RHIC Collider Projections (FY2009 – FY2013)

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This note discusses in Part I the running modes for the RHIC Run-9 (FY2009) operating period including constraints from cryogenic cool-down, machine set-up and beam commissioning. In Part II a 5-year outlook is given. This latest update is based on the experience gained during the Run-8 operation, the planned luminosity upgrades in RHIC, and the physics plans for Run-9. We assume a relatively short polarized proton run at 250 GeV beam energy, possibly followed by a longer polarized proton run at 100 GeV beam energy.

In the following all quoted luminosities are delivered luminosities. Recorded luminosities are smaller due to vertex cuts, detector uptime, and other considerations. An estimate of how much of the delivered luminosity can be recorded must be made by every experiment individually.

Part I – Run-9 Projections

Cryogenic operation – After the shutdown the two RHIC rings will be at room temperature. After bringing the rings to liquid nitrogen temperature, 1 ½ week will be required to cool them down to 4 K. At the end of the run, ½ a week of refrigerator operation is required for the controlled warm-up to liquid nitrogen or room temperature.

Running modes – The likely running modes for Run-9 include a relatively short polarized proton run at 250 GeV beam energy, possibly followed by a longer polarized proton run at 100 GeV beam energy. We make projections for those two modes, and, for reference, also for a hypothetical gold-gold run.

When starting the 250 GeV run we plan for about 2 weeks of machine set-up with the goal of establishing collisions, and about 1 week machine development period ("ramp-up") after which stable operation can be provided with integrated luminosities that are a fraction of the maximum goals shown below. The set-up and ramp-up period for polarized protons is longer than for ions to allow for the set-up of polarimetry, snakes, and rotators. During the ramp-up period detector set-up can occur, however with priority for machine development. Estimates for set-up and ramp-up times are based on past performance and improvements are still possible.

Higher weekly luminosities and polarization can be achieved with a continuous development effort in the following weeks. We propose to use the day shifts from Monday to Friday for this effort as needed. The luminosity or polarization development efforts should stop when insurmountable limits, posed by the current machine configuration, are reached.

After a running mode has been established, the collision energy in the same mode can be changed in about 2 days assuming that the energy is lowered, and no unusual machine downtime is encountered. If the β^* at the lower energy is different from the β^* at this energy during the ramp to the higher energy more time is required. A change of the polarization orientation at any or all of the experiments requires 1-2 days.

For example, 20 weeks of RHIC refrigerator operation in FY 2009 could be scheduled in the following way:

Cool-down from 80 K to 4 K	1 ½ week	
Set-up mode 1 (p↑-p↑ at 250 GeV)	2 weeks	(no dedicated time for experiments)
Ramp-up mode 1	1 week	(8 h/night for experiments)
Data taking mode 1 with further ramp-up	5 weeks	
Set-up mode 2 (p↑-p↑ at 100 GeV)	1 week	(no dedicated time for experiments)
Data taking mode 2 with further ramp-up	9 weeks	
Warm-up	½ week	

Past performance – Table 1 shows the luminosities achieved for Au-Au (Run-7), Cu-Cu (Run-5), d-Au (Run-8), and polarized protons (Run-6/Run-8). The time in store was 58% and 60% of the total time for d-Au (Run-8) and p-p (Run-8) respectively. Note that the total time includes all interruptions such as ramping, set-up, maintenance, machine development, and accelerator physics experiments. A comprehensive overview of the past performance can be found at http://www.rhichome.bnl.gov/RHIC/Runs.

Table 1: Achieved beam parameters and luminosities for Au-Au (Run-7), Cu-Cu (Run-5), d-Au (Run-8), and p-p (Run-6/Run-8). All numbers are given for operation at a beam energy of 100 GeV/nucleon.

Mode	No of bunches	Ions/bunch $[10^9]$	β^* [m]	Emittance [μm]	$\mathcal{L}_{peak}$ $[cm^{-2}s^{-1}]$	$\mathcal{L}_{store\ avg}$ $[cm^{-2}s^{-1}]$	L_{week}
Au-Au	103	1.1	0.85	17-35	30×10^{26}	12×10^{26}	380 μb^{-1}
Cu-Cu	37	4.5	0.9	15-30	2×10^{28}	0.8×10^{28}	2.4 nb^{-1}
d-Au	95	100d / 1.0Au	0.85	17-30	25×10^{28}	12.5×10^{28}	40 nb^{-1}
p↑-p↑ *	109	150	1.0	20-25	35×10^{30}	23×10^{30}	7.5 pb^{-1}

* Blue and Yellow ring average polarization of $\mathcal{P}$ = 58%, in RHIC stores at 100 GeV in Run-6. Luminosity numbers are for Run-8 which had only $\mathcal{P}$ = 45%. To have a few non-colliding bunches in both STAR and PHENIX only 109 out of 111 bunches were filled, with 107 collisions at PHENIX and 102 collisions at STAR. If either experiment had elected to have all 111 bunches colliding, the luminosity would have been larger.

