The RHIC Proton Luminosity Upgrade Project

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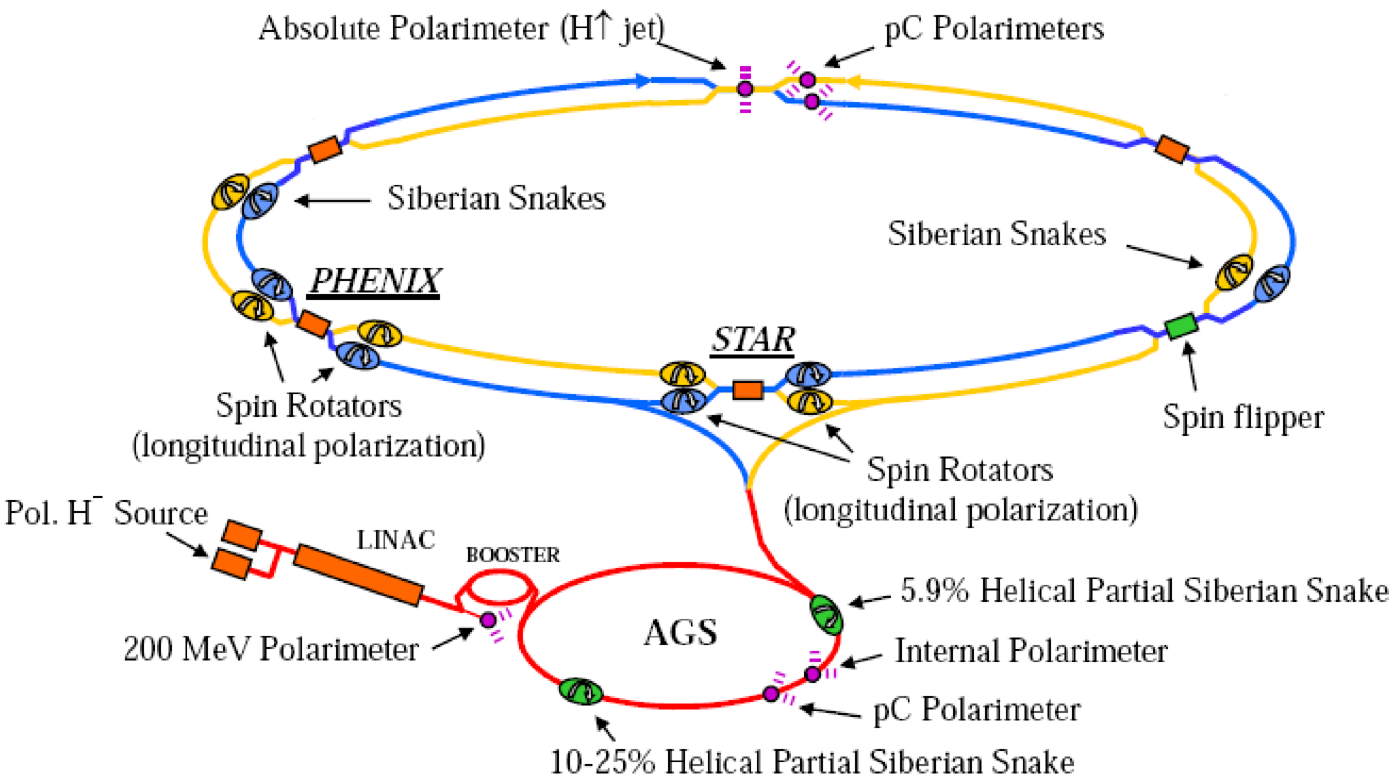
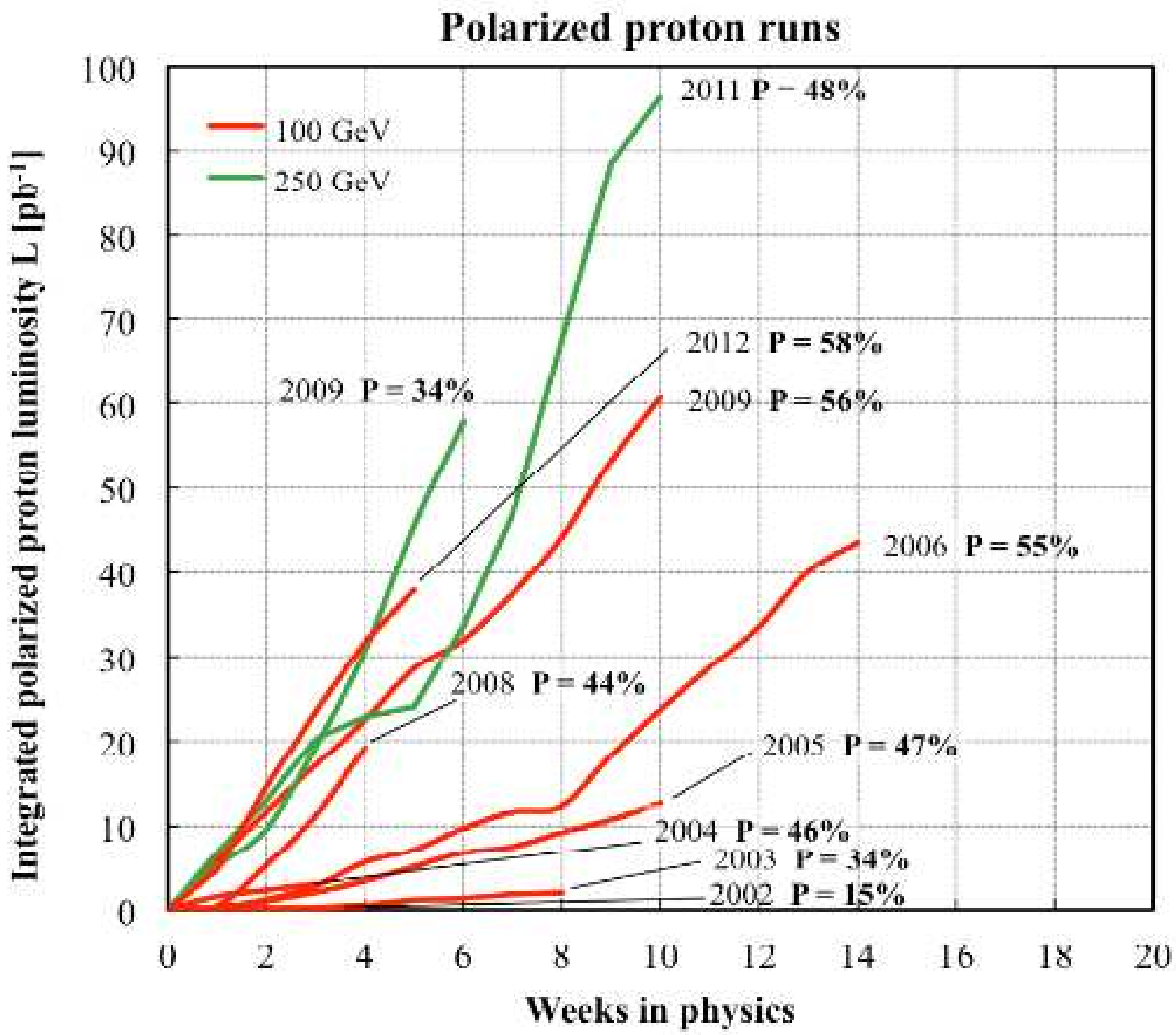
RHIC as a polarized proton collider



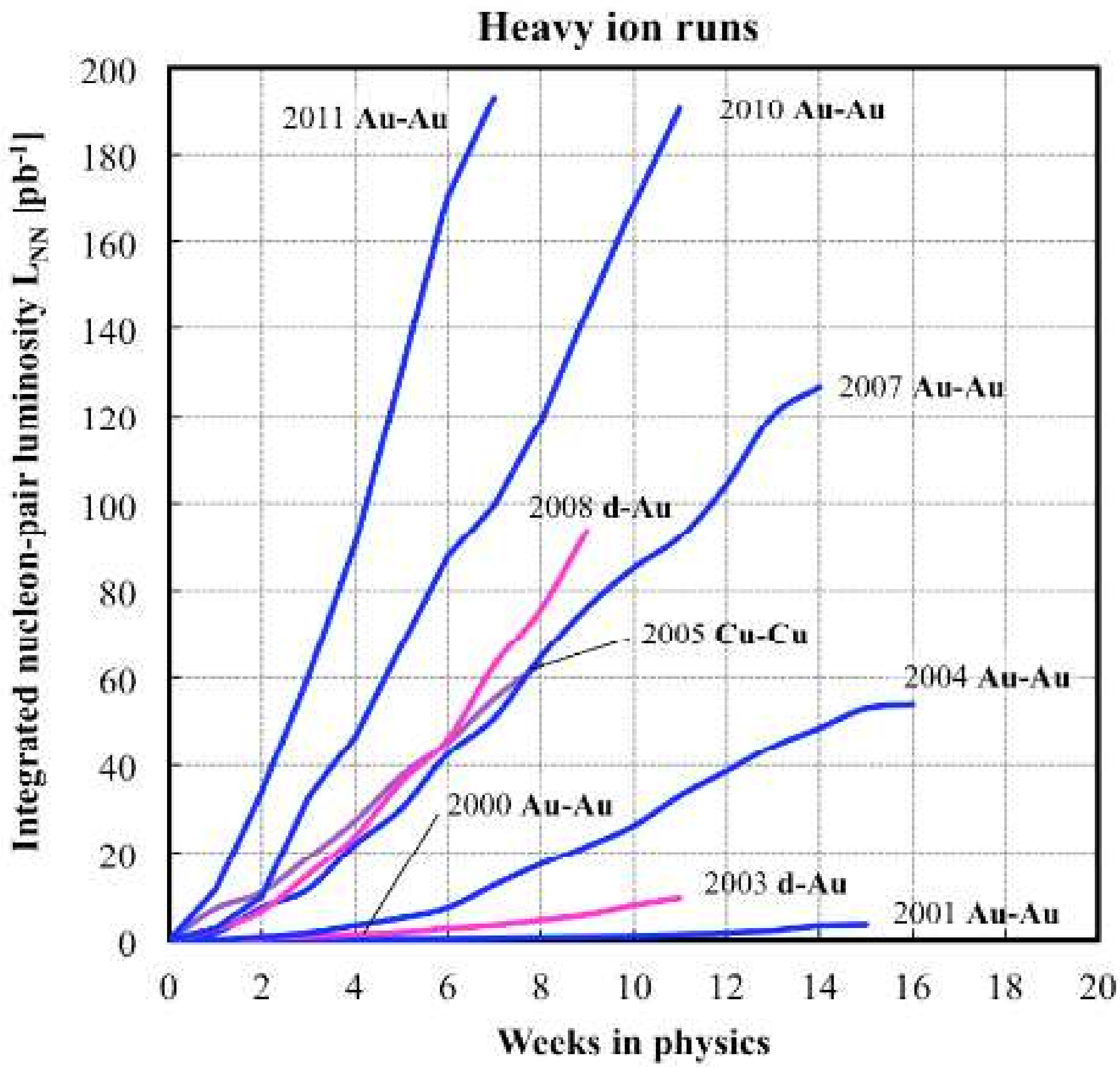
Two full Siberian snakes to overcome ≈ 1000 depolarizing resonances in RHIC

