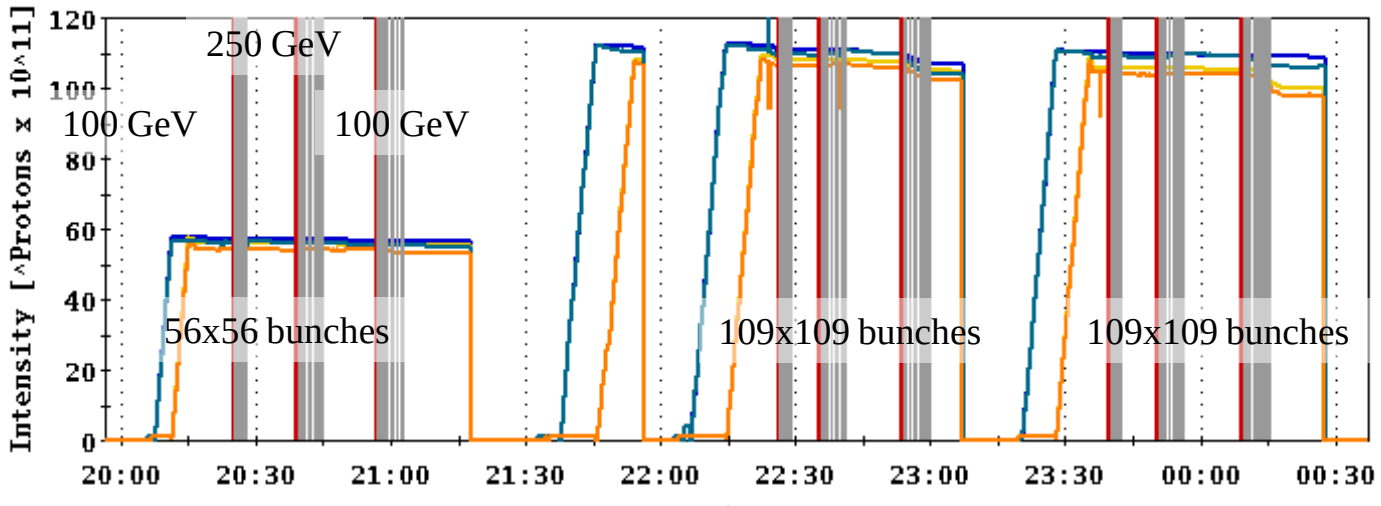
- Changes in source/LEBT/MEBT
- Smaller emittance growth (less *P* profile in AGS and RHIC)
- Small change in store energy in RHIC (*P* lifetime reduction)

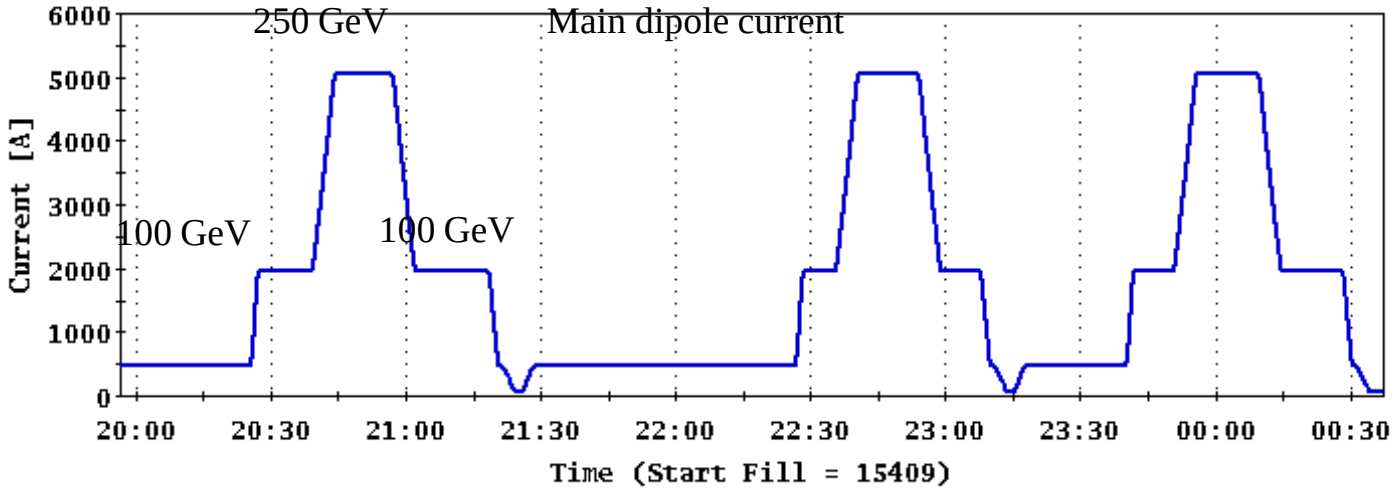
Up/down ramp with polarized protons in Run-11

Another measurement of the store polarization

Setup and 3 up and down ramps with up to 109x109 bunches in only 2 shifts

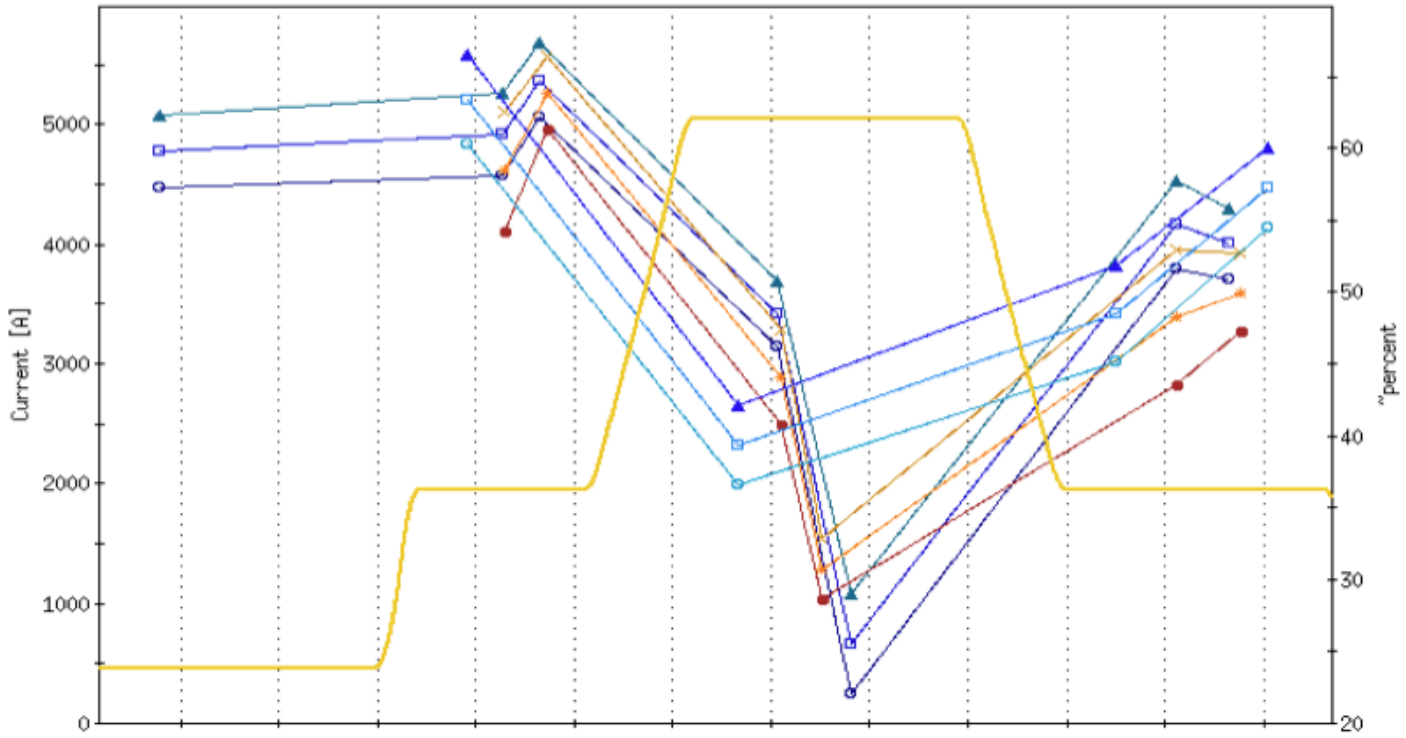
(simultaneous orbit/tune/coupling/chromaticity feedback essential)





Up/down ramp with polarized protons in Run-11

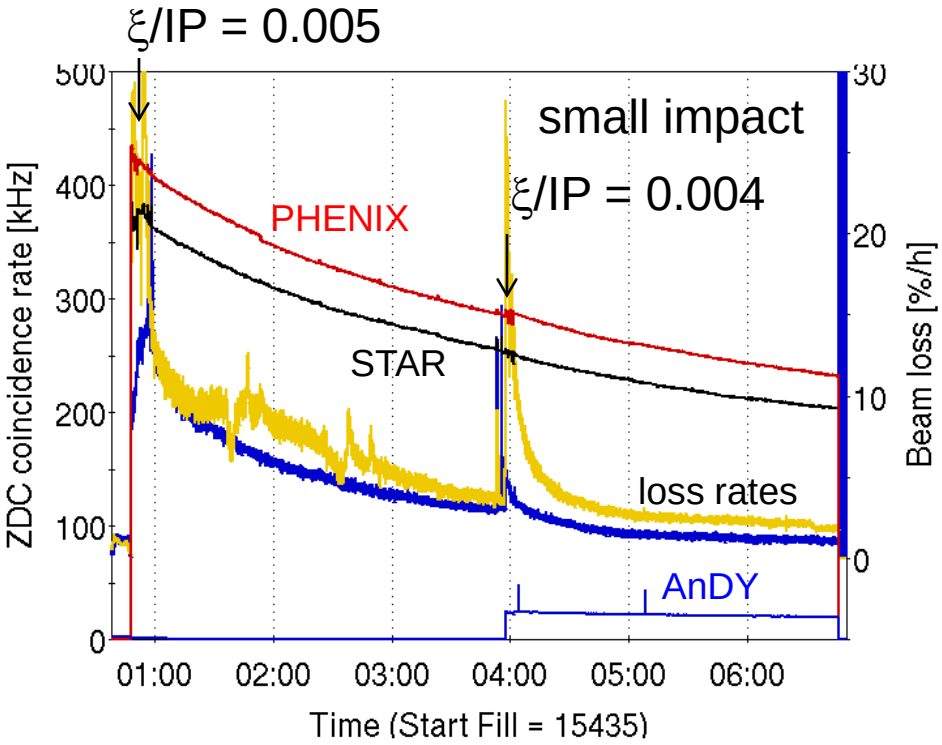
Compare CNI measurement at 100 GeV before and after up/down ramp