Luminosity projections – Table 2 lists the expected maximum peak and average luminosities for possible modes in Run-9 that could likely be achieved after a sufficiently long running period, typically a few weeks, unless thus far unknown machine limitations are encountered. With experience from past runs we expect luminosities at the end of the initial ramp-up period to be lower than at the end of the running period by about a factor 4. Unless stated otherwise for all modes it was assumed that the beam energy is 100 GeV/nucleon. The average store luminosity is derived from the predicted beam parameters and the calendar time in store. The expected diamond rms length for ions is 20 cm due to the availability of the full voltage from the 197 MHz storage cavities and due to longitudinal stochastic cooling. For protons a new 9 MHz cavity will be commissioned to reduce the longitudinal emittance. After successful commissioning of this cavity we expect for protons an rms diamond length of 40 cm or better at 100 GeV (h = 360, V_{gap} = 300 kV, A_s = 1eVs), and 30 cm or better at 250 GeV. The minimum luminosity projections are based on previous run performances except for polarized proton operation at 250 GeV beam energy. In this case a conservative estimate based on experience with 100 GeV operation is used.

Due to the required abort gaps in both beams, the maximum number of collisions can only be provided for either STAR or PHENIX. The other experiment will have an approximately 9% reduction in the number of collisions. During the Run-8 polarized proton operation both STAR and PHENIX required to have a few non-colliding bunches. Only 109 out of 111 bunches were filled, with 107 collisions at PHENIX and 102 collisions at STAR.

To minimize the time from store to store, stores of pre-determined length are desirable. They allow for a synchronized check of the injector chain before the store ends. The optimum store length is determined from the luminosity lifetime, the average time between stores, and the detector turn-on times.

Table 2: Maximum luminosities that can be reached after a sufficiently long running period. All numbers are given for operation at an energy of 100 GeV/nucleon unless stated otherwise.

Mode	No of bunches	Ions/bunch [10^9]	β^* [m]	Emittance [μm]	$\mathcal{L}_{peak}$ [$cm^{-2}s^{-1}$]	$\mathcal{L}_{store\ avg}$ [$cm^{-2}s^{-1}$]	L_{week}
Au-Au	103	1.1	0.7	17-35	39×10^{26}	17×10^{26}	610 μb^{-1}
Cu-Cu	68	6	0.7	15-30	9×10^{28}	4×10^{28}	14 nb^{-1}
Si-Si	68	12.5	0.7	15-30	40×10^{28}	20×10^{28}	65 nb^{-1}
d-Au	95	110d / 1.1Au	0.85	18-30	27×10^{28}	14×10^{28}	50 nb^{-1}
p↑-p↑* 100 GeV	111	175	0.7	20-25	70×10^{30}	40×10^{30}	16 pb^{-1}
p↑-p↑* 250 GeV	111	170	0.7	20-25	180×10^{30}	110×10^{30}	40 pb^{-1}

*We expect that an average store polarization $\mathcal{P}$ between 50 and 60% can be reached. In Run-8 PHENIX had 107 and STAR 102 colliding bunches. This reduces the luminosity compared to the 111 bunches assumed in the table.

Operation at energies other than 100 GeV/nucleon – It is preferable to lower the energy when the collision energy is changed in any given mode. This can be done in about 2 days. For Au-Au operation at 100 GeV/nucleon the limiting aperture is in the triplet. For energies less than 100 GeV/nucleon the un-normalized beam emittance is larger and, to maintain the beam size within the triplet, the β-function in the triplet has to be reduced, which results in a larger β^*. The combined effect is that the luminosity scales with the square of the energy. This is shown in Figure 1. Note that operation near the transition energy is not possible, and that the storage rf

system cannot be used below the transition energy. With operation at the injection energy refilling is very efficient, and β^* can be reduced to 3 m.
For p-p operation the luminosity is expected to increase linearly with energies above 100 GeV, and decrease quadratically with energies below 100 GeV.