Two partial Siberian snakes in AGS

Delivered Proton Luminosity and Polarization



Delivered Heavy Ion Luminosity



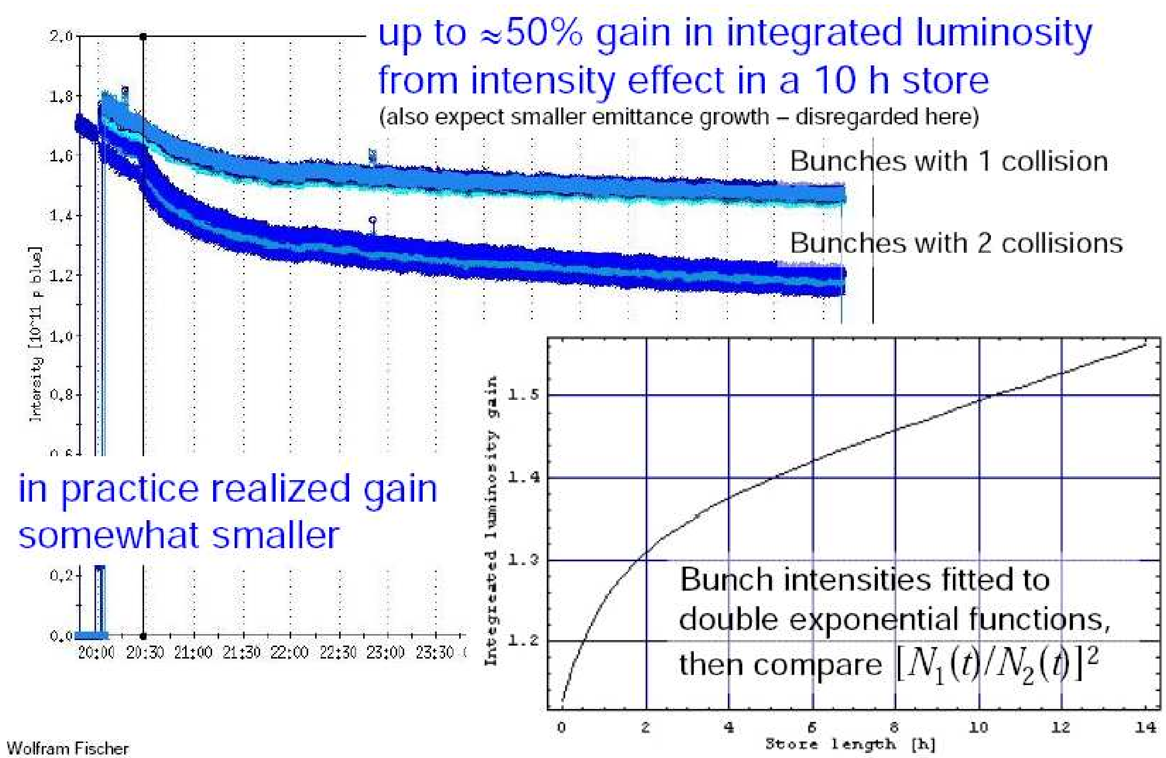
Achieved RHIC Parameters

mode	no. of bunches	ions/bunch $[10^9]$	β^* [m]	pol. %	$\mathcal{L}_{\text{store avg.}}$ $[\text{cm}^{-2}\text{sec}^{-1}]$	$A_1A_2\mathcal{L}_{\text{store avg.}}$ $[\text{cm}^{-2}\text{sec}^{-1}]$	$A_1A_2\mathcal{L}_{\text{peak}}$ $[\text{cm}^{-2}\text{sec}^{-1}]$
Au-Au	111	1.3	0.75		$30 \cdot 10^{26}$	$115 \cdot 10^{30}$	$190 \cdot 10^{30}$
Cu-Cu	37	4.5	0.9		$80 \cdot 10^{26}$	$32 \cdot 10^{30}$	$79 \cdot 10^{30}$
d-Au	103	100/1.0	0.85		$13 \cdot 10^{28}$	$51 \cdot 10^{30}$	$99 \cdot 10^{30}$
$\vec{p}$-$\vec{p}$ 100 GeV	109	160	0.85	58.5	$33 \cdot 10^{30}$	$33 \cdot 10^{30}$	$46 \cdot 10^{30}$
$\vec{p}$-$\vec{p}$ 250 GeV (2011)	109	165	0.6	48	$90 \cdot 10^{30}$	$90 \cdot 10^{30}$	$145 \cdot 10^{30}$

Nucleon-pair luminosity $A_1A_2\mathcal{L}$ treats nucleons of nuclei independently and allows for comparison of luminosities of different species

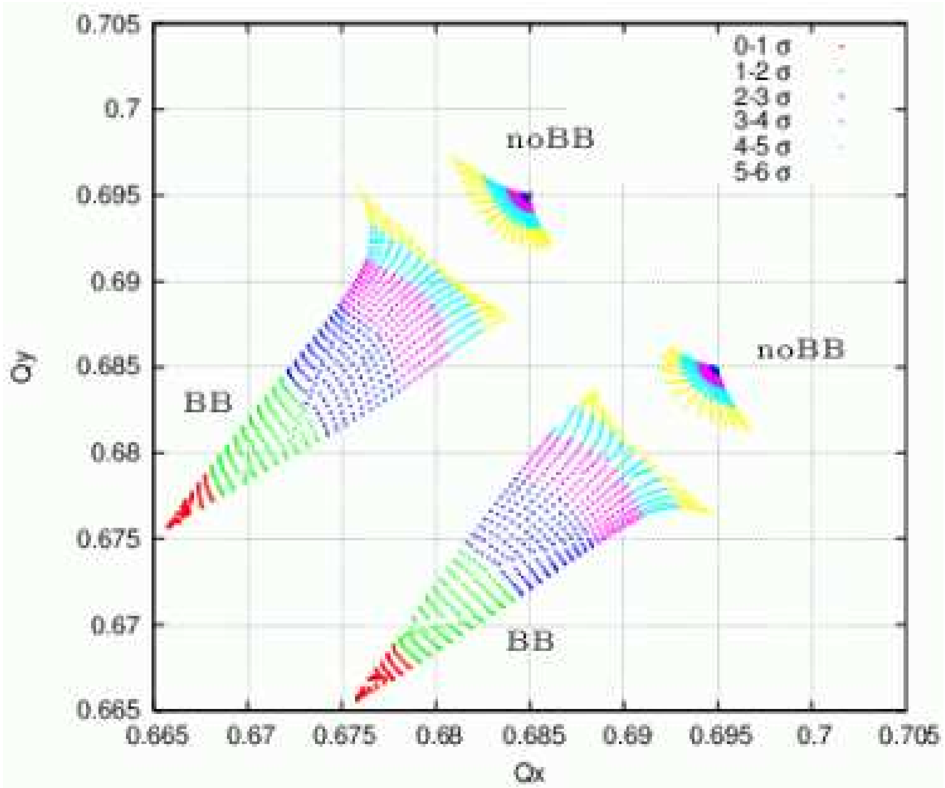
Beam-beam Compensation

Proton Luminosity Limitation: Beam-Beam



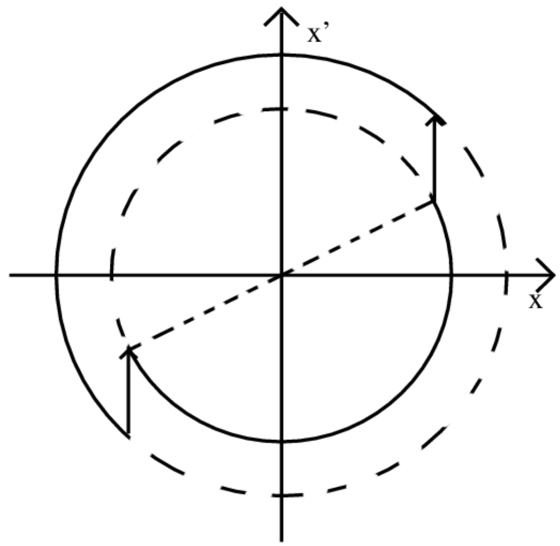
Proton beam lifetime is limited by beam-beam effect; bunches with one collision have longer lifetime than bunches with two.