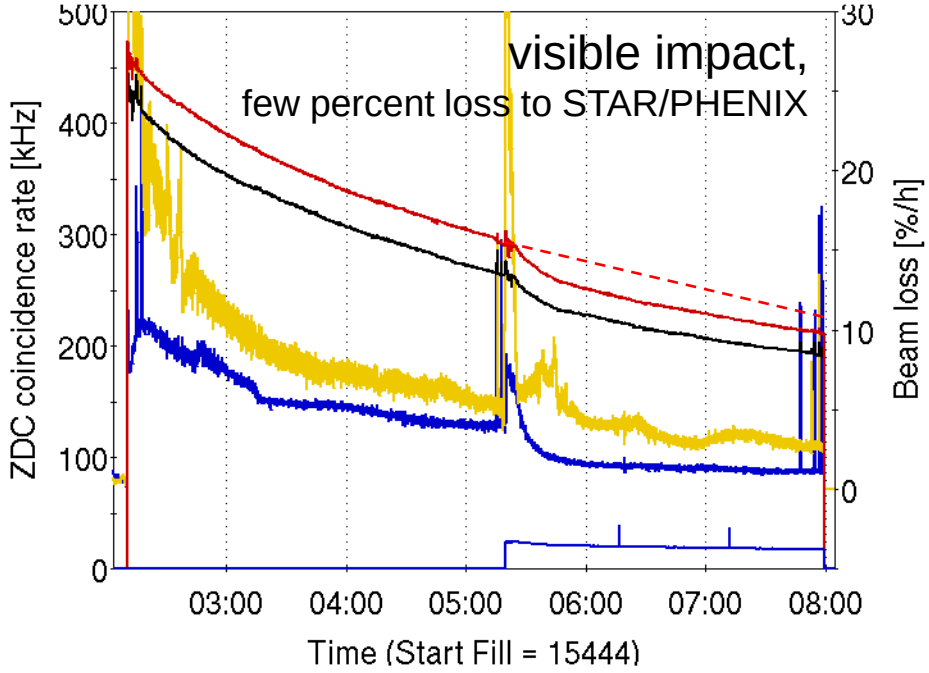


- Polarization ratio 100 GeV before / 100 GeV after: **0.79±0.02%**
- If up and down ramps are identical, loss from 100 to 250 GeV is **11%**
- With 63% polarization at 100 GeV (Run-9 H-jet) expect **56%** at 250 GeV
- H-jet measurement in Run-11 was **46%**

A_nDY in Run-11 (250 GeV pp)

- Beam envelope function β^* = 3.0 m at IP2
- Reduced IP2 crossing angle from initially 2.0 mrad to zero
- Added 3rd collision with following criteria (last instruction):
  1. $N_b \leq 1.5 \times 10^{11}$
  2. Beam loss rate <15%/h in both beams
  3. Not before first polarization measurement 3h into store





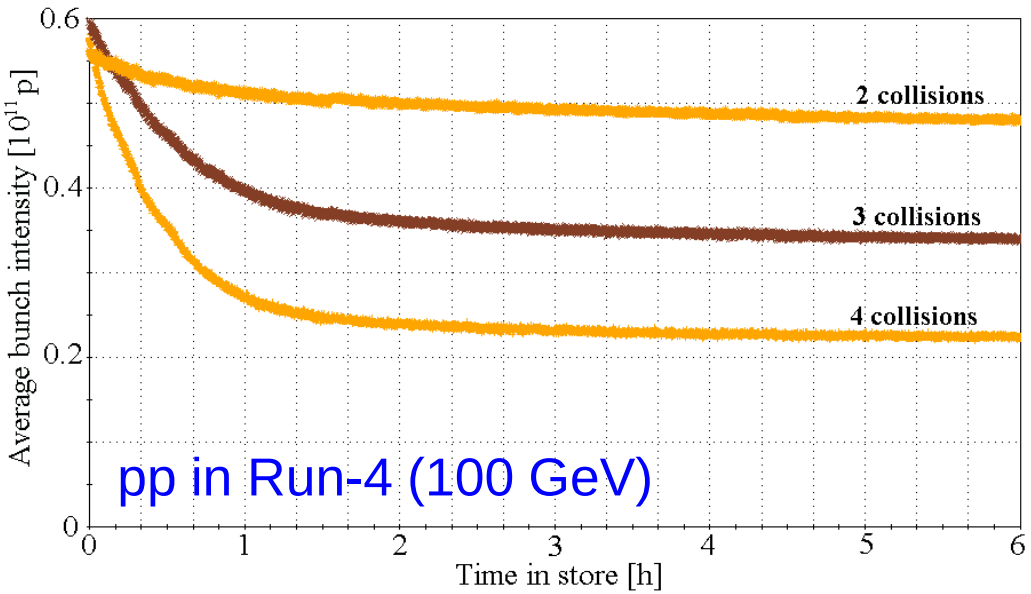
Future operation of A_nDY

- Can reduce β^* at IP2
  - have run with β^* = 2.0 m previously for BRAHMS
  - β^* = 1.5 m probably ok, needs to be tested
- Longer stores
  - 10h instead of 8h in Run-11 (depends on luminosity lifetime and store-to-store time)
- Collide earlier in store when conditions are met
  - needs coordination with polarization measurement, PHENIX and STAR
- Electron lenses (see later) if A_nDY runs beyond Run-13
  - increases max beam-beam tune spread, currently $\Delta Q_{max,bb} \approx 0.015$
  - can be used for to increase $\xi \sim N_b/\varepsilon$ and/or number of collisions

Run-11 luminosity at A_nDY:
max ~0.5 pb^{-1}/store

With improvements:
~3x increase,
~10 pb^{-1}/week

(A_nDY sees stronger impact of prematurely aborted stores than STAR and PHENIX)



Run-11 peak polarization and luminosity

Run Coordinator: Haixin Huang

		Run-9 achieved	Run-11 achieved	Run-11 projections
Polarization P	%	35★	**46★**	35–50★
Peak luminosity L_{peak}	$10^{30}\,cm^{-2}s^{-1}$	85	**145***	85–170
Avg. store luminosty L_{avg}	$10^{30}\,cm^{-2}s^{-1}$	55	**90***	55–100
Luminosity per week L_{week}	pb^{-1}	18	**25**	18–35
Time-in-store	%	53	**37** (46**)	55

★ Online H-jet measurement (average over transverse profile)

* Average of 6 best stores.

** Excluding down time due to refrigerator and AGS power cable failure.

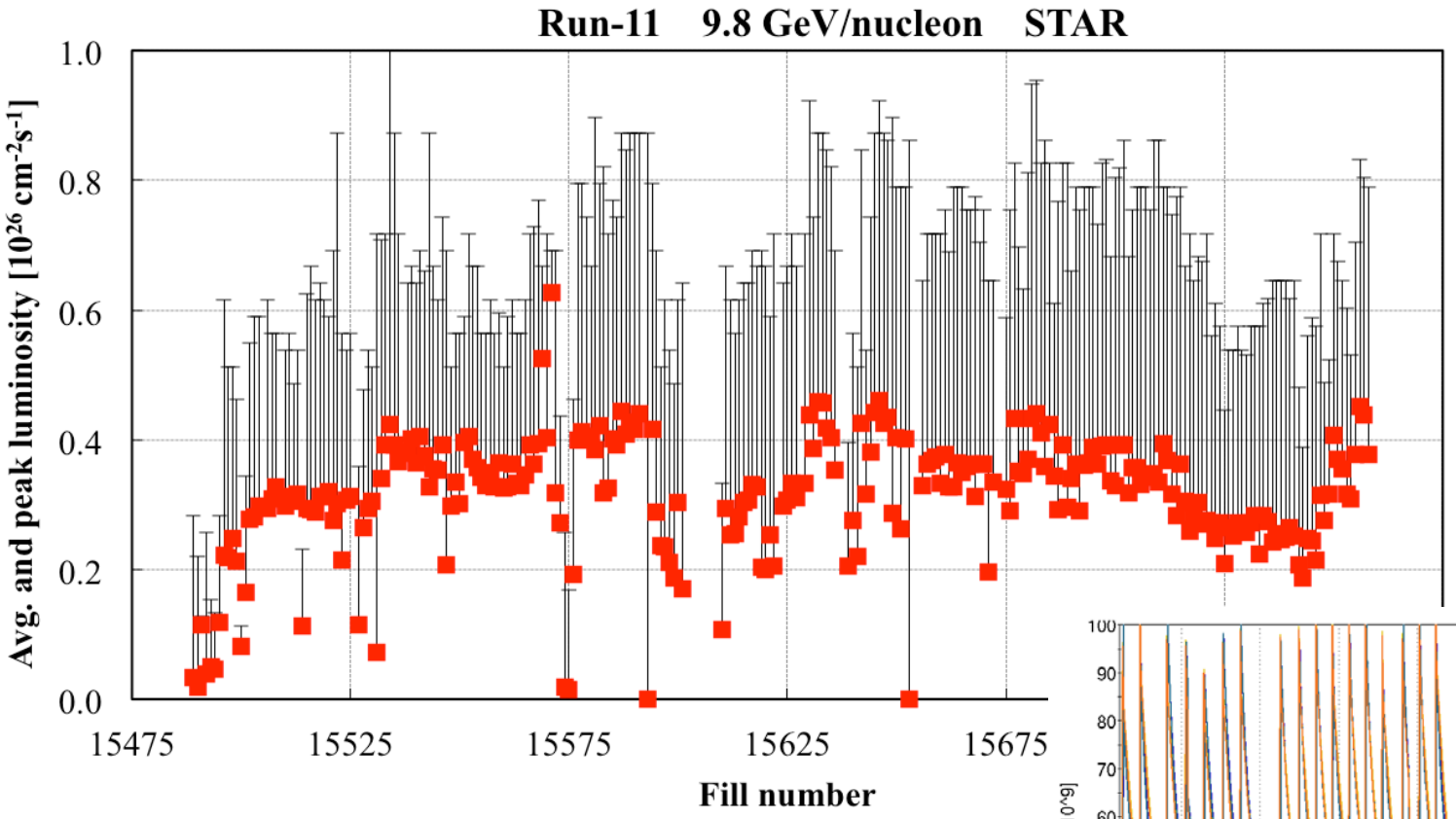
- Good progress with peak performance
- Overall performance held back by reduced reliability
- Established operation of A_nDY with small impact on STAR/PHENIX