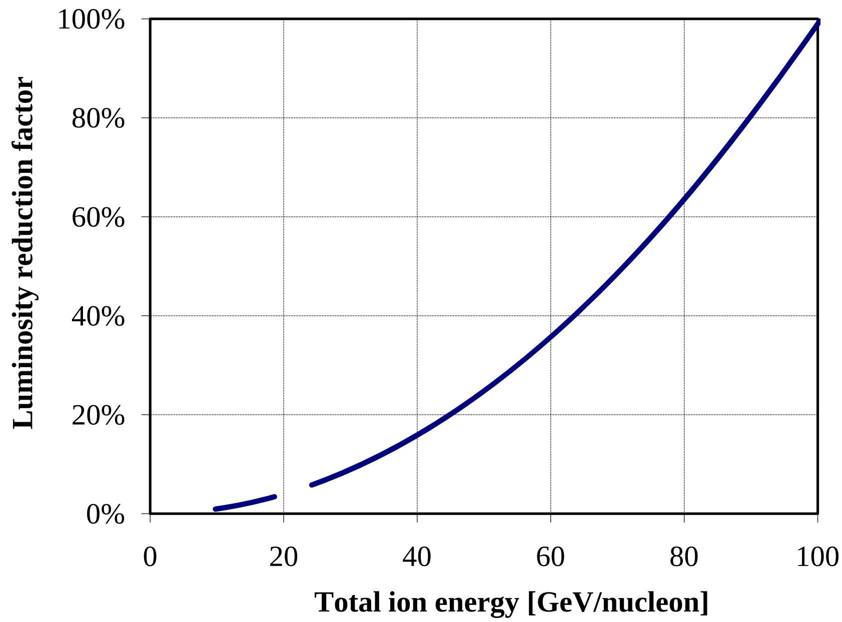

Figure 1: Luminosity scaling for Au-Au operation at energies below 100 GeV/nucleon. The gap is around the transition energy at which operation is not possible.

Following are specific comments on polarized proton running at 250 GeV and 100 GeV beam energy, as well as gold-gold running for reference.

Polarized protons at 250 GeV – We expect that the polarization values from Run-6 can be demonstrated at 250 GeV. We expect at least 40% average polarization in store after set-up and ramp-up. This should be improved to 50 to 60% throughout the run. During the run a horizontal tune jump system will be commissioned in the AGS. If successful it may increase the polarization out of the AGS by about 5%. A spin flipper will be commissioned in the Blue ring.
We plan to operate with $\beta^* = 0.7$ m, and may test $\beta^* = 0.6$ m later in the run. Nonlinear corrections of interaction region magnetic errors and chromaticity will be implemented again. With changes in the LEBT/MEBT sections and the Booster injection we expect a lower emittance in the injector chain, which should also be beneficial to the polarization. A new 9 MHz cavity will allow for shorter bunches at store, thereby reducing the hourglass effect. At store the 28 MHz system will be used, and tests with the 197 MHz system are planned. Due to the higher beam energy losses have to be controlled better since it will be easier to quench magnets at the top energy. In the Yellow vertical plane a transverse stochastic cooling system will be tested with a low intensity proton bunch. Stochastic cooling has no operational impact on the polarized proton operation.
Figure 2 shows the projected minimum and maximum luminosity for 250 GeV beam energy, where it is assumed that the peak performance is reached after 8 weeks of linear ramp-up, starting with 25% of the final value.

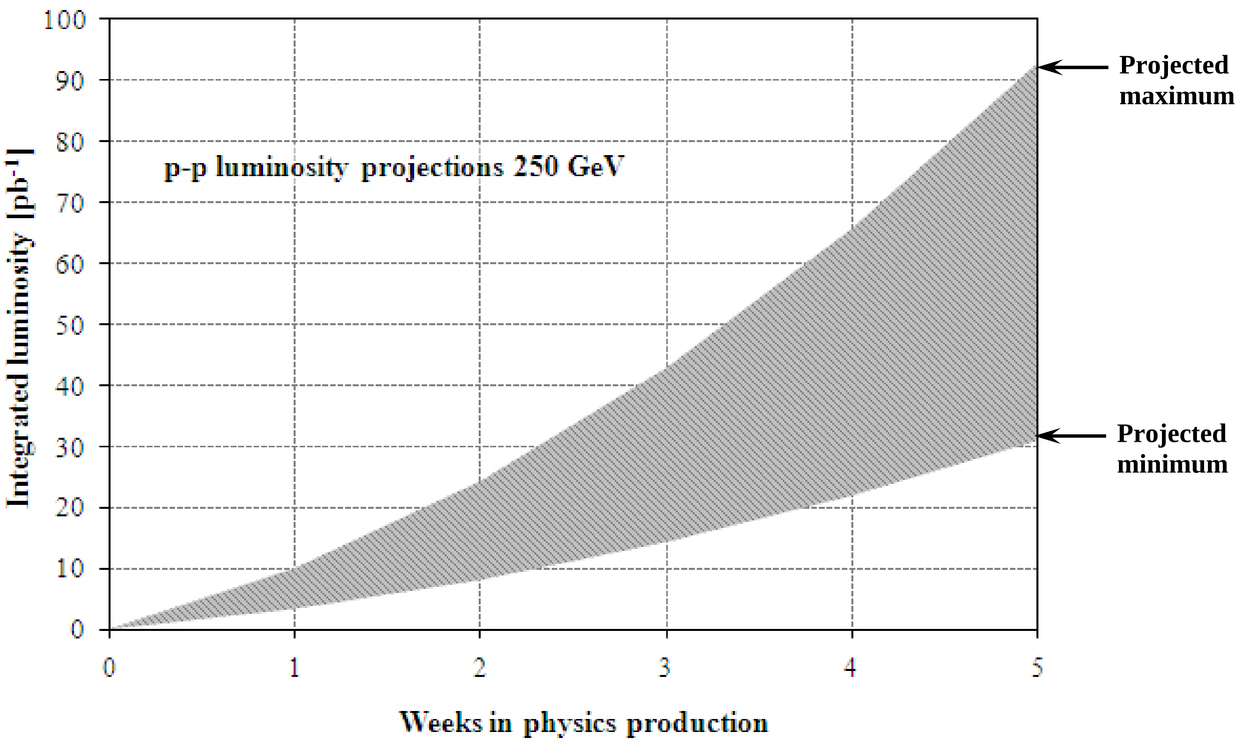

Figure 2: Projected minimum and maximum integrated luminosities for polarized proton collisions at 250 GeV beam energy, assuming linear weekly luminosity ramp-up in 8 weeks. An average store polarization between 50 and 60% is expected.