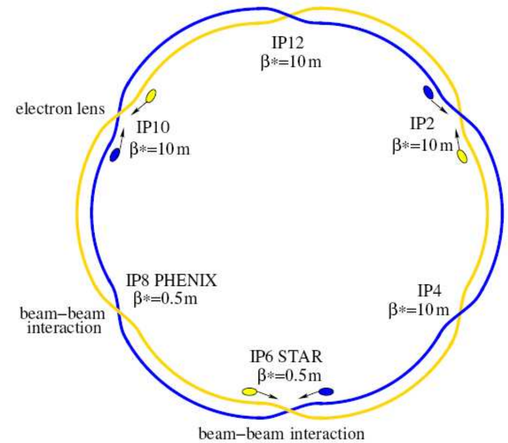
Tune footprints with and without beam-beam



At 2e11 protons/bunch, tune footprint barely fits between 2/3 and 7/10 resonances

⇒ Beam-beam limit

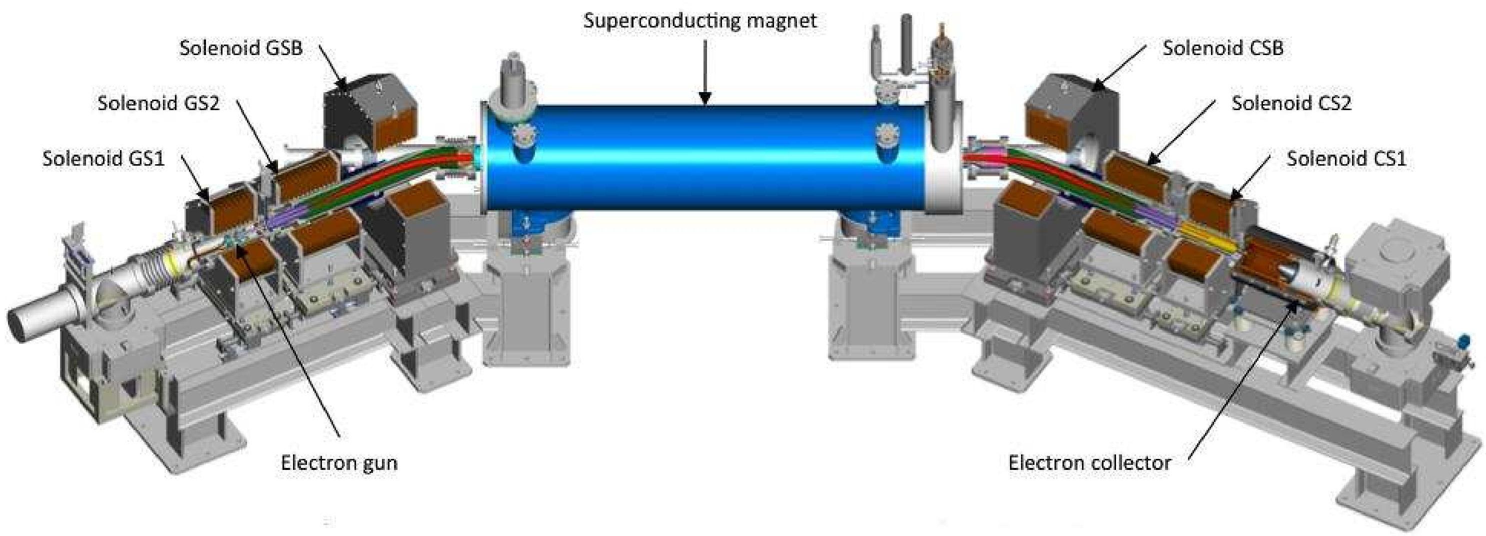




Idea:

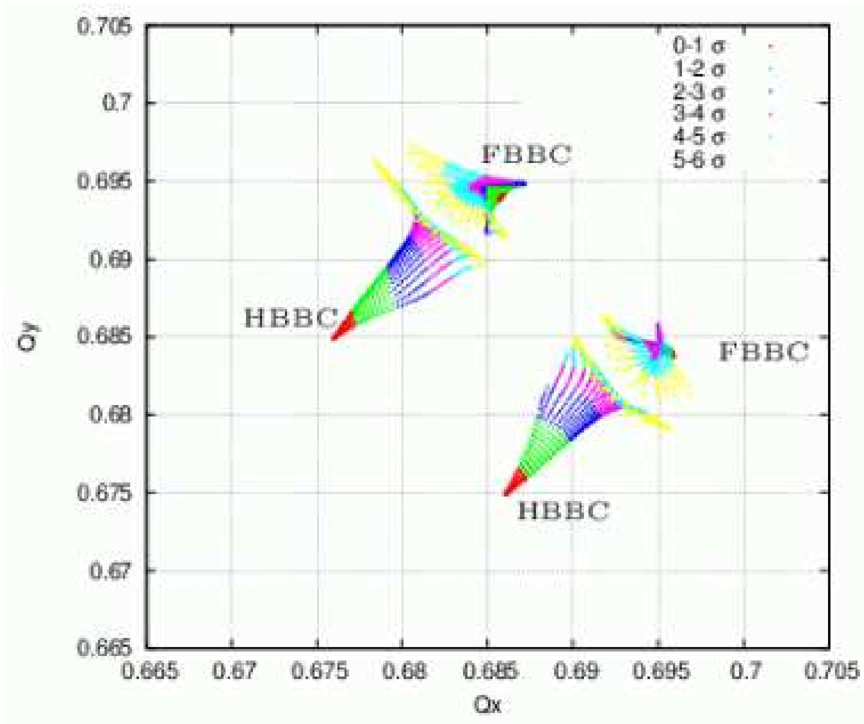
- Nonlinear beam-beam kick in one IP is compensated by opposite kick after $\Delta\phi = k \cdot \pi$ betatron phase advance
- Beam-beam nonlinearities cancel and tune footprint shrinks due to beam-beam compensation
- Allows for higher intensities/larger beam-beam tuneshift; therefore higher luminosity
- Scheduled for 2013

RHIC electron lens



Gaussian electron beam guided by solenoids

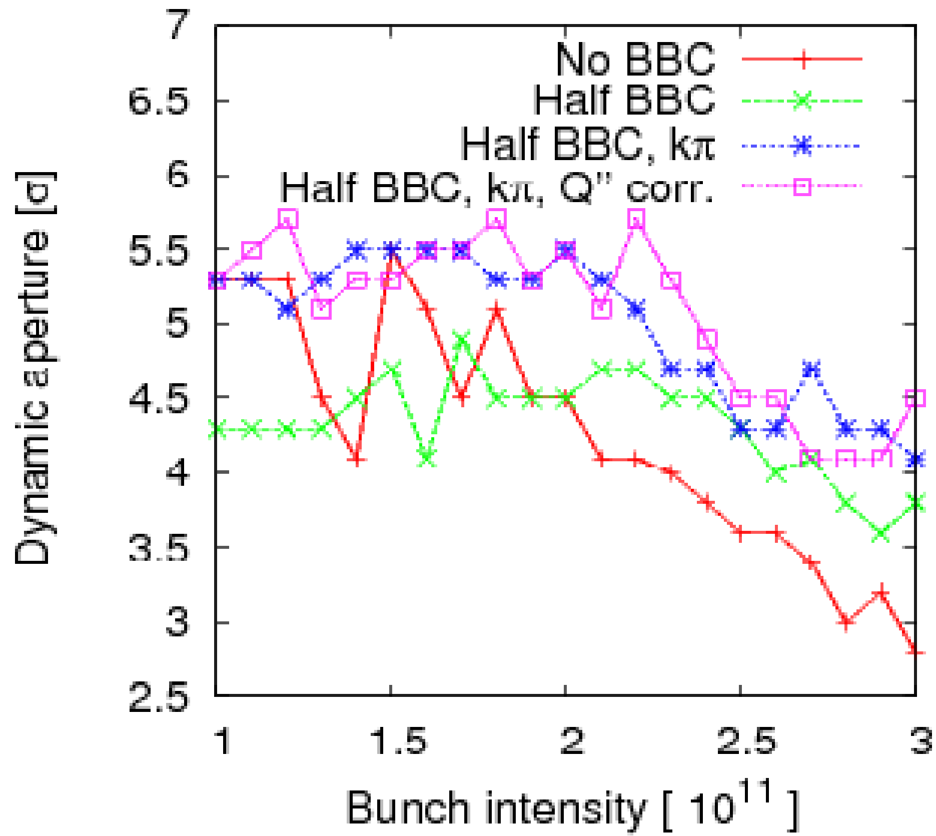
Tune footprints with full and half compensation



Full beam-beam compensation (FBBC) compensates two IPs, half compensation (HBBC) only one

