RHIC Collider Projections (FY2007 – FY2008)

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This note discusses in Part I possible modes for the RHIC Run-7 (FY2007) operating period including constraints from cryogenic cool-down, machine set-up and beam commissioning. In Part II a 2-year projection is given for gold-gold and polarized proton collisions. This latest update is based on the experience gained during the Run-6 polarized proton operation.

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-7 Projections

Cryogenic operation – After the shutdown the two RHIC rings will be at liquid nitrogen temperature. 1 ½ week will be required to cool them down to 4 Kelvin. 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 running modes for Run-7 are not decided yet. Under discussion are ion operation with Au-Au or d-Au, primarily at 100 GeV/n, and polarized proton operation also primarily at 100 GeV. We propose to run with ions first to allow more time to prepare for improvements in the proton polarization and luminosity. To reach the luminosities projected in the Research Plan for Spin Physics at RHIC[1] it is necessary to have a long polarized proton run in every year. We also propose to run with polarized protons for 1 week at 250 GeV to test the combined polarization and luminosity performance at this energy.

When starting the run we plan for 1 ½ week of machine set-up with the goal of establishing collisions, and a 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 period for polarized protons can be ½ to 1 week longer to allow for the implementation of new lattice solutions, and possibly 2 days of beam scrubbing. 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.

[1] C. Aidala, M. Bai, L. Bland, A. Bravar, G. Bunce, M. Chiu, A. Deshpande, D. Fields, W. Fischer, Y. Fukao, Y. Goto, M. Grosse Perdekamp, W. Guryn, M. Hirai, D. Kawall, E. Kistenev, S. Kretzer, A. Ogawa, K. Okada, J. Qiu, G. Rakness, V. Rykov, N. Saito, H. Spinka, M. Stratmann, K. Sudoh, B. Surrow, A. Taketani, M. Tannenbaum, M. Togawa, L. Trueman, F. Videbaek, S. Vigdor, W. Vogelsang, Y. Watanabe, "Research Plan for Spin Physics at RHIC", Formal Report BNL-73798-2005 (2005).

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. 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 2-3 days, assuming that the energy is lowered and no unusual machine downtime is encountered. A change of the polarization orientation at any or all of the experiments requires 1-2 days.

For example, 30 weeks of RHIC refrigerator operation in FY2007 could be scheduled in the following way:

Cool-down from 80K to 4K	1 ½ weeks
Set-up mode 1 (ions)	1 ½ weeks
Ramp-up mode 1	1 week
Data taking mode 1 with further ramp-up	11 weeks
Set-up mode 2 (polarized protons)	2 weeks
Ramp-up mode 2	1 week
Data taking mode 2 with further ramp-up	11 ½ weeks
Warm-up	½ week

Past performance – Table 1 shows the luminosities achieved for Au-Au (Run-4), Cu-Cu (Run-5), d-Au (Run-3), and polarized protons (Run-6). The time in store was 53% and 56% of the total time for Au-Au (Run-4) and p-p (Run-5) respectively. The time in store for polarized proton operation in Run-6 reached only 46% (as of 05/26/06). Note that the total time includes all interruptions such as 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-4), Cu-Cu (Run-5), d-Au (Run-3), and p-p (Run-6). All numbers are given for operation at a beam energy of 100 GeV/n.

Mode	# 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	45	1.1	1	15-40	15×10^{26}	5×10^{26}	160 μb^{-1}
Cu-Cu	37	4.5	0.9	15-30	2×10^{28}	0.8×10^{28}	2.4 nb^{-1}
d-Au	55	110d / 0.7Au	2	15	7×10^{28}	2×10^{28}	4.5 nb^{-1}
p↑-p↑ *	111	135	1	18-25	30×10^{30}	20×10^{30}	7.0 pb^{-1}

* Blue and Yellow ring average polarization of 65%, in RHIC stores at 100GeV. Both STAR and PHENIX elected to have 9 non-colliding bunches. If either experiment elects to have all 111 bunches colliding in the experiment, the luminosity will be increased by 9%.