Polarized protons at 100 GeV – A 100 GeV run could possibly follow the 250 GeV polarized proton operation. We expect a similar polarization performance as at 250 GeV, with slightly higher polarization values coming from the AGS if the horizontal tune jump system is successfully commission. After tests during Run-8, we plan to operate with β^{*}= 0.7 m. To lower the energy, the ramp from the 250 GeV operation can be used, but an additional β-squeeze at the flat top energy is required, and the store conditions have to be optimized again. This should take ½ to 1 week.

Figure 3 shows the projected minimum and maximum luminosity for 100 GeV beam energy, where it is assumed that the peak performance is reached after 4 weeks of linear ramp-up, starting with 25% of the final value.

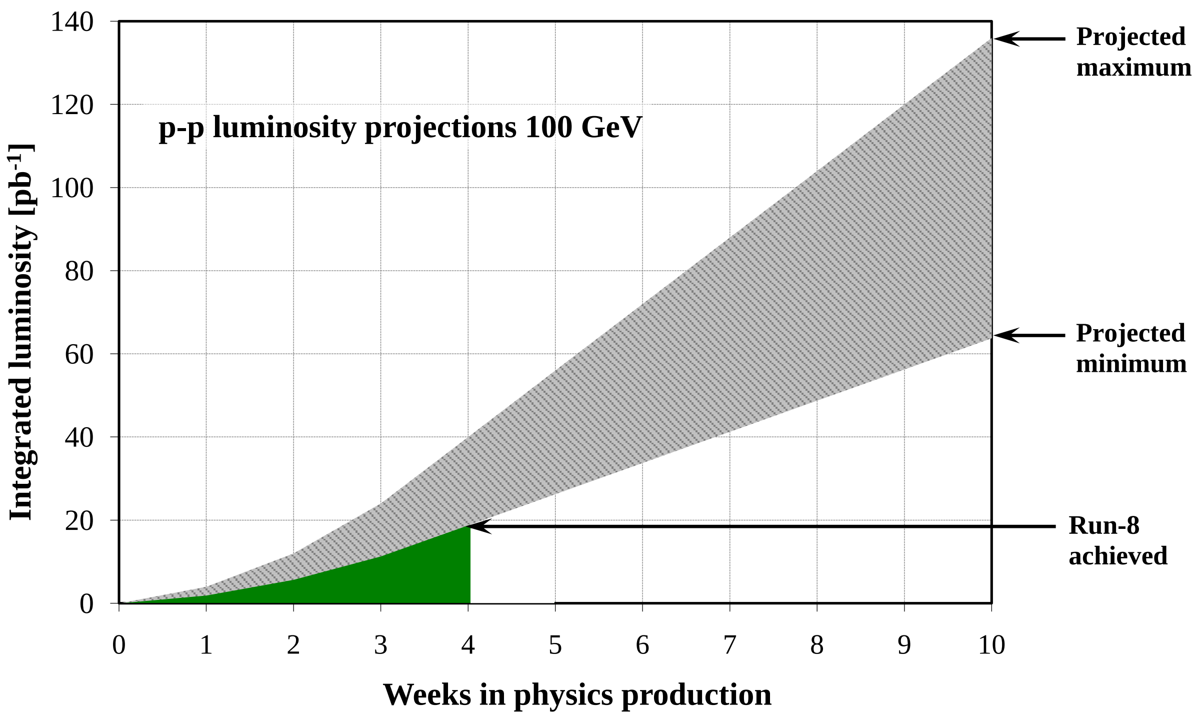

Figure 3: Projected minimum and maximum integrated luminosities for polarized proton collisions at 100 GeV beam energy, assuming linear weekly luminosity ramp-up in 4 weeks. An average store polarization between 50 and 60% is expected.

Gold-Gold at 100 GeV/nucleon – A number of improvements can be implemented compared to Run-7. With experience from previous Au-Au and the most recent d-Au operation, we assume that β^* can be reduced to 0.7 m or less. Longitudinal stochastic cooling should become operational also in the Blue ring. Transverse stochastic cooling will be tested in the Yellow vertical plane in Run-9 and may be available in the following run. A lattice version with a reduced transverse emittance growth rate from intrabeam scattering was used for the gold beam in d-Au operation in Run-8, and can also be used in Au-Au operation. The beam intensity is expected to be limited by fast transverse instabilities at transition, driven by the machine impedance and electron clouds. To mitigate electron cloud effects, a few days of scrubbing with short proton bunches at injection would be needed. We also expect a larger time in store than in Run-7. The projected minimum and maximum luminosities are shown in Figure 4, where it is assumed that the peak performance is reached after 4 weeks of linear ramp-up, starting with 25% of the final value.