Improvements for heavy ions in Run-11

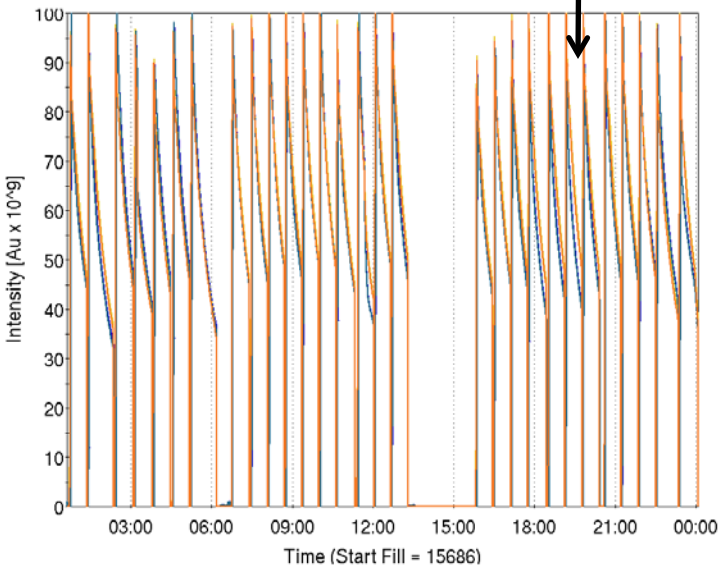
- Upgrade of longitudinal and vertical stochastic cooling systems
  - addressed feedthrough vacuum problems, mechanical problems, Blue-Yellow cross-talk of vertical planes
- Separate common storage rf cavities (197 MHz)
  - less beam loading during rebucketing – main intensity limit in Run-10
- Improved feedbacks (orbit, tune, coupling, chromaticity) on ramp
  - reduced ramp setup time, ramp reproducibility
- 10 Hz orbit feedback at store
  - reduced background
- Improved store orbit feedback
  - improves stability of store conditions
- Better collimation on ramp
  - fewer aborted ramps with beam losses
- Beam dump upgrade
  - needed for higher intensity
- New Be beam pipe in PHENIX (smaller ID – 40 mm vs. 74 mm now)

Run-11 Au-Au $\sqrt{s_{NN}}$ = 19.6 GeV (nominal injection energy)

Run Coordinator: Greg Marr



Typical day (04/25/11)



3 days to physics, 10 days in physics

35 min store length

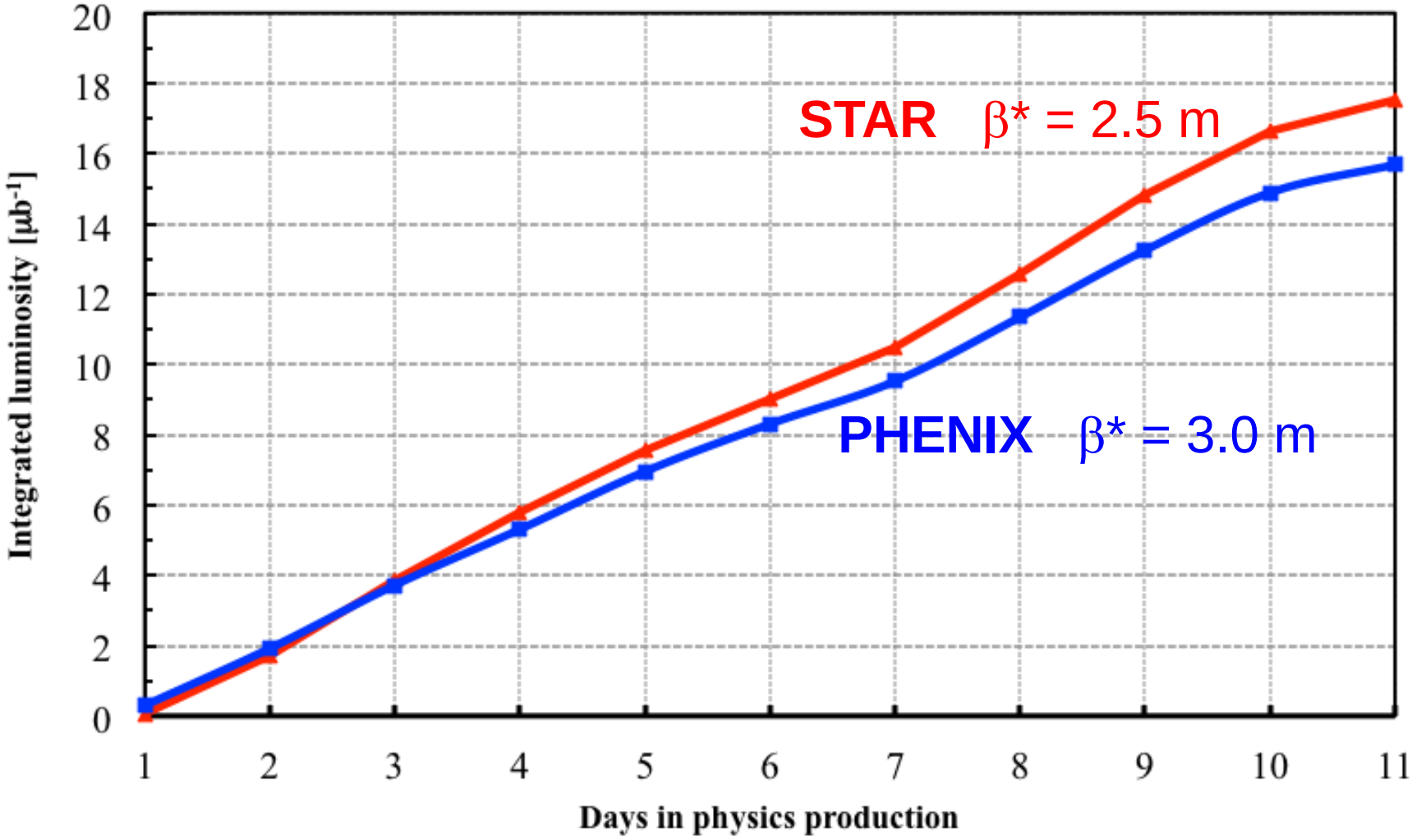
71% of calendar time in store

STAR: 17.5 μb^{-1} (175x Run-2)

PHENIX: 15.7 μb^{-1} (157x Run-2)

Run-11 Au-Au $\sqrt{s_{NN}}$ = 19.6 GeV (nominal injection energy)