Luminosity projections – Table 2 lists the expected maximum peak and average luminosities for possible modes in Run-7 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. For all modes it was assumed that the beam energy is 100 GeV/n. The average store luminosity is derived from the predicted beam parameters, and calendar time in store. The expected diamond rms length for ions is 20 cm due to the availability of the full voltage from the 200 MHz storage cavities. The minimum luminosity projections are based on previous run performances.

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 a 9% reduction in the number of collisions.

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/n.

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	111	1.1	0.9	15-40	36×10^{26}	8×10^{26}	290 μb^{-1}
Cu-Cu	111	6	0.9	15-30	12×10^{28}	4×10^{28}	14 nb^{-1}
Si-Si	111	12.5	0.9	15-30	50×10^{28}	17×10^{28}	60 nb^{-1}
d-Au	111	140d/1.1Au	1.5	15-30	30×10^{28}	7.5×10^{28}	25 nb^{-1}
p↑-p↑ *	111	175	1.0	20-25	60×10^{30}	40×10^{30}	14 pb^{-1}

*We expect that an average store polarization of 65% can be reached. If both STAR and PHENIX elect again to have 9 non-colliding bunches, the luminosity is reduced by 9% compared to the numbers stated in the table.

Operation at energies other than 100 GeV/n – It is preferable to lower the energy when the collision energy is changed in any given mode. This can be done in about 2-3 days. For Au-Au operation at 100 GeV/n with $\beta^* = 0.9$ m the limiting aperture is in the triplet. For energies less than 100 GeV/n the unnormalized 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 3m. The operation below the current injection energy will be evaluated in a daylong test shortly.

For p-p operation the luminosity is expected to increase linearly with energies above 100 GeV, and decrease quadratically with energies below 100 GeV. Initial operation at 250 GeV requires about 5 weeks of commissioning time for both luminosity and polarization development.

Following are specific comments on gold-gold, and deuteron-gold, and polarized proton running at the energies considered for Run-7.

Gold-Gold at 100 GeV/n – With the completion of major vacuum upgrades in both the warm and cold sections we expect that the machine can be operated with 111 bunches. Compared to Run-4, a reduction in β*, and an extra rf bunch merge in the Booster are considered to increase the luminosity further. The projected minimum and maximum luminosities are shown in Figure 2, where it is assumed that the peak performance is reached after 4 weeks of linear ramp-up, starting with 25% of the final value.

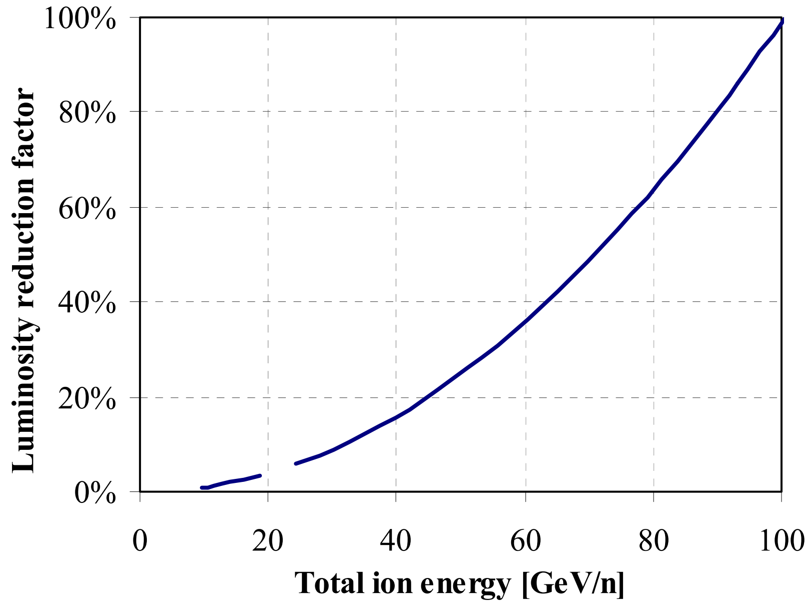

Figure 1: Luminosity scaling for Au-Au operation at energies below 100 GeV/n.