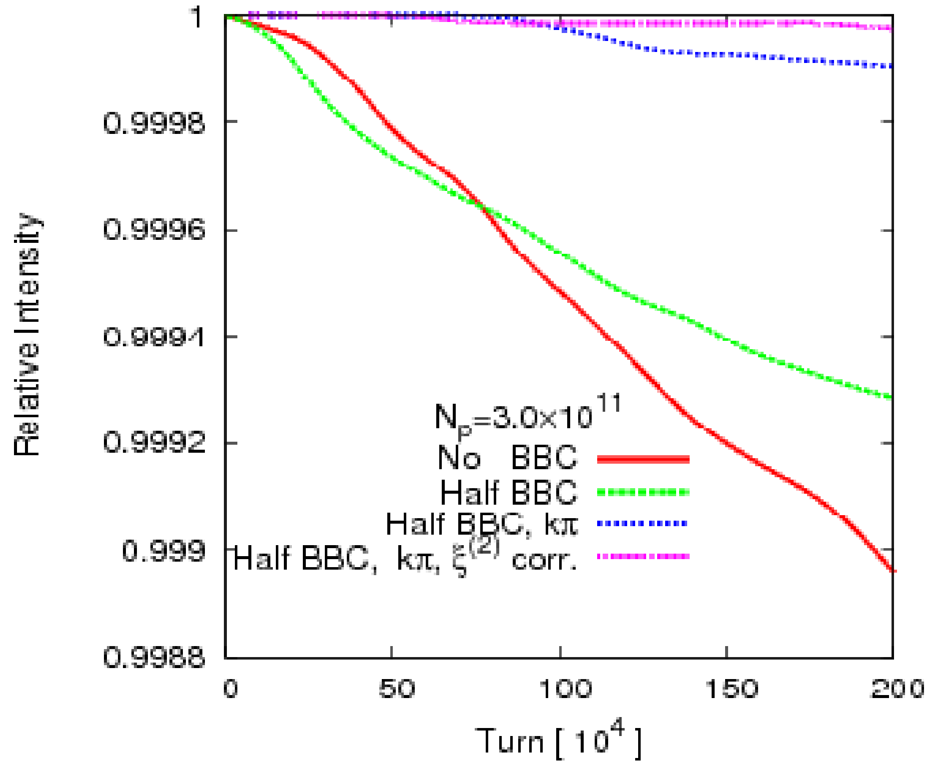
Tune footprint shrinks significantly, providing room for higher intensity

Dynamic aperture as function of intensity



Half beam-beam compensation and phase advance adjustment significantly improves dynamic aperture

Intensity evolution with 3e11 protons/bunch



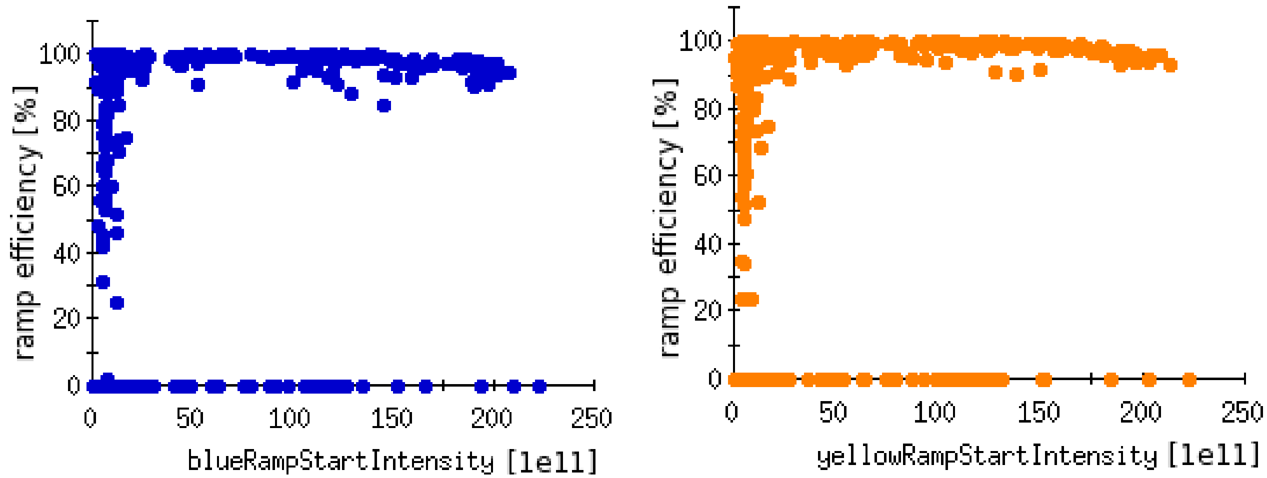
Half beam-beam compensation and phase advance adjustment significantly improves lifetime

The path towards higher intensity

Goals:

- Bunch intensity 2.5e11 protons/bunch, and 3e11 with additional upgrades
- RMS bunch length $\sigma_s = 20\,\text{cm}$

Ramp efficiency

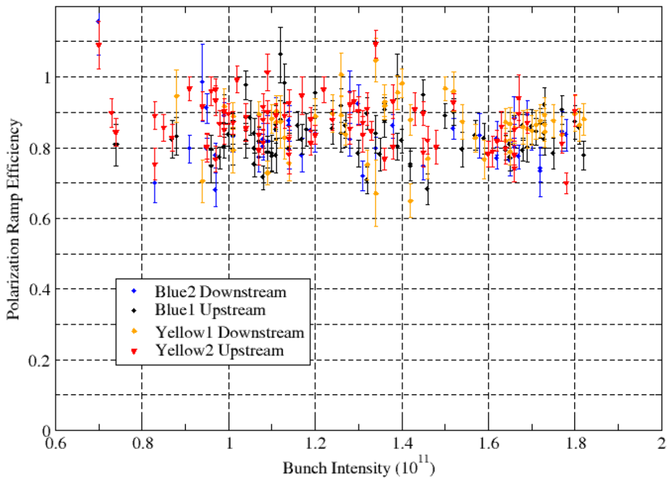


Blue and Yellow ramp efficiencies in percent vs. total beam intensity in Run-11
95 percent ramp efficiency at 1.8e11 protons/bunch

Losses occur predominantly during final squeeze - high intensity bunches have larger emittance out of AGS, and may be blown up by electron cloud

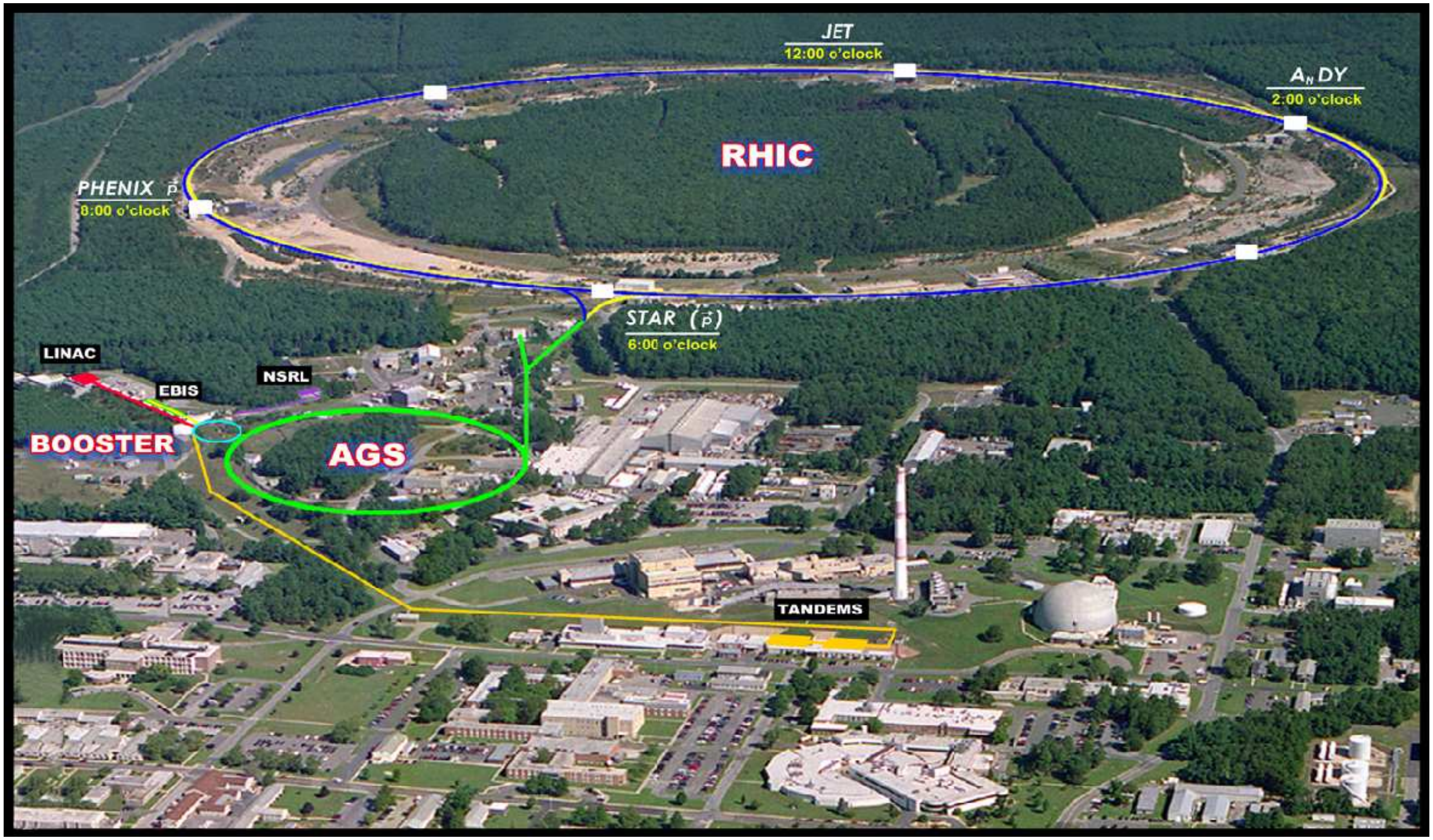
Polarization transmission on the ramp

$$\eta = \frac{P_{\text{250 GeV store}}}{P_{\text{injection}}}$$



Polarization transmission on the ramp is independent of intensity

Radiation safety



RHIC is built at surface level - not in a deep tunnel

- Accelerator Safety Envelope (ASE) is being increased to 5e13 protons/beam at 250 GeV, or 4.5e11 protons/bunch in 109 bunches/beam

- Fences around ventilation shafts will be installed next summer, as well as improved shielding walls