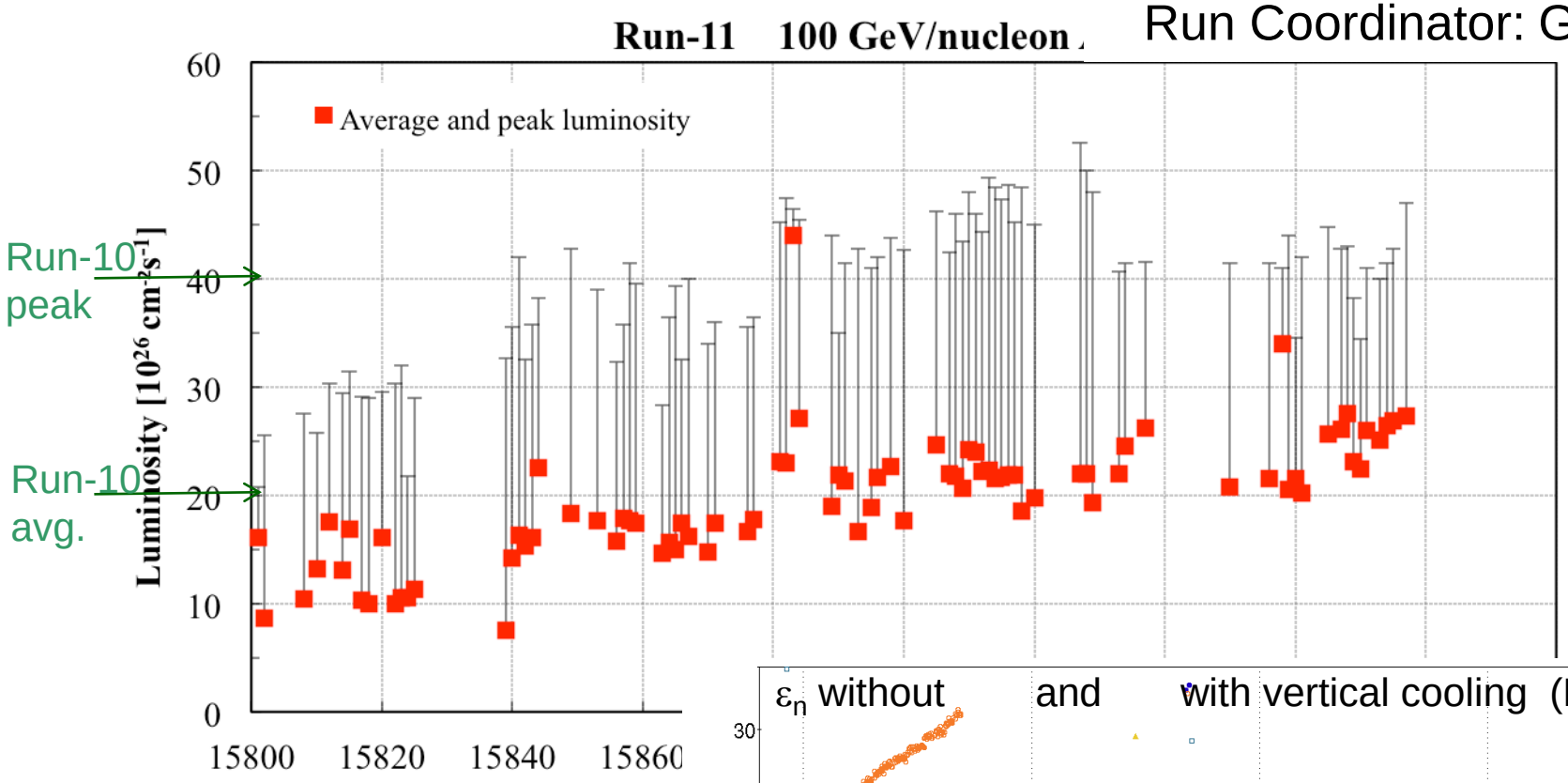
Run Coordinator: Greg Marr

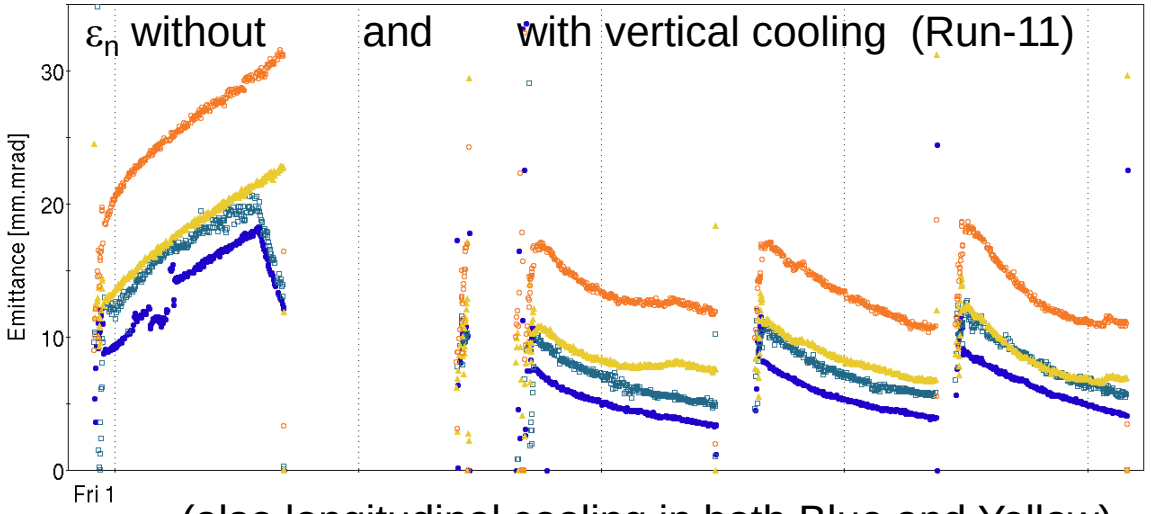


Steady operation throughout whole period

Run-11 Au-Au $\sqrt{s_{NN}}$ = 200 GeV (still under way)

Run Coordinator: Greg Marr





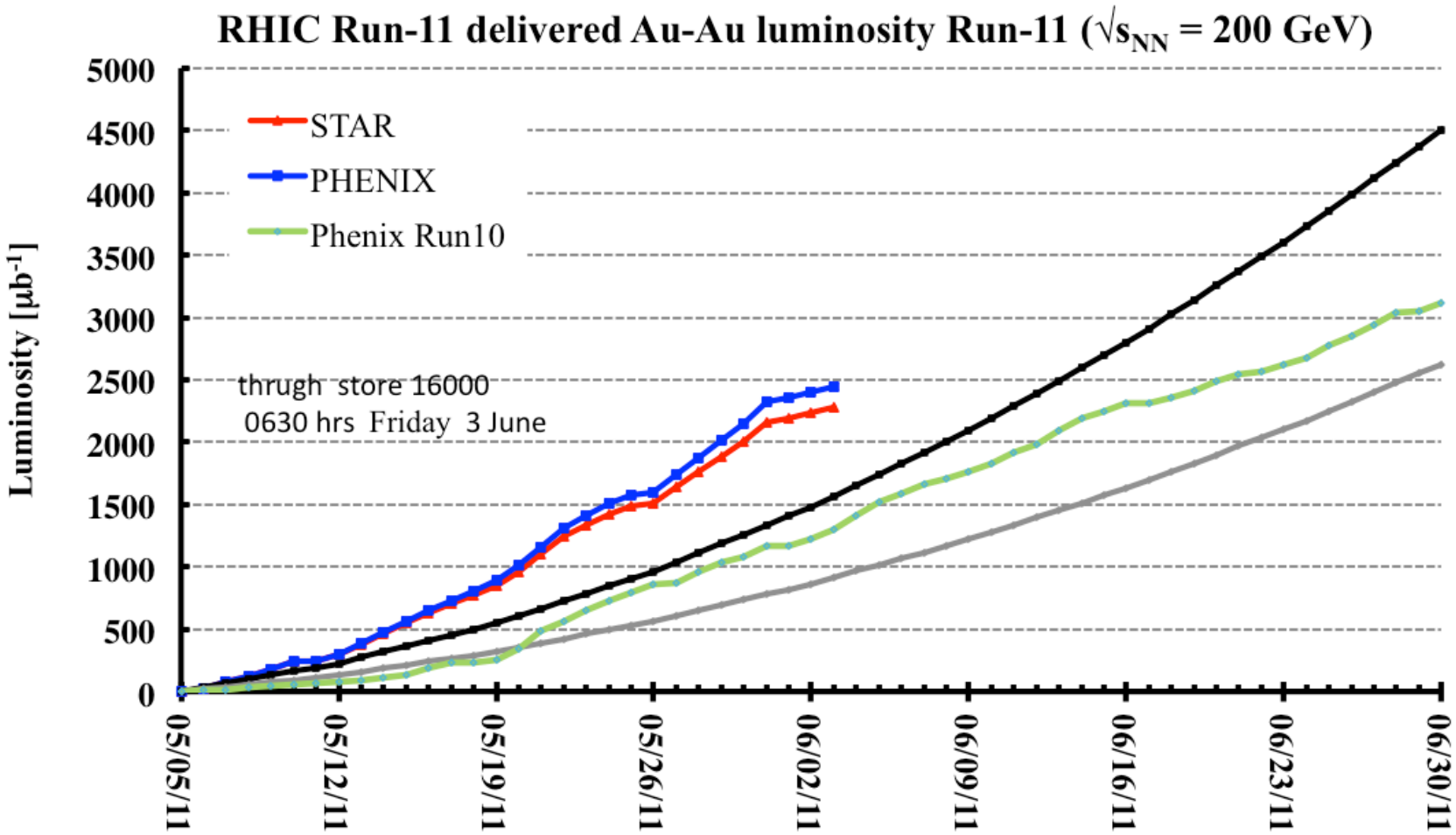
Setup to physics in 4 days
(from operation at injection energy)

Exceed peak and average luminosities from Run-10.

(also longitudinal cooling in both Blue and Yellow)

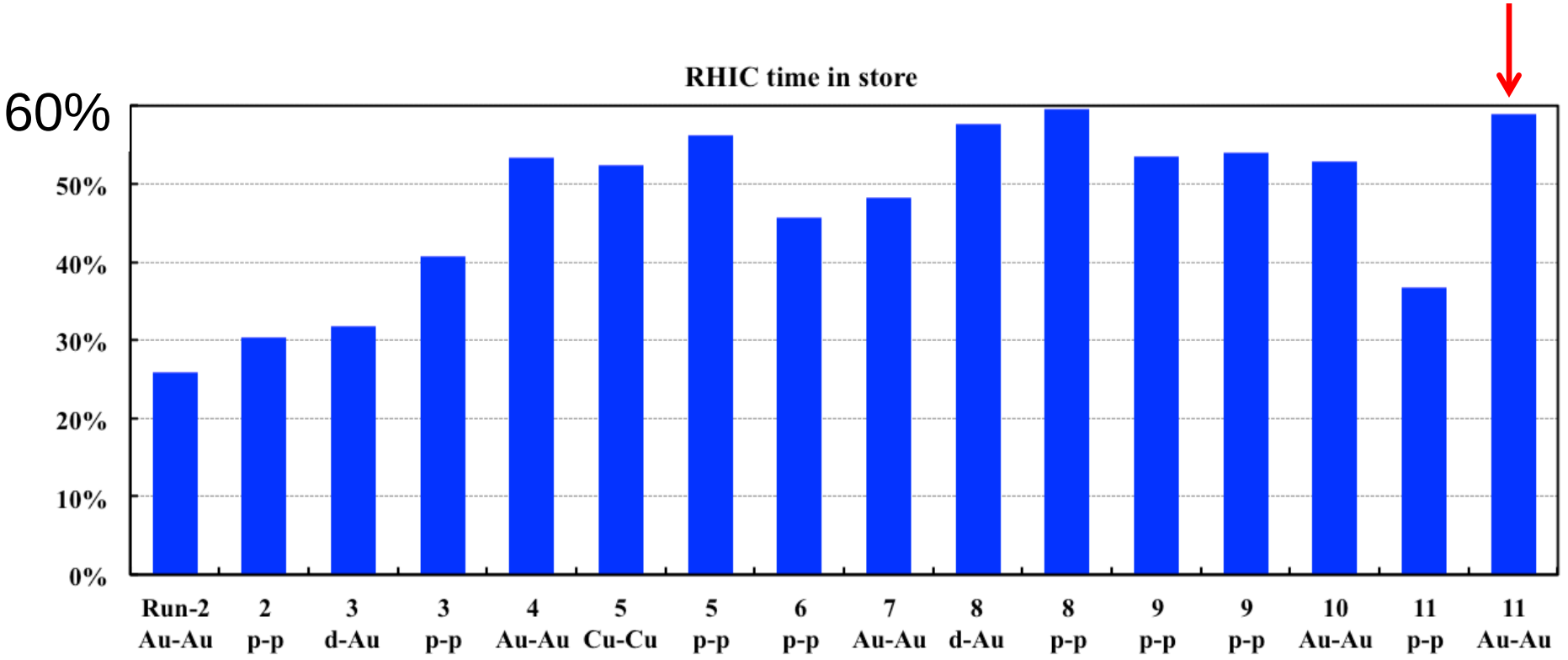
Run-11 Au-Au $\sqrt{s_{NN}}$ = 200 GeV (still under way)

Run Coordinator: Greg Marr



Presently on track to meet projections …

Run-11 Au-Au $\sqrt{s_{NN}}$ = 200 GeV (still under way)



Time in store recovered to historical value

- Number of hardware problems resolved during pp operation
- Profit from commissioning of feedbacks and ramp collimation during pp
- Fewer new systems

Run-11 Au-Au luminosity (still under way)