Deuteron-Gold at 100 GeV/n – d –Au collisions can be set-up with the deuteron beam in either the Blue or Yellow ring. The present preferred option is with deuterons in the Blue ring, since RHIC has operated in this configuration in Run-3 and stochastic cooling installed in the Yellow ring can benefit the gold beam. With asymmetric species β^* cannot be made as small as with symmetric species. After the experience in Run-3 with β^* = 2m, we expect that β^* = 1.5m is possible. A bunch merging technique in the Booster has been used for deuterons, and is considered for gold ions. Both electrostatic Tandem accelerators are needed for continuous operation, which could increase downtime in case of a failure since no backup is available. The switching time between species in the injector chain was approximately 5min in Run-3, while it is only seconds for symmetric species. Due to the need to have both Tandems available for all injections, and the longer switching time, we expect that the calendar time in store is approximately 5% (or 8h/week) less than for asymmetric species. The projected minimum and maximum luminosities are shown in Figure 3, where it is assumed that the peak performance is reached after 6 weeks of linear ramp-up, starting with 25% of the final value.

Polarized protons at 100 GeV – We expect that the peak polarization values in Run-6 (65% store average) can be reliably demonstrated in Run-7. We expect at least 40% average polarization in store after 2 ½ weeks of set-up and ramp-up. This should be improved to the values demonstrated in Run-6 (see Table 1) within a week. We aim at doubling the luminosity through an increase in the bunch intensity. This requires a better understanding of the nonlinearities in the machine. Under investigation are a new working point for one of the beams, the correction of the lowest order limiting resonance, and the correction of the nonlinear chromaticity. Figure 4 shows the projected minimum and maximum luminosity for 100 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.

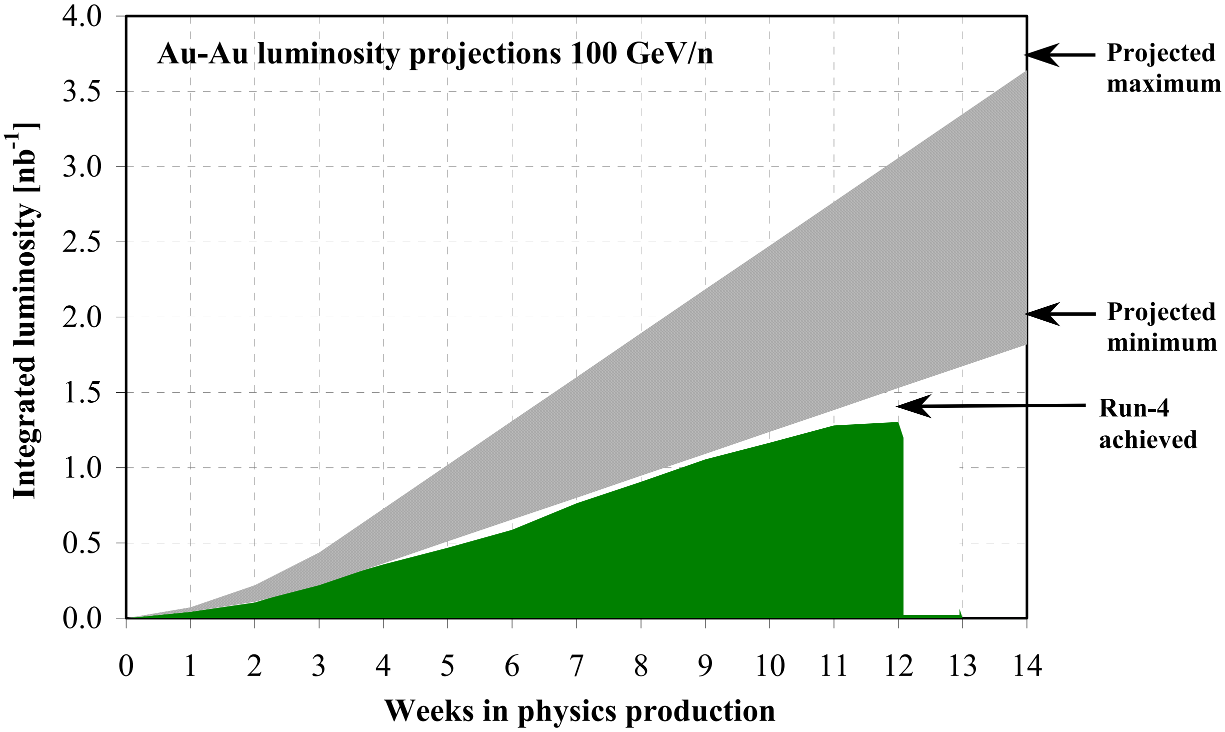

Figure 2: Projected minimum and maximum integrated luminosities for gold-gold collisions at 100 GeV beam energy, assuming linear weekly luminosity ramp-up in 4 weeks.