- Upgrades need to be reviewed

- Present limit: 2.5e13 protons/beam at 250 GeV, scaling with energy as $E^{0.8}$

Sufficiently high limits will be in place by Run-13

RHIC beam dump

- RHIC beam dump was designed for 1e11 protons in 56 bunches per beam, with a safety factor of 2
- In Run-10, 250 GeV beam aborts at 1.2e11 in 109 bunches/beam caused magnet quenches downstream of the dump - not unexpected since safety factor 2 was exceeded
- Based on GEANT simulations, the wall thickness of the beam pipe for the circulating RHIC beam next to the dump ws increased to increase the safe limit by a factor 2 for Run-11

- Replacing the beam pipe raised concerns about exposing activated carbon to air

- Beam pipe was thickened by inserting 20 short (5 inches) sleeves

- No magnet quenches were observed during Run-11, with bunch intensities up to 2e11/bunch

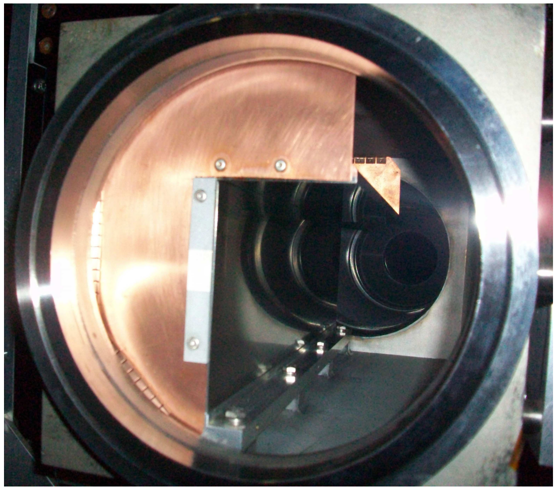
- OK up to 2.5e11/bunch according to simulations, need to learn whether 3e11/bunch causes problems

Beam dump is well understood, and predictive power of simulations is high
If needed, further upgrades can be designed and implemented

Collimation system

- Present two-stage system of one-sided collimators proven to reduce detector backgrounds sufficiently for intensities up to 2e11/bunch

- Recently inspected Yellow primary collimator shows flat surface with no damage



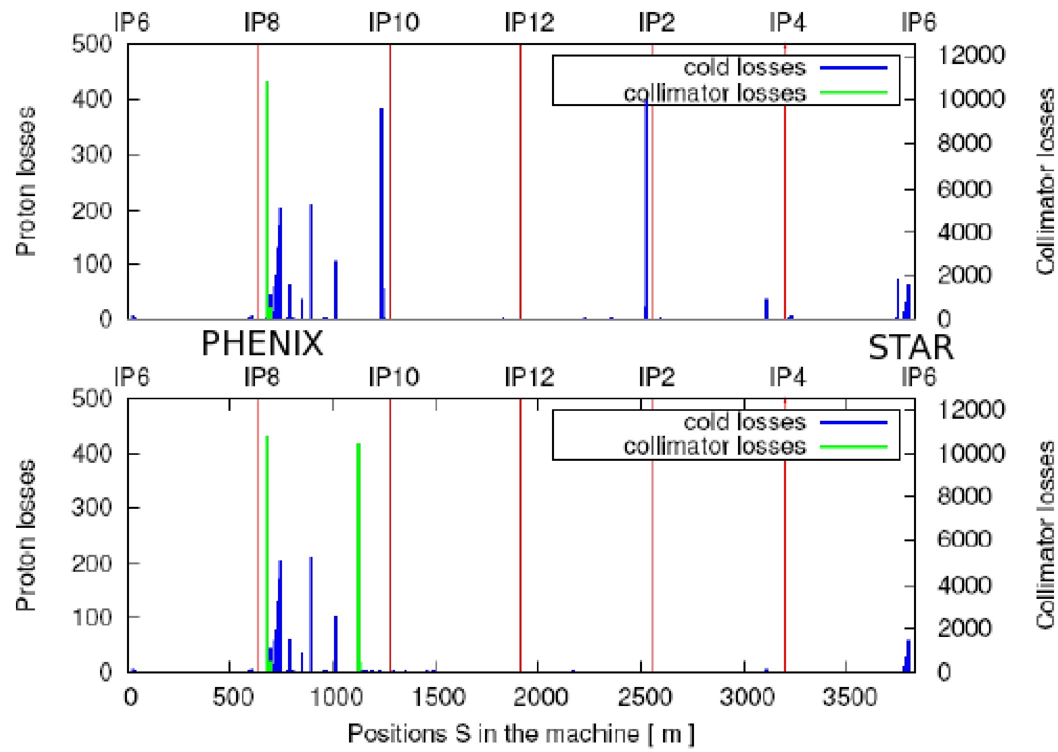
- Assuming that backgrounds scale linearly with intensity, both STAR and PHENIX expect no problems at 3e11/bunch

- Upgraded system with double-sided collimators and newly located secondary collimators is being investigated in simulations as a back-up

- Double-sided collimator system less sensitive to orbit changes

Loss pattern from BLUE horizontal collimators

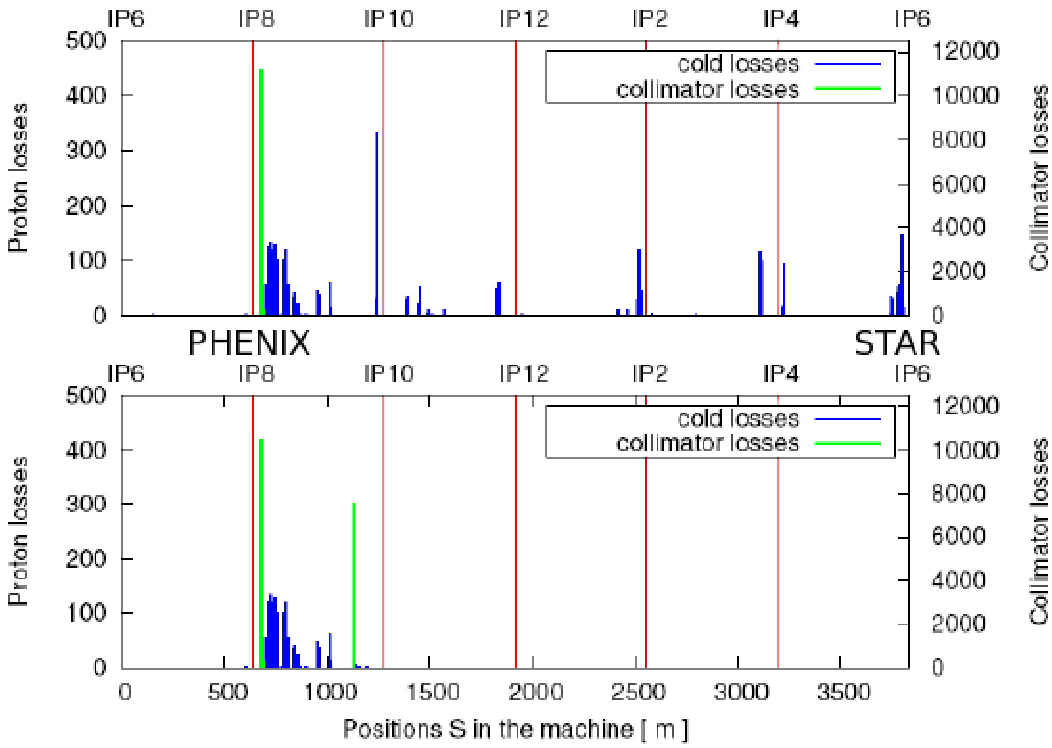
Beam direction left-to-right



Comparison of longitudinal loss patterns between the current RHIC collimation system (top) and its proposed upgrade (bottom) for Blue Horizontal.

Loss pattern from BLUE vertical collimators

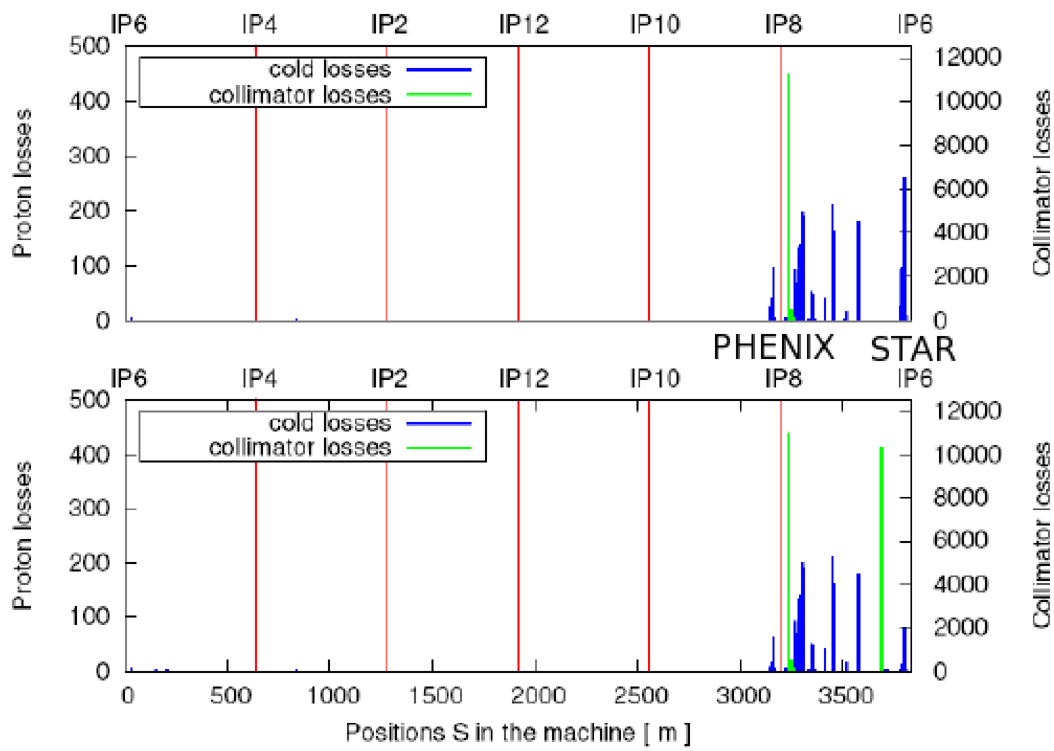
Beam direction left-to-right



Comparison of longitudinal loss patterns between the current RHIC collimation system (top) and its proposed upgrade (bottom) for Blue Vertical.