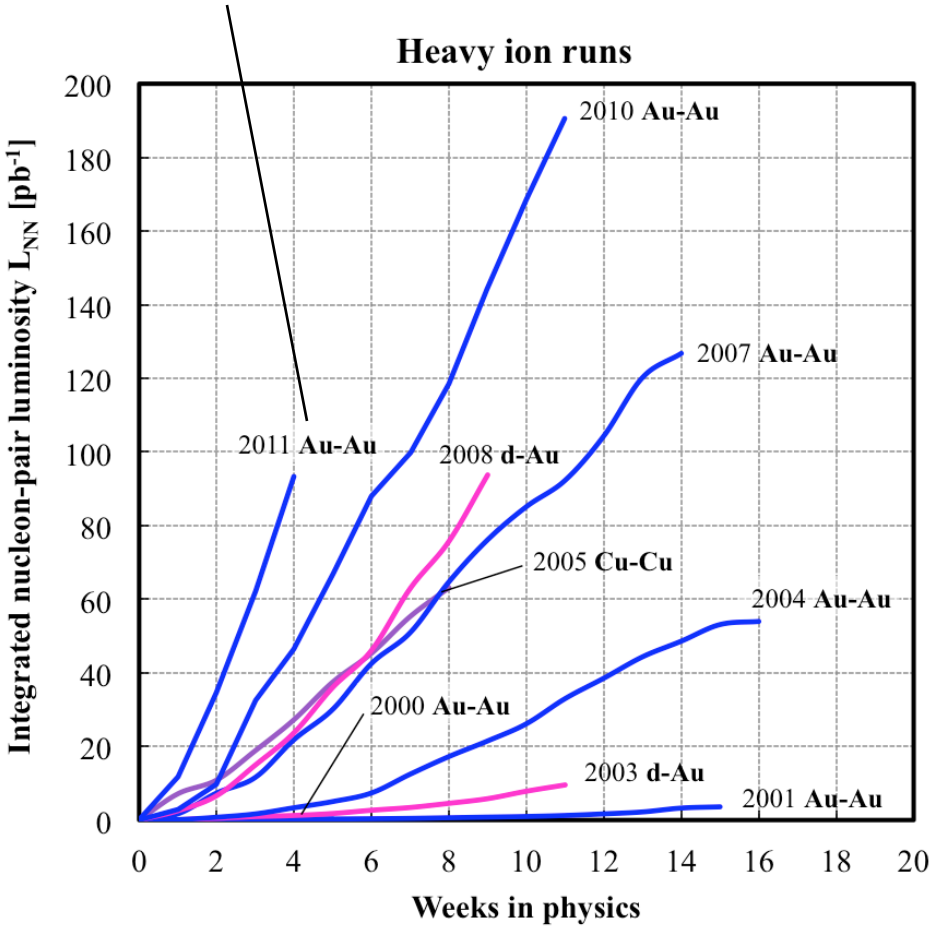
Run Coordinator: Greg Marr

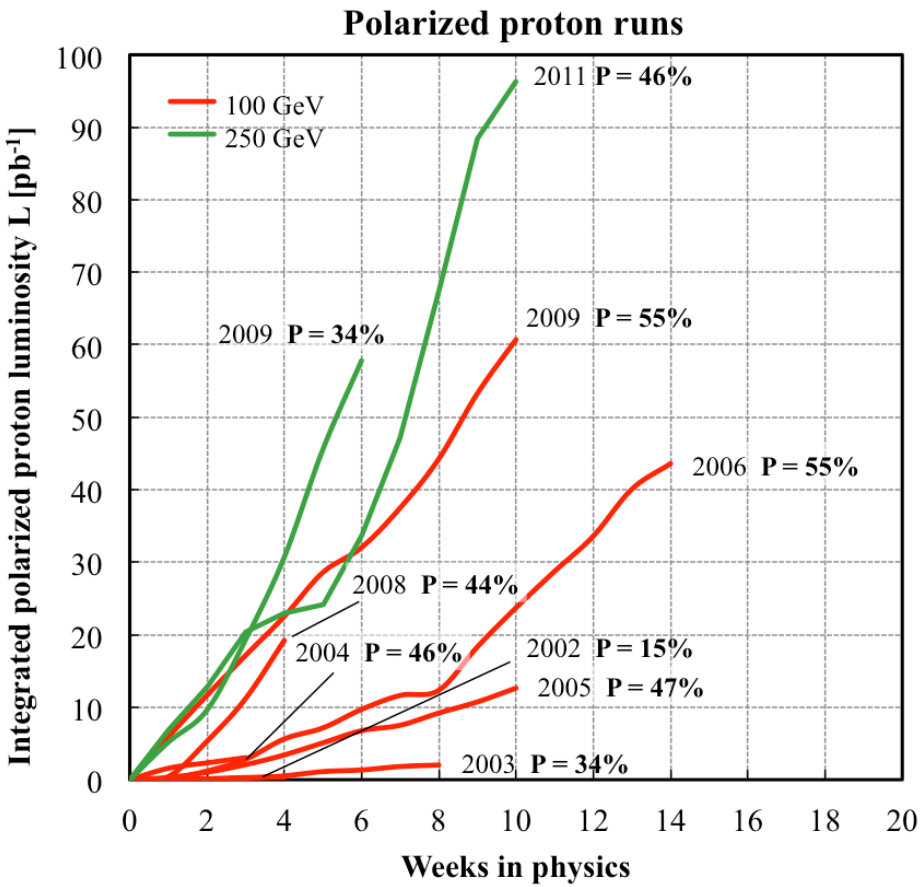
		Run-10 achieved	Run-11 achieved (to date)	Run-11 projections
Peak luminosity L_{peak}	$10^{26}\,cm^{-2}s^{-1}$	40	**45**	40-45
Avg. store luminosty L_{avg}	$10^{26}\,cm^{-2}s^{-1}$	20	**30**	20-25
Luminosity per week L_{week}	μb^{-1}	650	**800**	650-900
Time-in-store	%	53	**58**	55

- Setup faster than anticipated
- Good progress with peak and average performance
- About half the beam loss is now due to burn-off
- Integrated luminosity presently on track

RHIC heavy ion and polarized protons 2000-2011

2011 Au-Au run still under way





Main upgrades for Run-12

Heavy ions

- EBIS operation for RHIC (Au, U)
  needs to replace Tandem performance
- 1st use of horizontal stochastic cooling in both beams
  then 3D cooling in both planes
- Incremental changes to lattice (β^*, Q" reduction)
  β^* squeeze in store after emittance reduced through cooling

Polarized protons

- Incremental changes to improve polarization
  source, emittance growth – particularly in AGS, store energy, …
- Upgrade of 9 MHz RF system
  high-intensity acceleration, smaller vertex and hourglass effect
- Incremental changes to store lattice
  $\Delta\beta/\beta$ reduction

Upgrades for Run-13

Heavy ions

- Incremental changes to stochastic cooling
- Incremental changes to lattice (β^*, Q")

Polarized protons

- Upgraded polarized proton source
  - order of magnitude more intensity, P +5%
- Electron lenses
  - partial compensation of head-on beam-beam effect
  - will need commissioning time
- Incremental changes to store lattice
  - β^* reduction, optimization for e-lens operation

Upgrades for Run-14 and beyond

Heavy ions

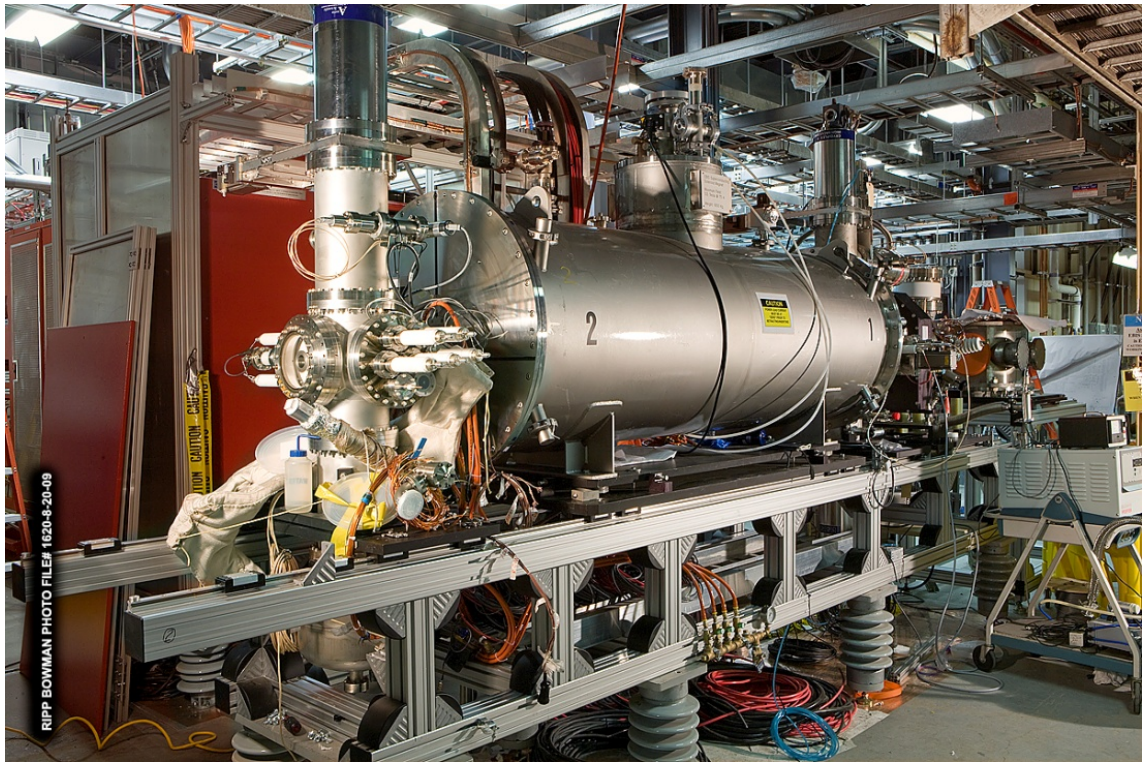
- 56 MHz SRF (Run-14)
  - increased longitudinal focusing, 30-50% more luminosity
- Low energy cooling (earliest for Run-17)
  - moved out by at least 2 years
  - need to finish e-lenses and 56 MHz SRF before resources are available

Polarized beams

- 56 MHz SRF (Run-14)
- Energy increase (+10% to 275 GeV)
  - yields +45% in W production cross section
- In-situ beam-pipe coating
  - reduction of Secondary Electron Yield in arcs, R&D under way
- Polarized ^{3}He
  - R&D on source started (EBIS as ionizer), need polarimetry

Electron Beam Ion Source (J. Alessi et al.)