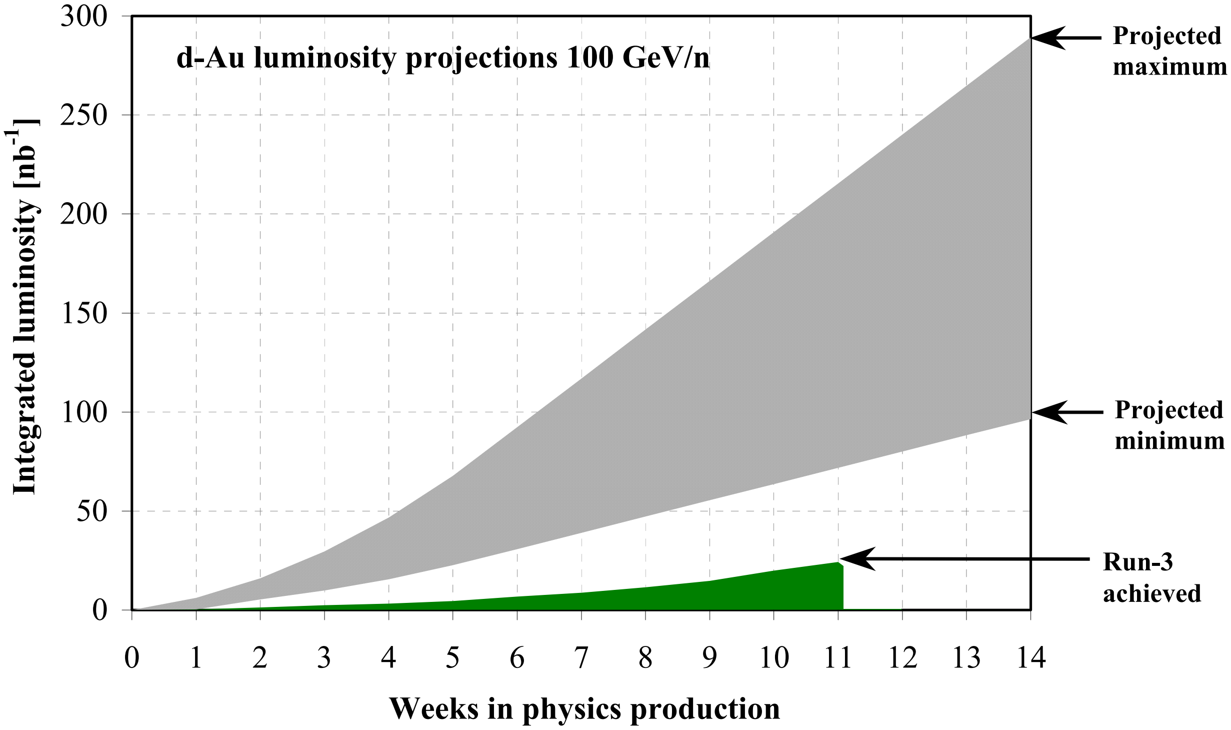

Figure 3: Projected minimum and maximum integrated luminosities for deuteron-gold collisions at 100 GeV beam energy, assuming linear weekly luminosity ramp-up in 6 weeks.