Loss pattern from YELLOW horizontal collimators

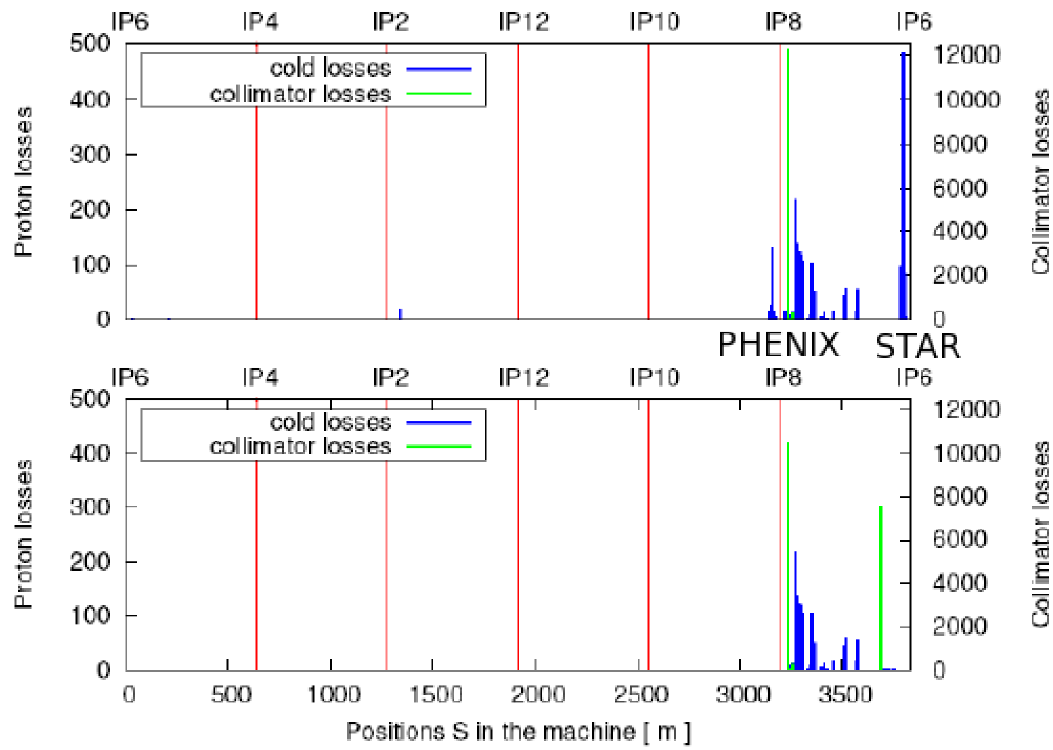
Beam direction left-to-right



Comparison of longitudinal loss patterns between the current RHIC collimation system (top) and its proposed upgrade (bottom) for Yellow Horizontal.

Loss pattern from YELLOW vertical collimators

Beam direction left-to-right



Comparison of longitudinal loss patterns between the current RHIC collimation system (top) and its proposed upgrade (bottom) for Yellow Vertical.

- Upgraded system would significantly reduce losses around the ring and in triplet upstream of STAR

- Effect of showers generated by new secondary collimators upstream of STAR in YELLOW ring to be investigated

- Installation of new secondary collimators in "missing magnet" location (dispersion suppressor) costly and labor intensive but feasible

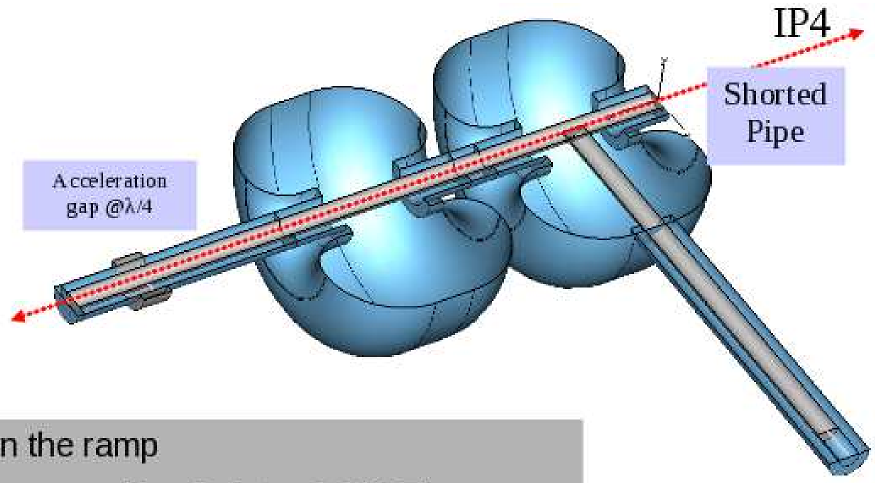
In case present system turns out to be insufficient at high intensity, an upgrade scenario has been developed

RF system

Three RF systems in RHIC:

1. 9 MHz system for injection and ramp
2. 28 MHz system for store (after rebucketing)
3. 197 MHz system for store (after rebucketing)

9 MHz RF



On the ramp

- Max B-dot = 0.015 T/s
- Vrf = 20 kV
- Elong.=0.66 eVs
- Frf = 9.3 MHz (120 bunches)

- New system, still being optimized
- Purpose of the system is to improve longitudinal injection matching from AGS
- Longer bunches during ramp have smaller peak current

Modifications for Run-12

- Re-designed cavity with lower impedance by lowering Q from 2400 to 642 (no copper plating)

- Very powerful amplifier now better matched for this low-Q cavity

- Spark gap protection allows higher feedback gains to fight instabilities

- Fast feedback reduces cavity $R/Q = 34.5\,\Omega$ by factor 30

- Shunt impedance is $R/Q \cdot Q = (\frac{34.5}{30} \cdot 642)\,\Omega = 738\,\Omega$

- Cavity induced voltage per beam with 3e11 in 120 short bunches ($I = 0.9\,\mathrm{A}$) is $U_{\mathrm{ind.}} = 0.9 \cdot 738\,\mathrm{V} = 664\,\mathrm{V} << U_{\mathrm{RF}} = 20\,\mathrm{kV}$

Induced voltage is small compared to cavity voltage

28 MHz RF

- Not involved in injection and ramping
- Used offset frequency technique so cavity is always active on the ramp, but does not couple to the beam (M. Brennan)
- Mechanical tuner does not have to move when cavity is coupled to the beam
- Fundamental beam loading limit is 9e11 protons/bunch

197 MHz RF

- System was limited by power dissipation in couplers
- Separating common cavities (common to both beams) increases the beam intensity limit by a factor 2 to at least 2.5e11/bunch
- Acceptable 197 MHz voltage expected to be limited by off-momentum dynamic aperture

Entire RF system expected to be able to handle 2.5e11 protons/bunch

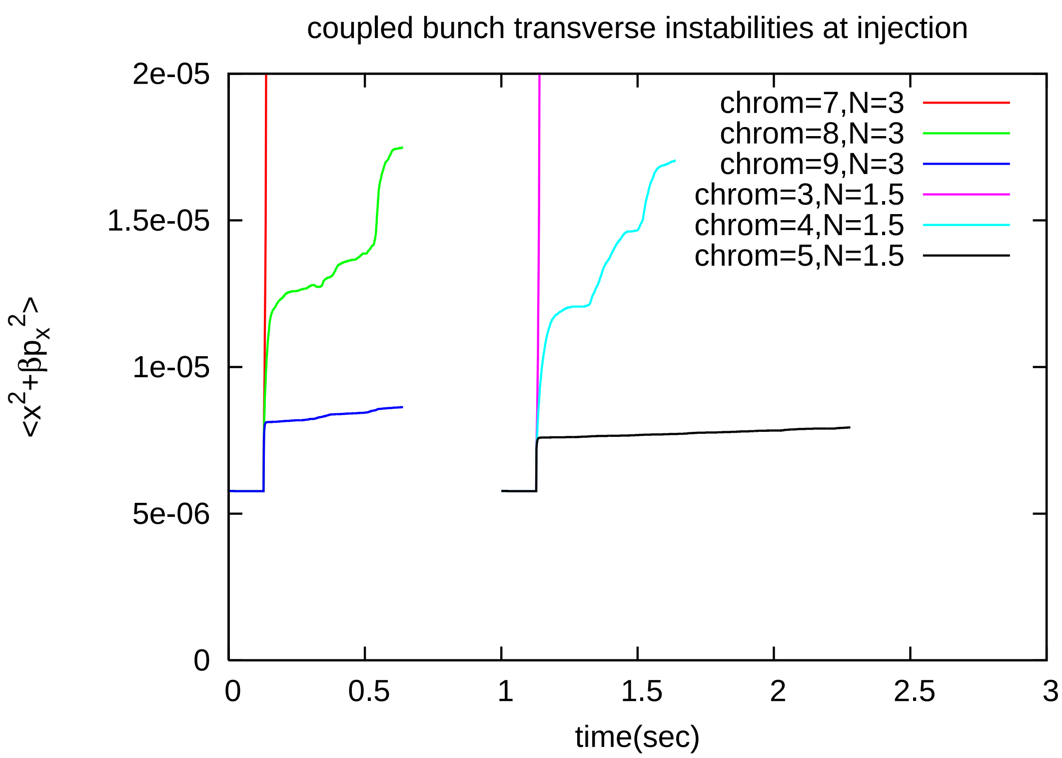
Instabilities

- With proton bunch intensities up to 2e11, never experienced any coherent instabilities that were not easily overcome by chromaticity corrections