- 10 A electron beam creates desired charge state in trap within 5 T superconducting solenoid
- Accelerated through RFQ and linac
- Injected into AGS Booster



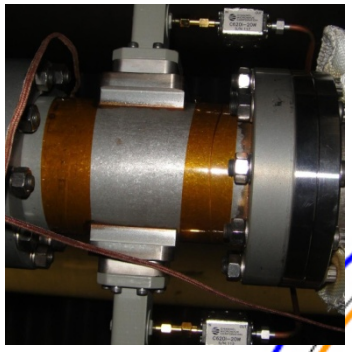
EBIS under commissioning:

- So far created He^{+}, He^{2+}, Ne^{5+}, Ne^{8+}, Ar^{11+}, Ti^{18+}, Fe^{20+}, Au^{32+}
- Delivered beam to NSRL

- Work on ~4x increase in Au^{32+} intensity in AGS Booster
  (2x from electron current, 2x from transmission)
- Received U cathode
- Tandem still available as backup next year

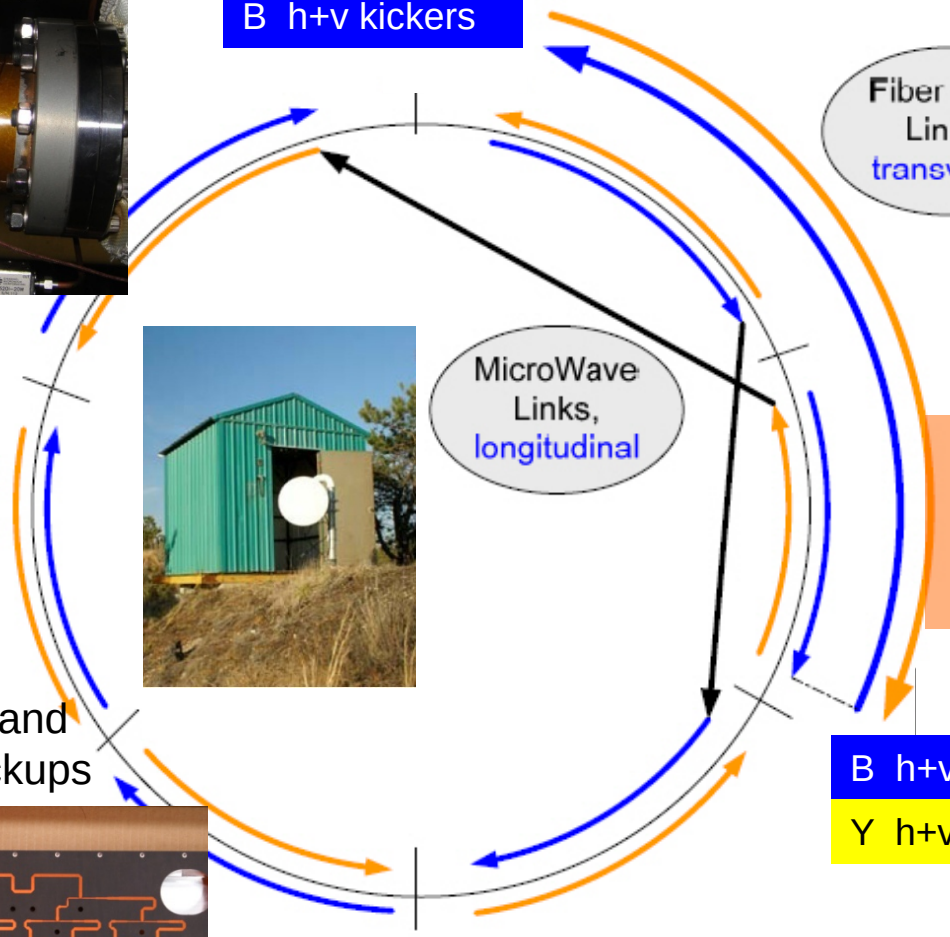
RHIC – 3D stochastic cooling for heavy ions

longitudinal pickup

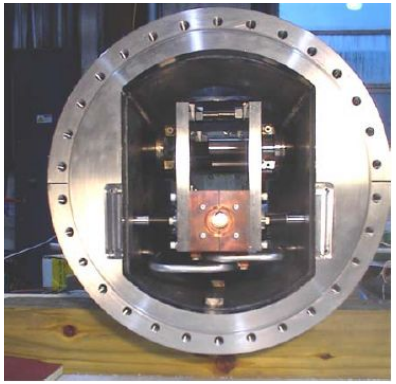


Y h+v pickups

B h+v kickers



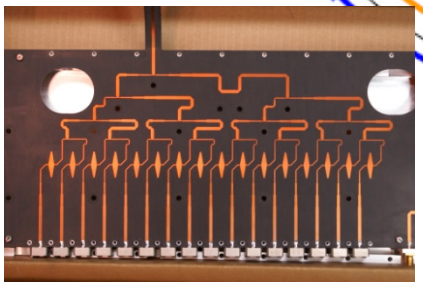
longitudinal kicker (closed)



horizontal kicker (open)

Last missing planes: B+Y horizontal installation in summer 2011

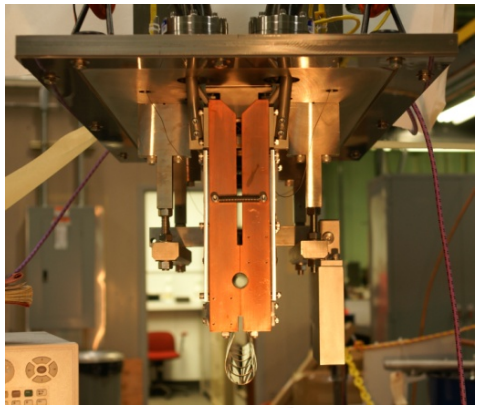
horizontal and vertical pickups



B h+v pickups

Y h+v kickers

vertical kicker (closed)



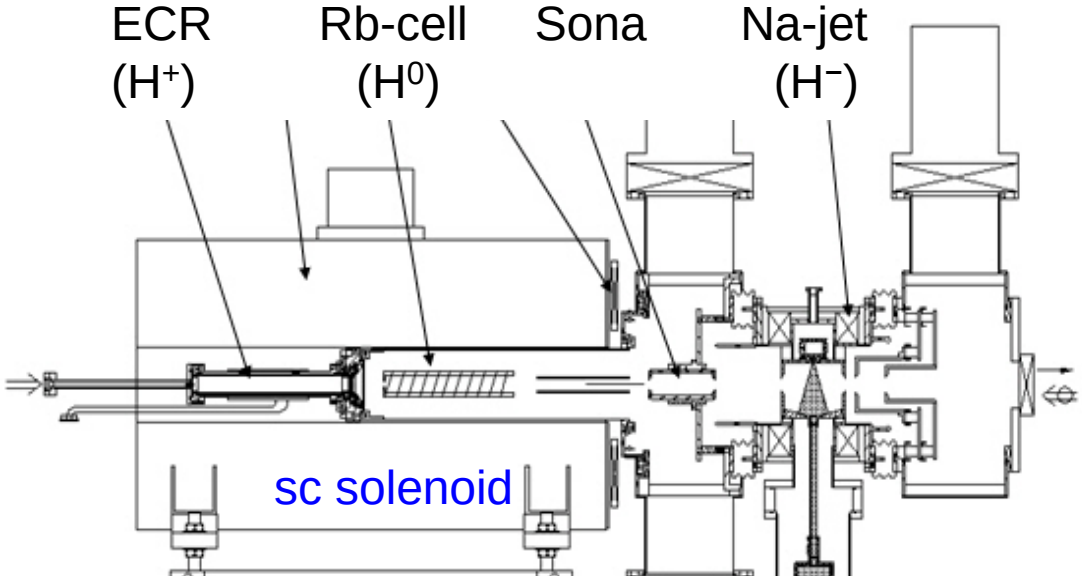
5-9 GHz, cooling times ~1 h

M. Brennan, M. Blaskiewicz, F. Severino, Phys. Rev. Lett. **100** 174803 (2008); PRST-AB, PAC, EPAC

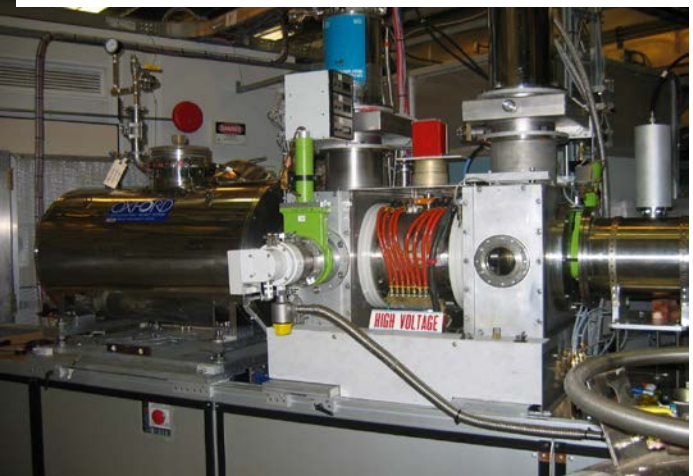
Optically Pumped Polarized H⁻ source (OPPIS)

Current OPPIS

A. Zelenski, PST2009



- 29.2 GHz ECR source used for primary H^+ generation
- source was originally developed for dc operation



RHIC OPPIS produces reliably 0.5-1.0 mA polarized H^- ion current.

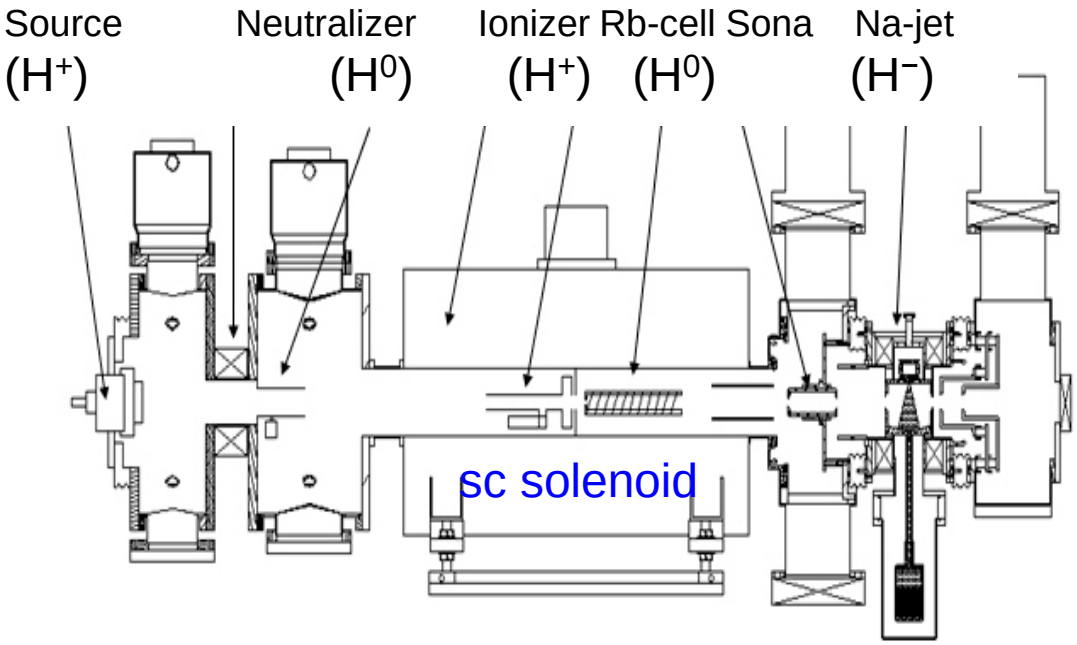
Polarization at 200 MeV:
P = 80-85%.