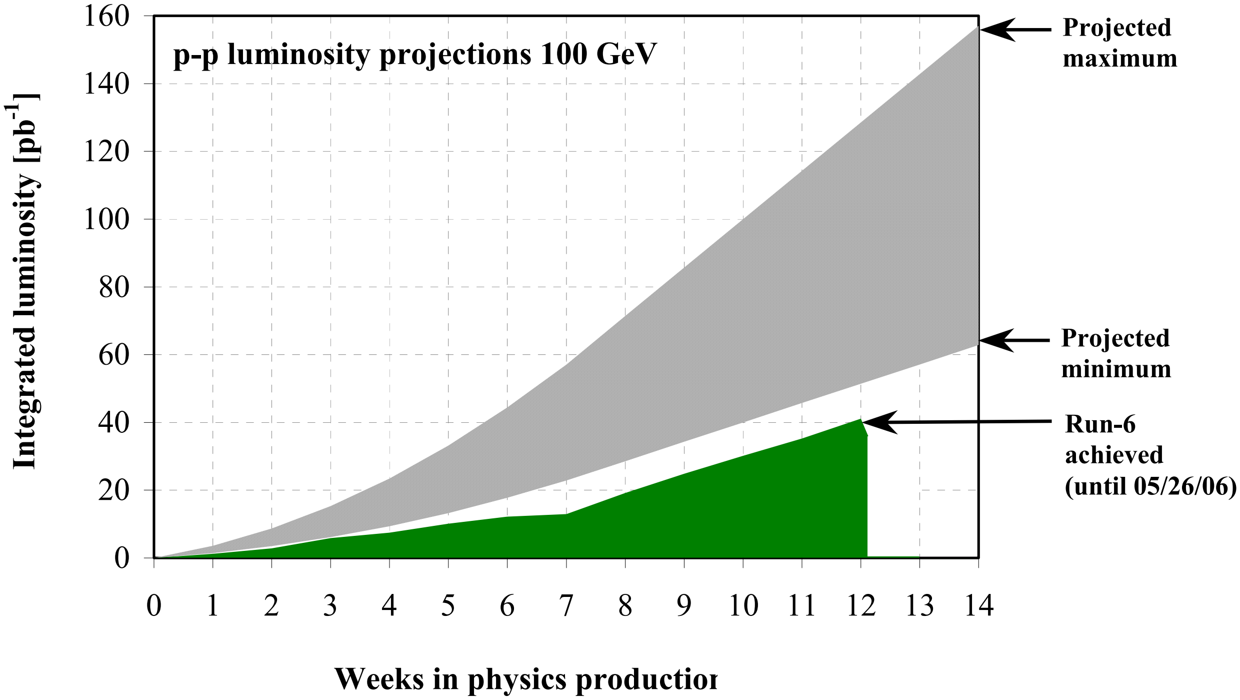

Figure 4: Projected minimum and maximum integrated luminosities for polarized proton collisions at 100 GeV beam energy, assuming linear weekly luminosity ramp-up in 8 weeks. 65% polarization is then expected in RHIC stores.

Polarized protons at 250 GeV – About one week of work is requested to develop the combined polarization and luminosity performance at this energy. A lattice with $\beta^* = 1$m can be tested with high intensity beams to evaluate both the polarization under these conditions, and intensity limits that can arise from the stored beam energy. A limited number of stores at the end of the development period may be available for physics.

Part II – 2-Year Projections

In both Au-Au and p-p operation RHIC exceeds the Design Luminosity. The 2-year plan laid out below aims at reaching the RHIC Enhanced Luminosity consisting of

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

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

Below we present 2-year luminosity projections for gold-gold collisions and polarized proton collisions. Should a major repair be necessary during a run, leading to weeks of downtime, the projections do not hold. Projections over several years are not very reliable and should only be seen as guidance for the average annual machine improvements needed to reach the enhanced luminosity goals.
We assume for both modes a set-up and ramp-up time of 2 ½ weeks and a luminosity production period of 12 weeks in each fiscal year from 2006 to 2008. Note that running 2 ½ + 12 weeks of Au-Au and p-p in a single year requires 31 weeks of cryo-operation.
The weekly luminosity starts at 25% of the final value, and increases linearly in time to the final value in 4 weeks for ions, and 8 weeks for polarized protons. During the remaining weeks the weekly luminosity is assumed to be constant at the values listed in Table 4 and Table 5. We take for the final minimum weekly luminosity a value that has been demonstrated in the past. The yearly evolution of the final maximum weekly luminosity is based on the assumption that the improvements outlined below are successful and that a minimum of 12 weeks of physics running in both ion and polarized proton operation is scheduled every year to allow for commissioning of the improvements and development of the machine performance. However, the most likely luminosity evolution is in between these two boundaries. Future updates will change these projections, in particular the minimum projections for polarized proton operation.