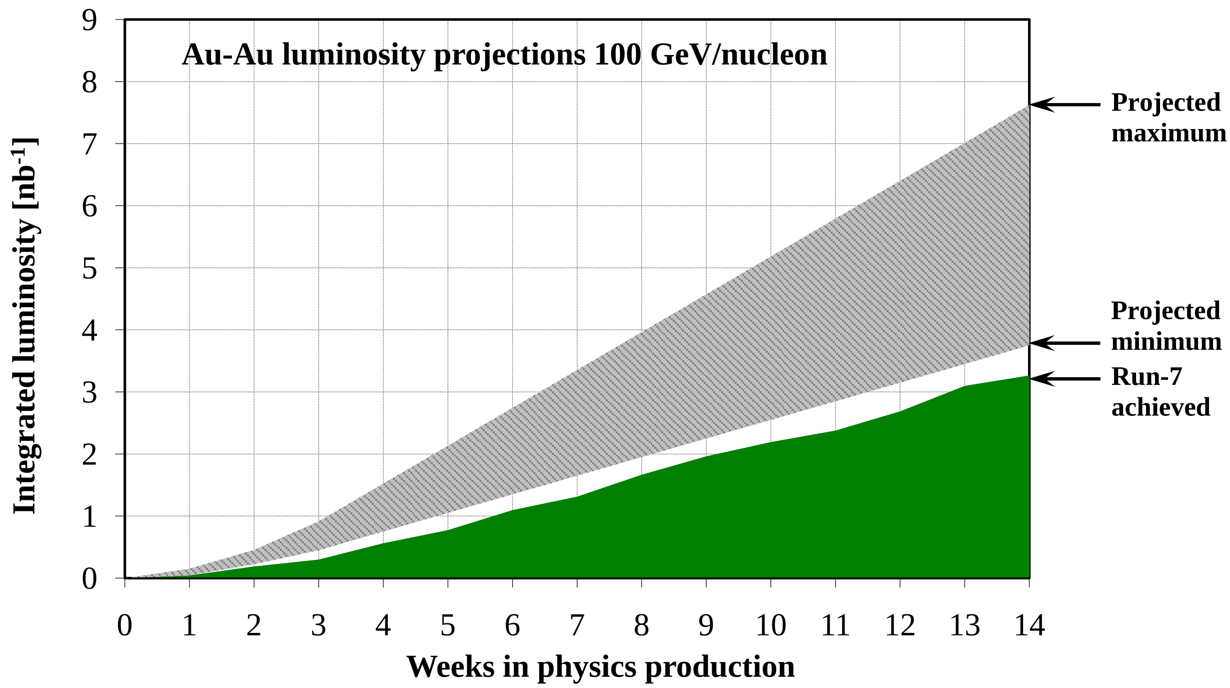

Figure 4: Projected minimum and maximum integrated luminosities for gold-gold collisions at 100 GeV beam energy, assuming linear weekly luminosity ramp-up in 4 weeks.

Part II – 5-Year Projections

A number of improvements are planned over the next five years to increase the RHIC luminosity and polarization. For heavy ions most of the luminosity increases are expected to come from transverse stochastic cooling and a 56 MHz superconducting radio frequency system. Over the next two years we plan to reach all of the RHIC Enhanced Design goals. These consist of

$\mathcal{L}_{store\ avg}$ = 8×10^{26} cm^{-2}s^{-1} for Au-Au at 100 GeV/nucleon (4× design)

$\mathcal{L}_{store\ avg}$ = 6×10^{31} cm^{-2}s^{-1} for p-p at 100 GeV,
$\mathcal{L}_{store\ avg}$ = 1.5×10^{32} cm^{-2}s^{-1} for p-p at 250 GeV (16× design)
both with 70% polarization

60% of calendar time in store (100h/week)

We have exceeded the Au-Au luminosity goal with routine stores of $\mathcal{L}_{store\ avg} = 12\times10^{26}$ cm^{-2}s^{-1}. Performance progress for proton luminosity and polarization is slower than anticipated due to the lack of polarized proton operation in RHIC in FY 2007, and only a short proton operating period in FY 2008. We plan to achieve the proton luminosity and polarization goals at 100 GeV within the next 2 years, assuming a long polarized proton run in each of these years. To reach the proton luminosity and polarization goals at 250 GeV a long run at this energy is required.

Heavy ion luminosity limitations – A number of effects limit the achievable luminosity. The main hardware upgrades to address these limits over the next five years are shown in Table 3. For heavy ions, intrabeam scattering is the most fundamental luminosity limitation, leading to debunching and transverse emittance growth. Debunching can be prevented by longitudinal stochastic cooling, operational in the Yellow ring and installed in the Blue ring, but not yet fully commissioned since heavy ion beams were not available in Blue since the installation. Even with longitudinal stochastic cooling ions migrate to neighboring buckets. This effect can be reduced with a superconducting rf system of harmonic number 180 (the acceleration system has harmonic number 360).