Beam intensity (ion/pulse) routine operation:

Source - 10^{12} H^-/pulse
Linac - 5×10^{11}
AGS - $1.8\text{-}2.0 \times 10^{11}$
RHIC - 1.8×10^{11}/bunch

Optically Pumped Polarized H^- source (OPPIS) – A. Zelenski

Upgraded OPPIS (Run-13)



10x intensity increase was demonstrated in a pulsed operation by using a very high-brightness Fast Atomic Beam Source instead of the ECR source

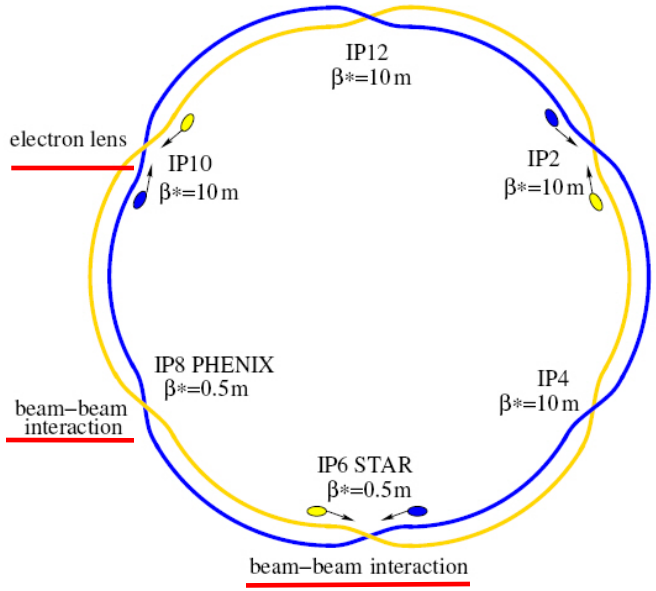
Goals:

1. H^- beam current increase to 10mA (order of magnitude)
2. Polarization to 85-90% (~5% increase)

Upgrade components:

1. Atomic hydrogen injector (collaboration with BINP Novosibirsk)
2. Superconducting solenoid (3 T)
3. Beam diagnostics and polarimetry

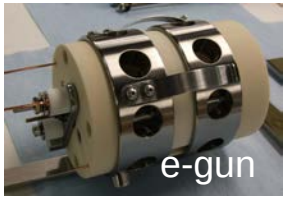
Electron lenses – partial head-on beam-beam compensation



Polarized proton luminosity limited by head-on beam-beam effect ($\Delta Q_{bb,max} \sim 0.02$)

Basic idea:

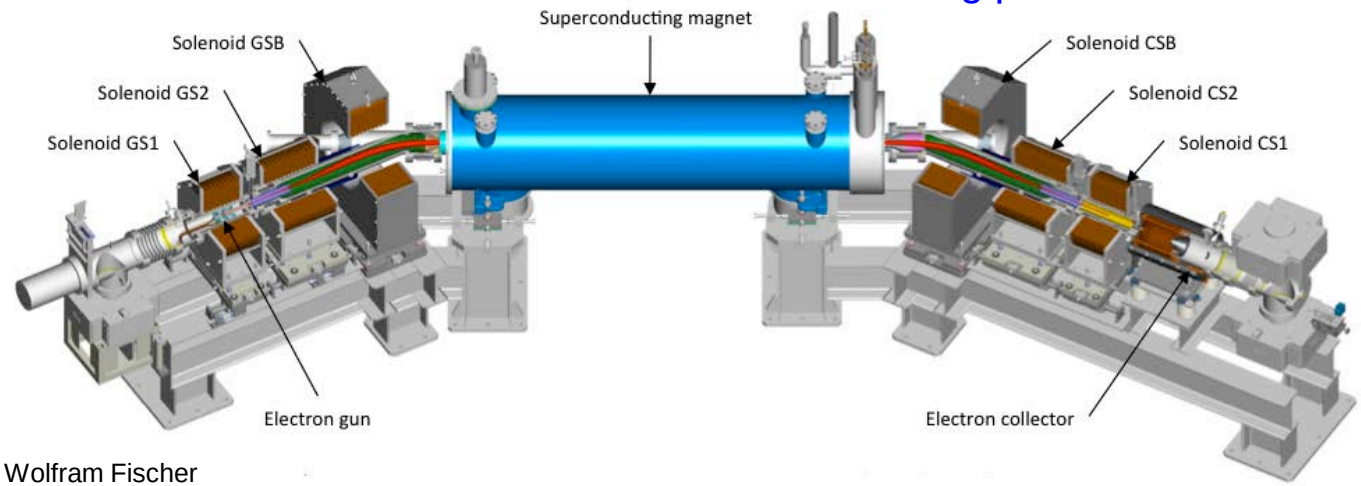
In addition to 2(3) beam-beam collisions with **positively** charged beam have another collision with a **negatively** charged beam with the same amplitude dependence.



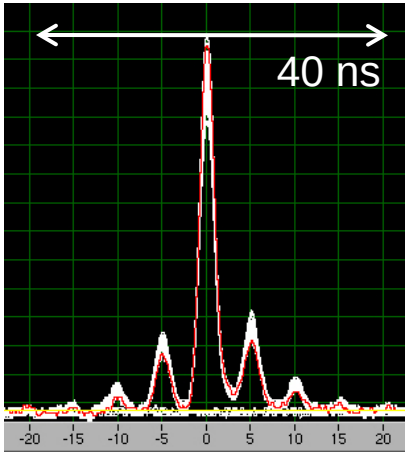
Exact compensation for:

- short bunches
- $\Delta\psi_{x,y} = k\pi$ between p-p and p-e collision
- no nonlinearities between p-p and p-e
- same amplitude dependent kick from p-p, p-e
- only approximate realization possible

Expect up to 2x more luminosity
with OPPIS upgrade
Commissioning planned for Run-13

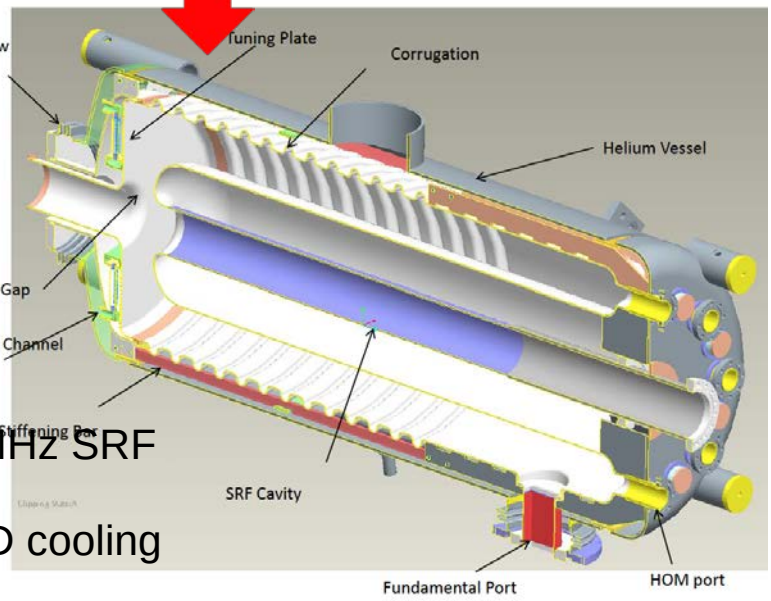


56 MHz SRF for heavy ions – under construction (I. Ben-Zvi et al.)

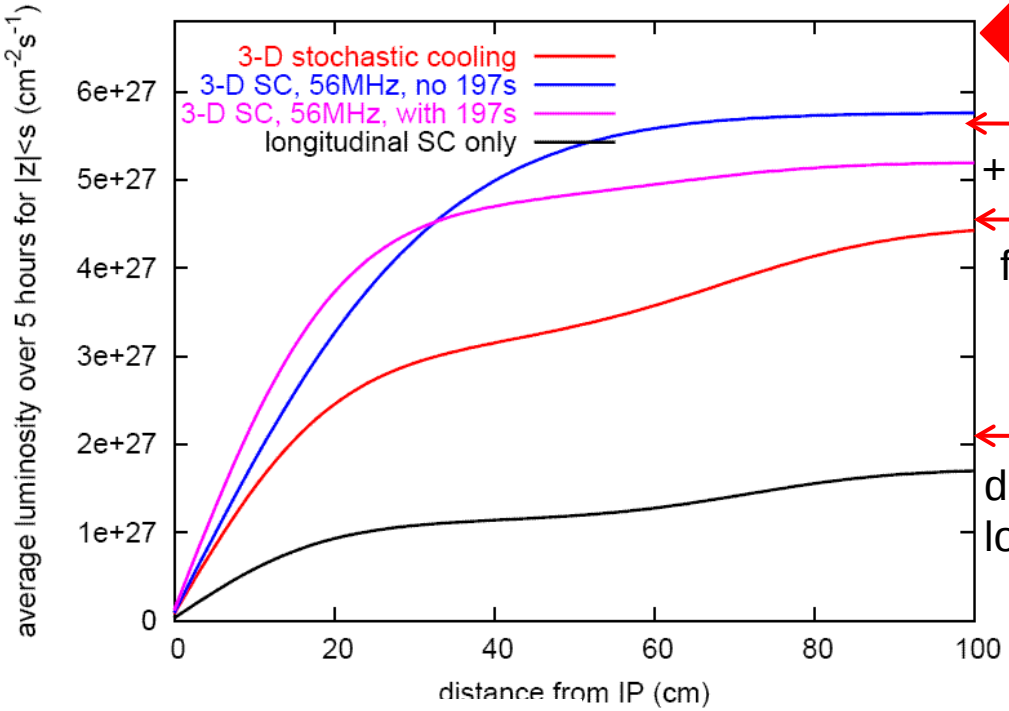


Longitudinal profile at end of store
- even with cooling ions migrate into neighboring buckets
- can be reduced with increased focusing