Luminosity limitations – A number of effects limit the achievable luminosity. High intensity beams lead to dynamic vacuum pressure rises, caused by electron clouds. This problem is cured through the installation of NEG coated beam pipes in the warm sections, and by pre-pumping the cold sections to a lower pressure before cool-down starts. We expect the majority of the vacuum upgrades to be finished for Run-7. Intrabeam scattering increases the transverse emittance during stores and causes debunching. A stochastic cooling system is being installed, and reduction of the debunching rate may be possible for medium or heavy ions towards the end of the Run-7. Ultimately, electron cooling is required, beyond the 2-year outlook of this note. The beam-beam interaction, in conjunction with other nonlinear and modulation effects, limits the beam and luminosity lifetime especially for protons. Table 3 lists the main projects to address these and other issues. Some of the listed projects may shift in time or extend further into the future. In addition, new projects will appear, as we better understand the machine limitations.

Time in store – The fraction of the time in stores divided by the total time, reached 53% for gold-gold collisions and 56% for polarized proton in Run-5. It fell back to 46% in Run-6 (as of 05/26/06). This can still be improved in a number of areas (see Table 3). Time can be gained through a more reliable access system, few failures in the LINAC, faster machine set-up, the reduction of magnet quenches, a careful scheduling of machine development time, an increase of automation in operation, and the reduction of scheduled maintenance. We project that the time in store can be increased to about 100 hours per week, or 60% of calendar time.

2-year projections – In Table 4 luminosities are estimated for gold-gold collisions, assuming 12 weeks of luminosity production. For the maximum luminosities quoted in this table, the projects listed in Table 3 need to be completed successfully. Figure 5 shows the total integrated luminosities for the period under consideration.
In Table 5 and Figure 6 the projection for polarized proton collisions are displayed. Table 5 also shows the expected evolution of proton beam polarization for operation at 100 GeV. The main improvements come from increased polarization in the AGS due the super-conducting strong partial snake installed in 2005. The benefits of a second super-conducting strong partial snake for the AGS are being investigated. The Enhance Luminosity goals at 250GeV can only be reached with a long operating period at this energy.

Table 3: Main improvement projects for the RHIC injectors, luminosity, polarization and background, and time in store.

For FY2007	For FY2008
RHIC injectors	
AGS MMPS transformer	AGS low level rf upgrade
AGS ion pump controllers	
LINAC reliability	
RHIC luminosity, polarization and background	
10Hz IR orbit feedback	Low level rf upgrade
Stochastic cooling	Stochastic cooling
NEG pipes (100 m)	Transverse damper
Gradient error correction	Rf storage cavity windows
New working point for Yellow	Rf system with h=120
2/3 resonance compensation	
Nonlinear chromaticity correction	
Partial horizontal and vertical alignment	
RHIC time in store	
QLI reduction	QLI reduction
Injection set-up	
Orbit correction	
Ramp feedbacks (Q, ΔQ_{min}, ξ)	Ramp feedbacks (Q, ΔQ_{min}, ξ)
Beginning-of-store automation	
PASS system reliability	
Rf accelerating cavity ferrite tuner	
Service building environment	Service building environment

Table 4: Projected RHIC Au-Au luminosities.

Fiscal year		2001A	2002A	2004A	2007E	2008E
No of bunches	…	55	55	45	111	111
Ions/bunch, initial	10^9	0.3	0.6	1.1	1.1	1.1
Average beam current/ring	mA	16	33	49	117	121
β^*	m	2	1.0	1.0	0.9	0.9
Peak luminosity	10^{26} cm^{-2}s^{-1}	0.3	5	15	36	40
Average store luminosity	10^{26} cm^{-2}s^{-1}	0.2	1.5	5.0	8.0	8.0
Time in store	%		25	53	60	60
Maximum luminosity/week	μb^{-1}	3	25	160	291	289
Minimum luminosity/week	μb^{-1}				160	160
Maximum integrated luminosity	μb^{-1}	7	89	1370	3060	3040
Minimum integrated luminosity	μb^{-1}				1680	1680