Transverse emittance growth will be addressed with transverse stochastic cooling. For this, hardware for a test will be installed in the Yellow vertical plane for Run-9, and one plane in each ring is expected to become operational in the following two years. If needed a second transverse cooling plane can be installed in both rings later. Transverse emittance growth from intrabeam scattering can also be reduced with lattices that have a reduced dispersion in the arcs. Such a lattice was used for the gold beam in the Run-8.

A significant luminosity increase is expected from a further reduction in β^* from 0.85 m in Run-7 down to 0.5 m. A number of tools were developed to measure and correct lattice errors, which become more pronounced with lower β^* values.

The beam intensity is limited by a fast transverse instability at transition, driven by the machine impedance and electron clouds. The RHIC vacuum upgrade to reduce electron clouds is almost complete, and these instabilities can be addressed with a transverse damper and/or extensive scrubbing. Scrubbing is only efficient at injection, and will require proton bunches. Short proton bunches, which can be prepared in the AGS and injected close to transition, can also have a

larger charge per bunch than gold bunches. With short proton bunches a scrubbing time of a few days is estimated.
We also note that it is planned to begin commissioning of the new Electron Beam Ion Source (EBIS) in FY 2010. EBIS could become ready for operation and may be used for uranium beams in the following years. Table 4 and Figure 5 show the previously delivered and the projected minimum and maximum Au-Au luminosity until FY 2013. For these projections we assume 12 weeks of Au-Au physics operation in each year from FY 2010 to FY 20013. Should there be years without heavy ion operation, the luminosity development will be delayed.

Proton luminosity and polarization limitations – The beam-beam interaction, in conjunction with other nonlinear and modulation effects, is the main luminosity limitation for polarized protons. The head-on beam-beam interaction in proton-proton colliders leads to a tune shift for small amplitude particles (called the beam-beam parameter), and a tune spread of the particles in the transverse distribution. This tune spread is in addition to the tune spread from other sources, including linear and nonlinear chromaticity and magnetic field errors in the interaction region magnets. Only a limited amount of tune spread can be tolerated.
To accommodate the largest possible beam-beam induced tune spread all other source of tune spread should be minimized. A correction of the magnetic field errors in the interaction regions has been developed. A nonlinear chromaticity correction has been implemented in Run-7. In the short Run-8 a new near-integer working point was studied that was expected to accommodate a larger tune spread. This working point can currently not be made operational because of 10 Hz orbit oscillations stemming from mechanical triplet vibrations (see below).
To further increase the beam-beam parameter, electron lenses may be used. These are low-energy electron beams that collide head-on with the proton beam and reduce some the of tune spread caused by the collision with the other proton beam. Electron lenses are currently studied in simulations.
Modifications in the low (LEBT) and medium (MEBT) energy proton beam transport as well as modification to the Booster injection will reduce the transverse emittance in the injectors. In FY 2009 a new 9 MHz rf system will be commissioned. This will allow longitudinal matching at injection, and thereby reduce the bunch length at store, which also reduces the hour glass effect. With the 9 MHz rf system bunches can also be kept longer at injection. With short bunches at injection an increased emittance growth was observed, suspected to be caused by electron clouds.
As for heavy ions we expect that β^* for protons can be reduced down to 0.5 m at 250 GeV beam energy.
The triplet magnets oscillate with eigen-frequencies of around 10 Hz, leading to horizontal beam oscillations at the same frequency. With the previous working points these oscillations have amplitudes as large as 1 mm in the triplet, and about 10% of an rms beam size at the interaction point. With the near-integer working point oscillation amplitudes are amplified by about a factor 5. Modulated offset oscillations at the interaction point lead to enhanced emittance growth due to the beam-beam interaction. A feedback system has been built and tested to remove the offset oscillations at the IP, but has not yet been used in polarized proton operation. Active damping of the triplet cold masses will be tested in Run-9.
The polarization in RHIC stores is limited by the source polarization, and the AGS polarization transmission. A horizontal tune jump system is under development for the AGS to overcome the depolarizing effect of 82 resonances. Acceleration of proton beam to and storage at 100 GeV has not led to a loss in polarization. This still needs to be demonstrated for 250 GeV beam energy.

Further work in the AGS is expected to lead to better polarization transmission for full intensity bunches. In later years, an upgrade of the polarized proton source also can lead to better polarization. Table 5 and Figure 6 show the previously delivered and the projected minimum and maximum p-p luminosity until FY 2013. For these projections we assume 12 weeks of p-p physics operation in each year from FY 2009 to FY 20013. Should there be years without heavy ion operation, the luminosity and polarization development will be delayed.

Time in store – The fraction of the time in stores divided by the total time, reached 58% for d-Au collisions in Run-8 (after 48% in Au-Au operation in Run-7) and 60% for polarized protons in Run-8 (after 58% in Run-6). In Run-8, however, no rotator ramps were done for most of the run. All systems are periodically analyzed to bring up the time in store further. We expect that the time in store can be increased to about 100 hours per week, or 60% of calendar time.