Commissioning in Run-14



Average luminosity vs. vertex size



+ 56 MHz SRF

full 3D cooling

demonstrated 2010 long. + ver. cooling

Calculations by M. Blaskiewicz

Summary – RHIC luminosity and polarization goals

Parameter	Unit	Achieved	Upgraded	
Au-Au operation		(2011)	(>=2012)	
Energy	GeV/nucleon	100	100	
No of bunches	…	111	111	
Bunch intensity	10^9	1.3	1.0	
Average *L*	**10^{26}cm^{-2}s^{-1}**	**25**	**40**	
p↑- p↑ operation		(2011)	(>=2012)	(>=2014)
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.65	1.3 / 1.7	2.0
Average *L*	**10^{30}cm^{-2}s^{-1}**	**24 / 90**	**30 / 150**	**60 / 300**
Polarization *P*	**%**	**55 / 46**	**60**	**70**

Run-12 and Run-13 working assumptions

(from Beam Use Proposals)

Requests for Run-12

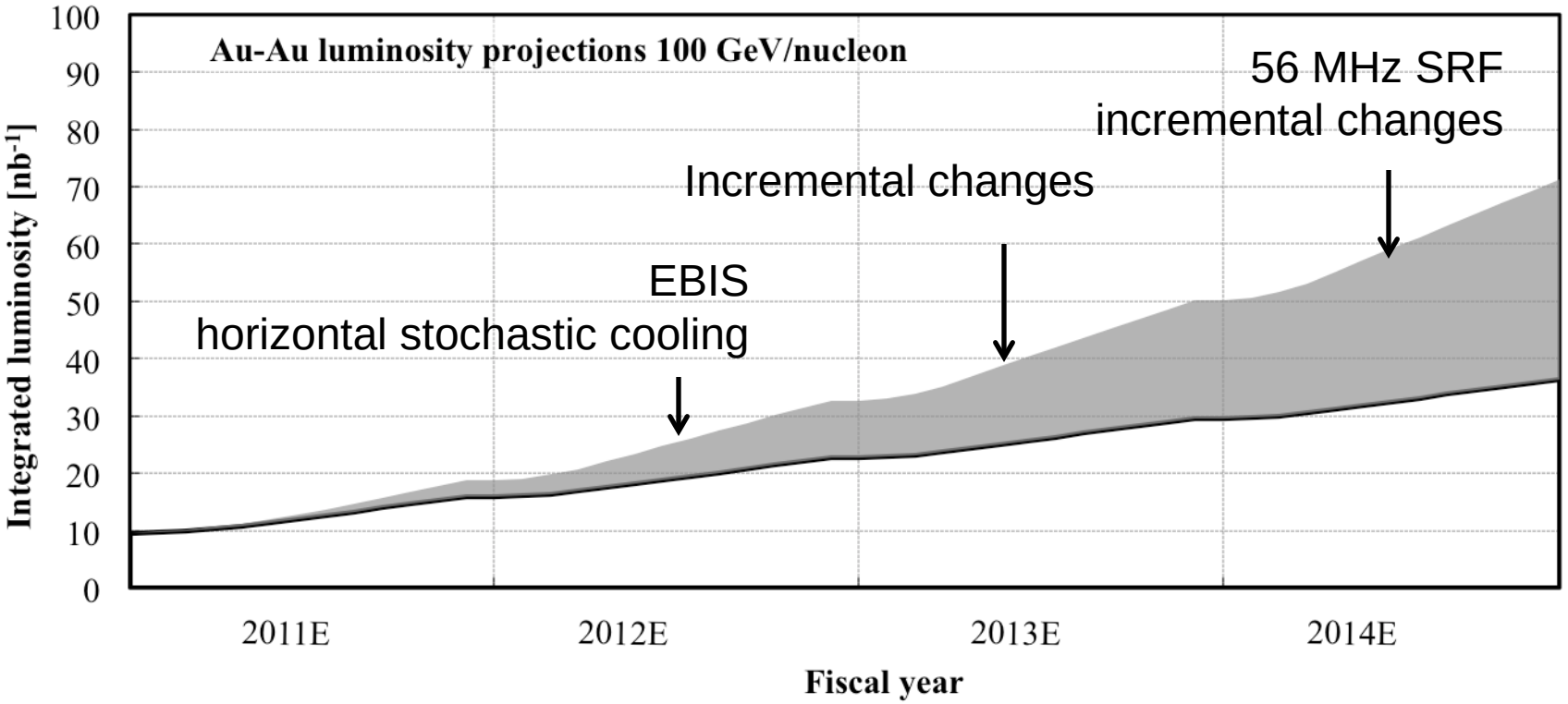
- Au-Au : $\sqrt{s_{NN}}$ = 27 GeV (STAR, PHENIX)
- Au-Au : $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)
- U-U : $\sqrt{s_{NN}}$ = 193 GeV (STAR, PHENIX)
- p^-p^ : $\sqrt{s}$ = 500 GeV (STAR, PHENIX)
- p^-p^ : $\sqrt{s}$ = 200 GeV (PHENIX)
- p-p (unpolarized) : $\sqrt{s}$ = 62.4, 39 GeV (PHENIX)

Requests for Run-13

- Au-Au : $\sqrt{s_{NN}}$ = 200 GeV (STAR)
- Cu-Au : $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)
- U-U : $\sqrt{s_{NN}}$ = 193 GeV (PHENIX)
- p^-p^ : $\sqrt{s}$ = 500 GeV (STAR, PHENIX)
- p^-p^ : $\sqrt{s}$ = 200 GeV (STAR, PHENIX)

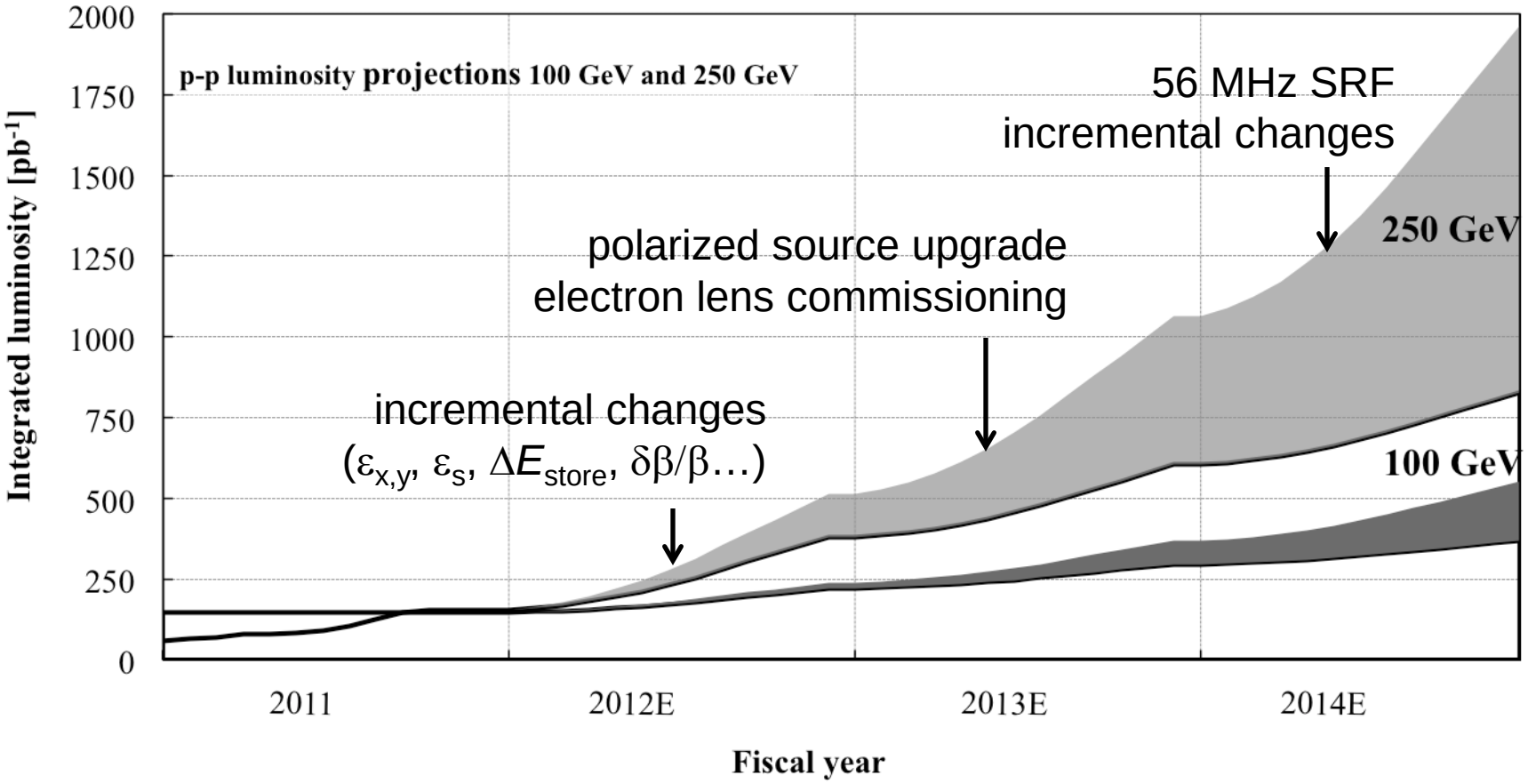
Preferred order for machine is: heavy ions first, polarized protons second.

Projections projection for Au-Au



[Note1 :assume 12 weeks of physics, 8 weeks of ramp-up, start at ¼ of max]
[Note 2: last projections from 11 May 2010 still valid – reached peak performance goals for both polarized protons and heavy ions, will update after Run-11]

Projections for p^-p^



[Note1:assume 12 weeks of physics, 8 weeks of ramp-up, start at ¼ of max]
Note 2: last projections from 11 May 2010 still valid – reached peak performance goals for both polarized protons and heavy ions, will update after Run-11
Note 3: A_nDY operation with ~10 pb^{-1}/week after ramp-up

Summary

Performance in Run-11

- p^-p^ at $\sqrt{s}$ = 500 GeV:
  P ~ 45-50%, L_{avg} = 90x10^{30}cm^{-2}s^{-1}, **25 pb^{-1}/week**
  (all new records for peak performance, and all within Run-11 projections)
  integrated luminosity lower than expected due to down time
  A_nDY tested, ran with relatively small impact on STAR/PHENIX
- Au-Au at $\sqrt{s_{NN}}$ = 19.6 GeV: **17.5 μb^{-1}/10 days** (175x Run-2 value for STAR)
- Au-Au at $\sqrt{s_{NN}}$ = 200 GeV: **~800 μb^{-1}/week** (still running)

Run-12

- Au-Au: EBIS, horizontal stochastic cooling (L +30%, U)
- p^-p^: incremental changes (L +30%, P +5%)
  A_nDY possible with ~10 pb^{-1}/week after full ramp-up

Run-13

- Au-Au: incremental changes
- p^-p^: source upgrade, electron lens commissioning