- Simulations of coherent instabilities at injection
  - transverse impedance:
    - space charge (direct and image currents)
    - resistive wall
    - BPMs, abort kicker, and unshielded bellows
  - longitudinal impedance: broadband, yielding correct $|Z/n|$

Simulation results for coherent instabilities at injection

14 ns FWHM bunch length

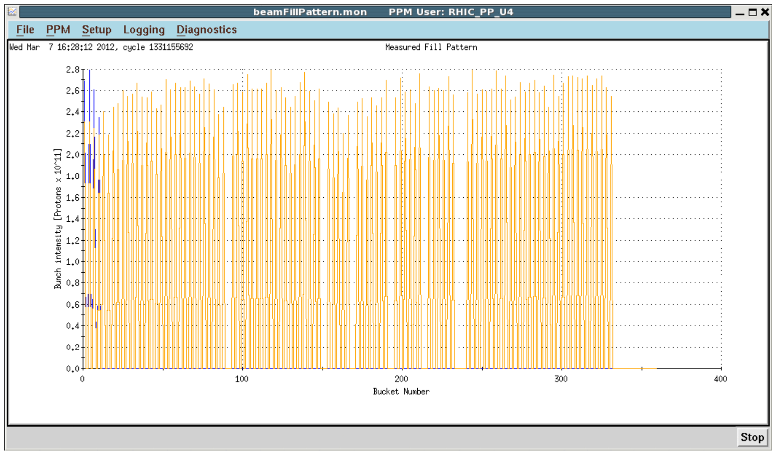


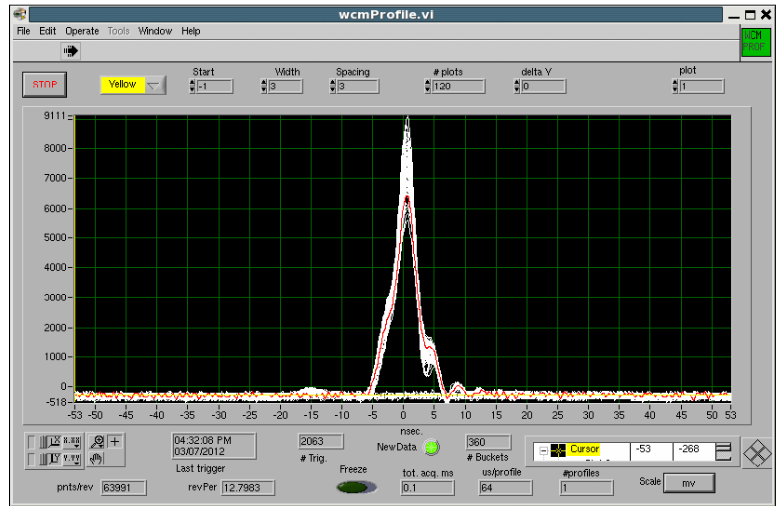
Injection situation expected to be worst due to low synchrotron frequency (5 Hz) and small γ

- Electron cloud induced dynamic pressure rise may cause emittance growth below instability threshold (Zhang and Ptitsyn, PRST-AB 11, 051001 (2008))

- Threshold has increased over the years (scrubbing?), from 1.3e11 in Run-6 to $\geq$ 2e11 in Run-11. In-situ NEG coating of cold beam pipes would make this a non-issue, if required

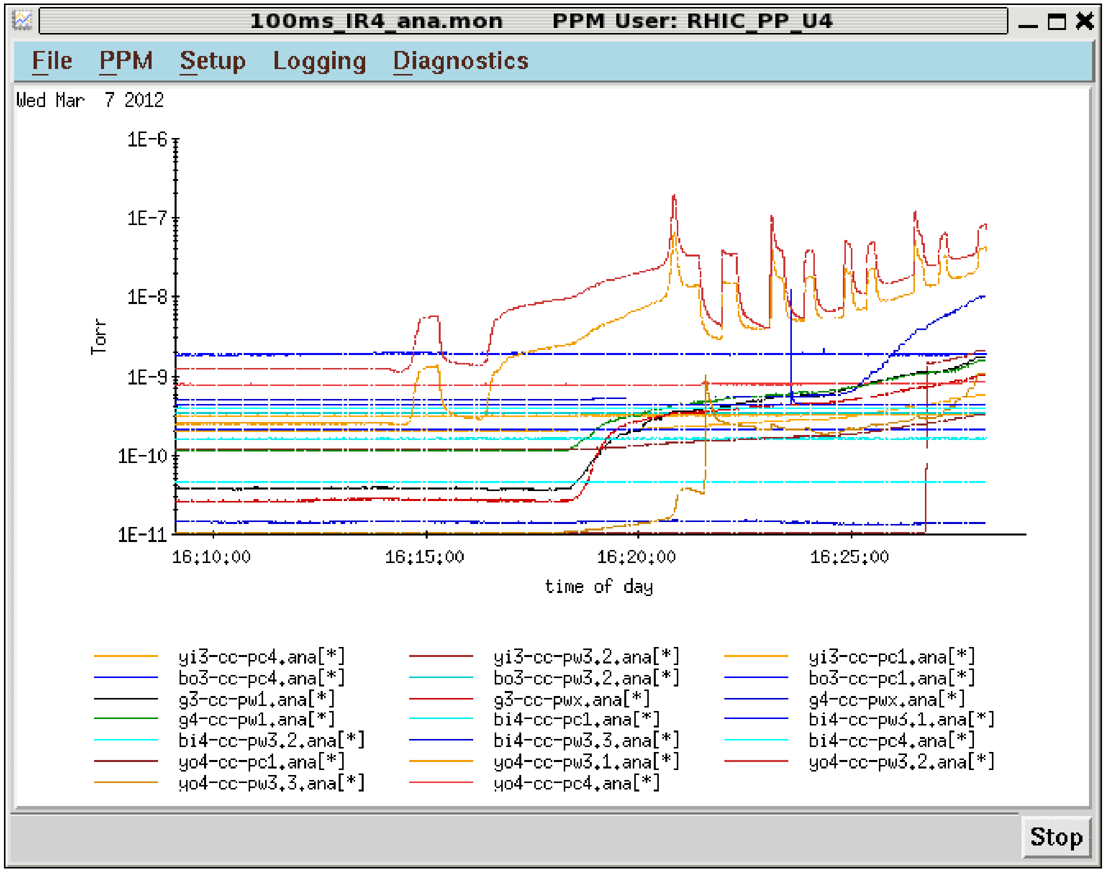
High intensity test at injection





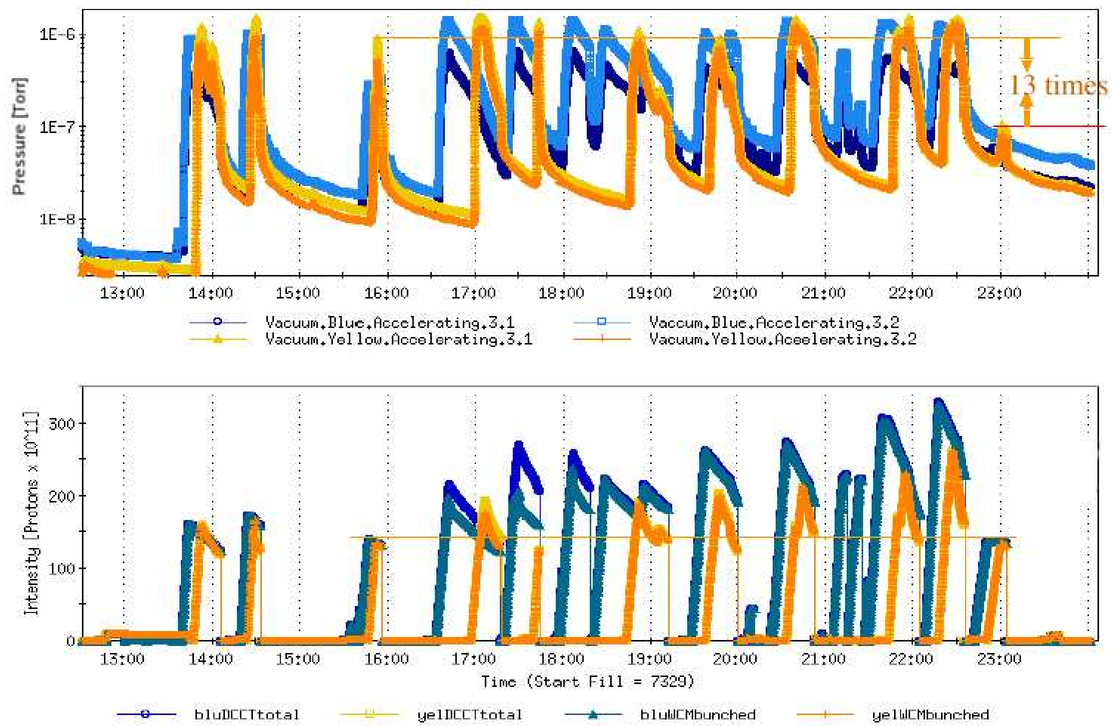
During recent tests in Run-12, 2.6e11 protons/bunch in 109 bunches were achieved at injection, at 2 nsec RMS bunch length and 9 A peak current, with no signs of instability