Table 3: Main hardware upgrades for RHIC Au-Au and p-p operation planned for FY 2009 to FY 2013.

	Au-Au	**p-p**
FY 2009	Blue longitudinal stochastic cooling Transverse stochastic cooling test A/C in all service buildings	LEBT/MEBT modification AGS horizontal tune jump system 9 MHz rf system RHIC CNI polarimeter upgrade RHIC spin flipper A/C in all service buildings
FY 2010	EBIS commissioning Transverse stochastic cooling, 1st plane 1st ring	Triplet vibration reduction
FY 2011	Transverse stochastic cooling, 1st plane 2nd ring	Electron lens 1st ring
FY 2012	56 MHz superconducting rf system (Transverse stochastic cooling, 2nd plane 1st ring)	56 MHz superconducting rf system Electron lens 2nd ring Polarized source upgrade
FY 2013	(Transverse stochastic cooling, 2nd plane 2nd ring) RHIC low energy cooling or top-off operation	

Table 4: Delivered RHIC luminosities of the last three Au-Au runs and projected Au-Au luminosities for 100 GeV/nucleon beam energy. Physics runs are assumed to be 12 weeks long in FY 2009 to FY 2013.

Parameter	Unit	FY2002	2004	2007	2010E	2011E	2012E	2013E
No of bunches	…	55	45	103	103	111	111	111
Ions/bunch, initial	10^9	0.6	1.1	1.1	1.1	1.1	1.1	1.2
Avg. beam current/ring	mA	33	49	112	112	121	121	132
β^*	m	1.0	1.0	0.85	0.7	0.6	0.5	0.5
Hour glass factor	…	0.96	0.96	0.95	0.93	0.91	0.88	0.88
Beam-beam param./IP	10^{-3}	0.9	1.7	1.5	1.5	1.5	1.5	1.6
Peak luminosity	10^{26} cm^{-2}s^{-1}	5	15	30	39	48	55	66
Avg./peak luminosity	%	30	33	40	43	57	72	70
Avg. store luminosity	10^{26} cm^{-2}s^{-1}	2	5	12	17	27	40	46
Time in store	%	25	53	48	60	60	60	60
Max. luminosity/week	μb^{-1}	25	160	380	610	980	1,450	1,680
Min. luminosity/week	μb^{-1}				380	380	380	380
Max. luminosity/run	nb^{-1}	0.09	1.37	3.3	6.4	10.3	15.2	17.6
Min. luminosity/run	nb^{-1}				3.3	3.3	3.3	3.3

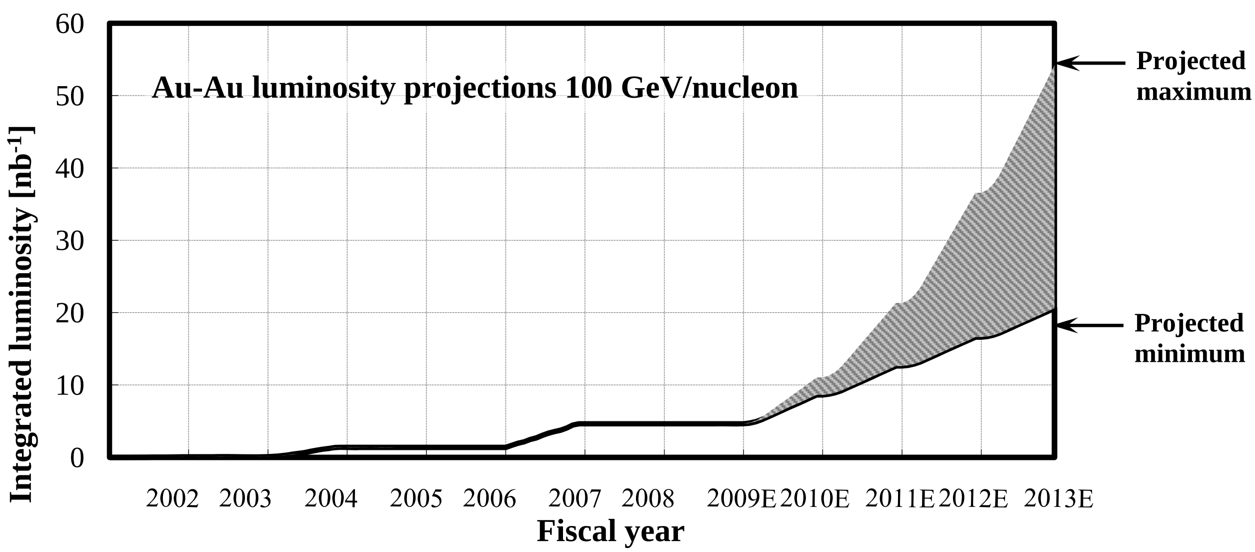

Figure 5: Previously delivered and minimum and maximum projected integrated luminosity for Au-Au collisions at 100 GeV/nucleon beam energy. Physics runs are assumed to be 12 weeks long.