Vacuum pressure rise



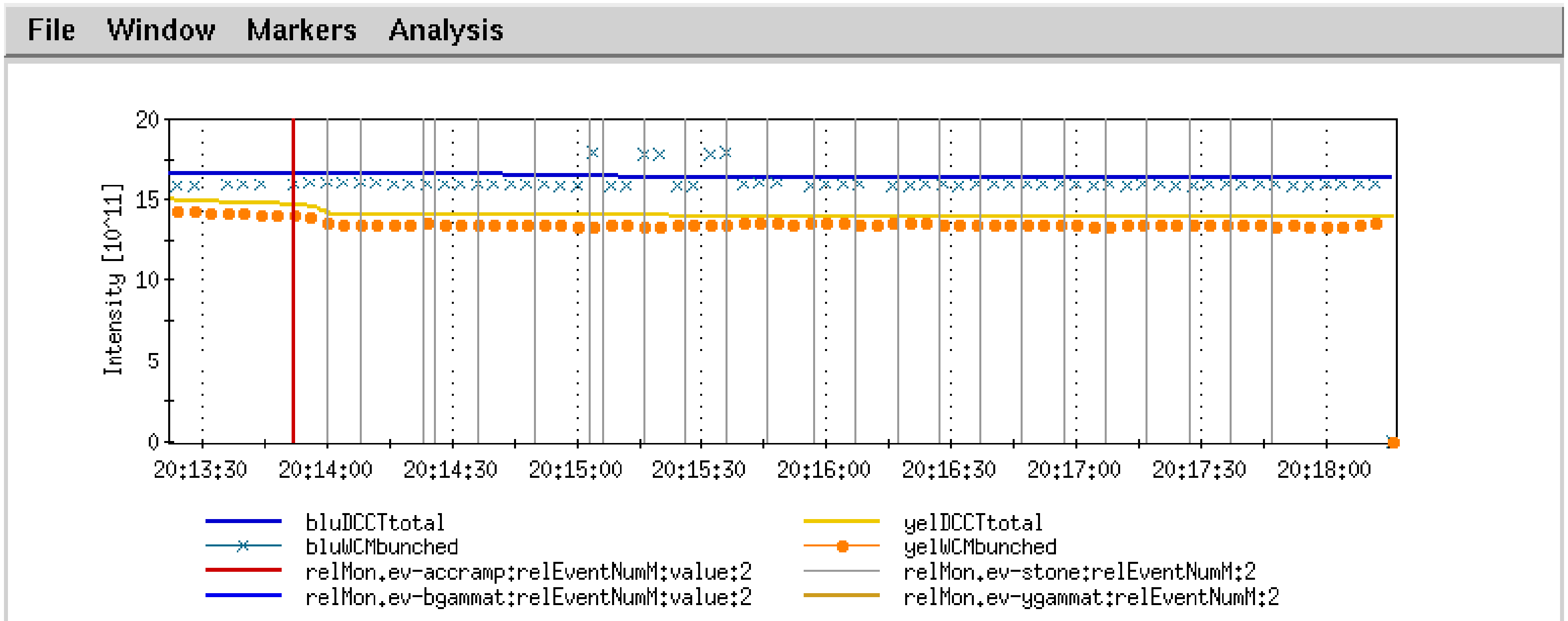
Fast pressure rise during one-by-one injection of last few bunches

Beam scrubbing



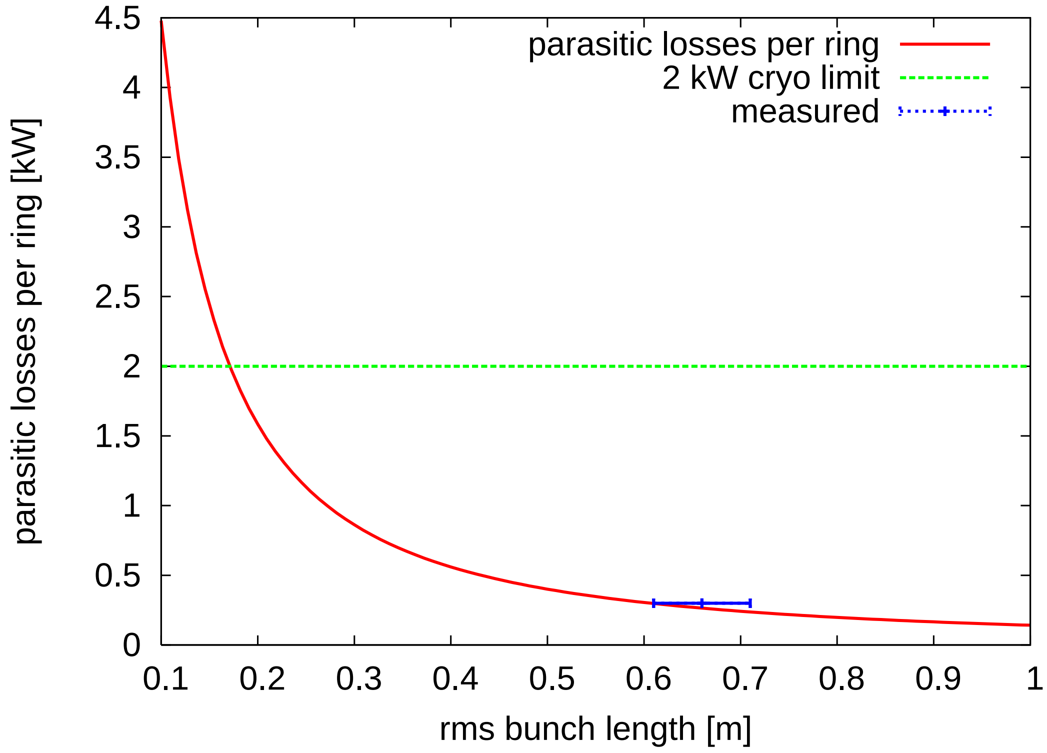
- Scrubbing with short, high intensity bunches creates an electron cloud that desorbs gas molecules
- Gas molecules adsorb in areas where the electrons do not hit the wall, resulting in improved vacuum conditions

High intensity 6-bunch ramp



- Almost 3e11/bunch in Blue, 2.6e11/bunch in Yellow
- Nearly perfect transmission
- 109 bunch ramp had lousy injection lifetime; intensity had dropped to ≈ 2e11 by the time the ramp started
- Lack of time prevented another attempt

Resistive wall heating

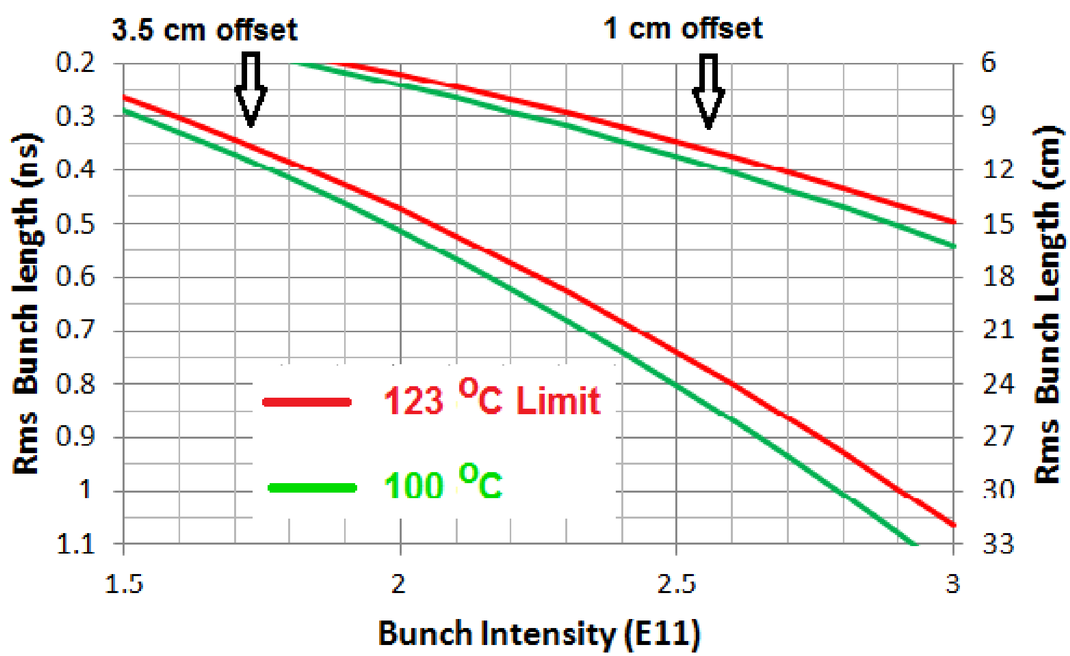


Good agreement with predictions at 2.6e11

At 3e11/bunch need to limit bunch length to $\sigma_s \geq 20\,\text{cm}$

Cryogenic BPM cables

Preliminary estimates of RHIC operational limits due to cryogenic BPM cable heating (specified maximum 123 degrees C).



- 3.5 cm orbit offset is limited by beam pipe radius; 1 cm maximum offset requires orbit interlock system.

- Using orbit feedback maximum offsets below a millimeter are routinely achieved. Need interlock for accidents; already in place during Run-12 beam studies.

At 3e11/bunch, rms bunch length as low as $\sigma_s = 17$ cm is permissible

Summary

- RHIC luminosity has steadily increased over the past 12 years

- Proton luminosity is limited by beam-beam effect

- Partial head-on beam-beam compensation expected to shrink the beam-beam tune footprint and reduce beam-beam nonlinearities, allowing for higher intensities

- RHIC is currently being readied for these higher beam intensities

Thank you

- For your attention
- To M. Vogt for the opportunity to give this seminar
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