Table 5: Delivered RHIC luminosities and polarization of the last three p-p runs and projected p-p luminosities and polarization for 100 GeV beam energy. Physics runs are assumed to be 10 weeks long in FY 2009 and 12 weeks long in FY 2010 to FY 2013.

Parameter	Unit	FY2005	2006	2008	2009E	2010E	2011E	2012E	2013E
No of bunches	…	106	111	109	111	111	111	111	111
Ions/bunch, initial	10^{11}	0.9	1.4	1.5	1.75	1.9	2.0	2.0	2.0
Avg. beam current/ring	mA	119	187	202	243	266	280	280	280
$\beta*$	m	1.0	1.0	1.0	0.70	0.65	0.60	0.55	0.50
Hour glass factor	…	0.76	0.76	0.81	0.82	0.80	0.81	0.78	0.76
Beam-beam param./IP	10^{-3}	2.7	5.6	5.5	5.9	7.1	7.5	7.5	7.5
Peak luminosity	10^{30} cm^{-2}s^{-1}	10	28	39	72	101	121	129	137
Avg./peak luminosity	%	60	64	59	60	60	60	60	60
Avg. store luminosity	10^{30} cm^{-2}s^{-1}	6	18	23	43	60	73	77	82
Time in store	%	56	46	60	60	60	60	60	60
Max. luminosity/week	pb^{-1}	1.9	6.5	7.5	16	22	26	28	30
Min. luminosity/week	pb^{-1}				7.5	7.5	7.5	7.5	7.5
Max. luminosity/run	pb^{-1}	13	46	19	130	210	260	270	290
Min. luminosity/run	pb^{-1}				64	64	64	64	64
AGS extraction, $\mathcal{P}_{max}$	%	55	65	55	65	70	75	80	80
AGS extraction, $\mathcal{P}_{min}$	%				55	55	55	55	55
RHIC store avg., $\mathcal{P}_{max}$	%	47	58	45	60	65	70	70	70
RHIC store avg., $\mathcal{P}_{min}$	%				50	50	50	50	50
Max. $\mathcal{L}\mathcal{P}^4$/week	pb^{-1}	0.09	0.74	0.31	2.0	3.9	6.3	6.7	7.2
Min. $\mathcal{L}\mathcal{P}^4$/week	pb^{-1}				0.47	0.47	0.47	0.47	0.47

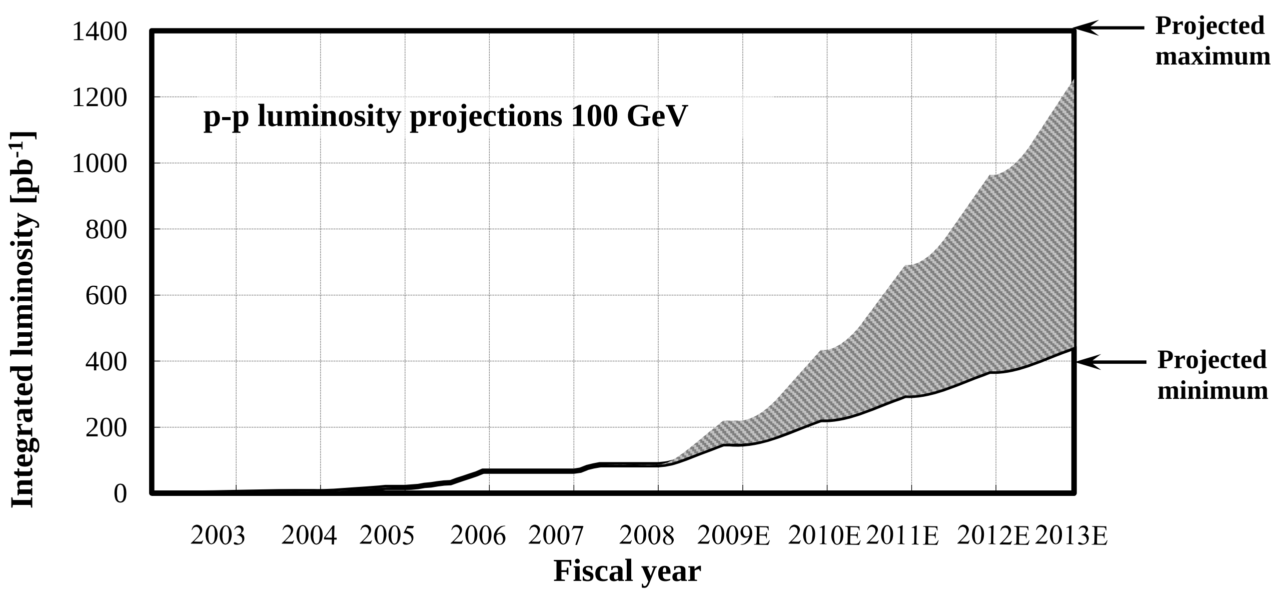

Figure 6: Previously delivered and minimum and maximum projected integrated luminosity for p-p collisions at 100 GeV beam energy. Physics runs are assumed to be 10 weeks long in FY 2009 and 12 weeks long thereafter.