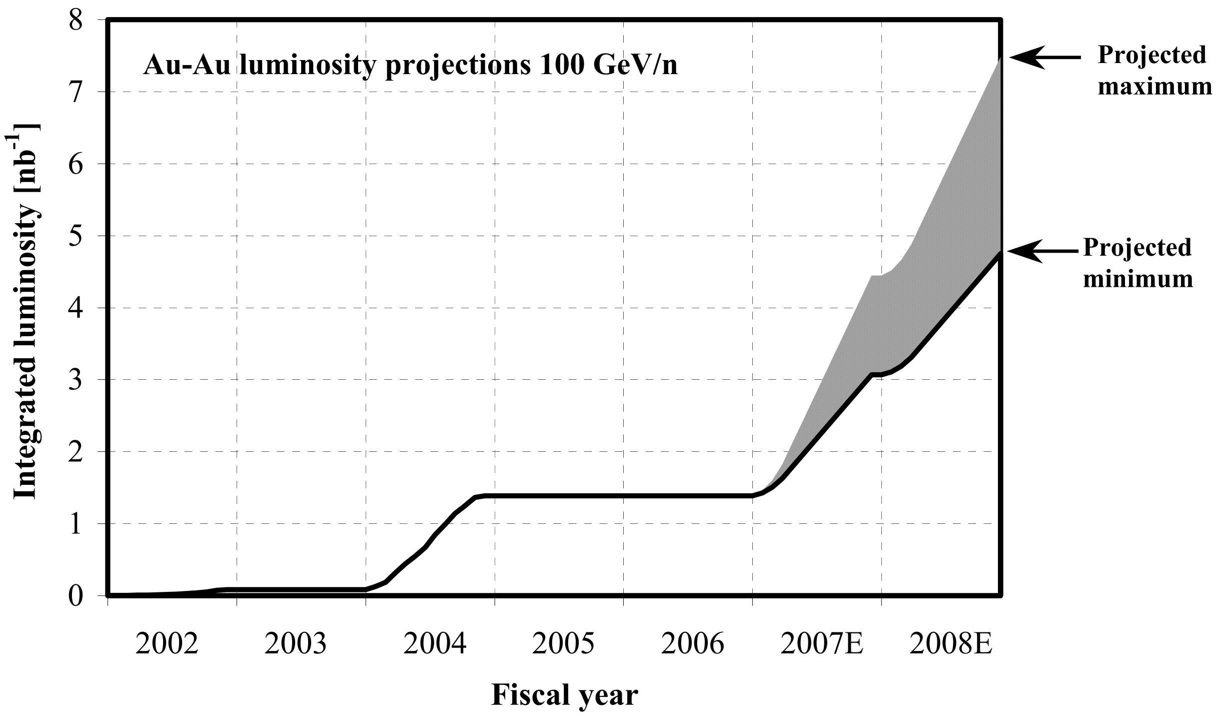

Figure 5: Minimum and maximum projected integrated luminosity for Au-Au collisions.

Table 5: Projected RHIC p-p luminosities and polarization.

Fiscal year		2002A	2003A	2004A	2005A	2006E	2007E	2008E
No of bunches	…	55	55	56	106	111	111	111
Ions/bunch, initial	10^{11}	0.7	0.7	0.7	0.9	1.4	1.8	2.0
Average beam current/ring	mA	48	48	52	119	187	243	280
β^*	m	3	1	1	1	1	1	0.9
Peak luminosity	10^{30} cm^{-2}s^{-1}	2	6	6	10	30	61	90
Average store luminosity	10^{30} cm^{-2}s^{-1}	1.5	3	4	6	20	41	60
Time in store	%	30	41	41	56	46	58	60
Maximum luminosity/week	pb^{-1}	0.2	0.6	0.9	1.9	7.0	14.3	21.9
Minimum luminosity/week	pb^{-1}						7.0	7.0
Maximum integrated luminosity	pb^{-1}	0.5	1.6	3	13	41	123	180
Minimum integrated luminosity	pb^{-1}						63	63
AGS polarization at extraction	%	35	45	50	55	65	70	75
RHIC store polarization, average	%	15	35	46	47	65	65	70
Maximum LP^4/week	nb^{-1}	0	9	40	90	945	2550	5250
Minimum LP^4/week	nb^{-1}						1250	1250

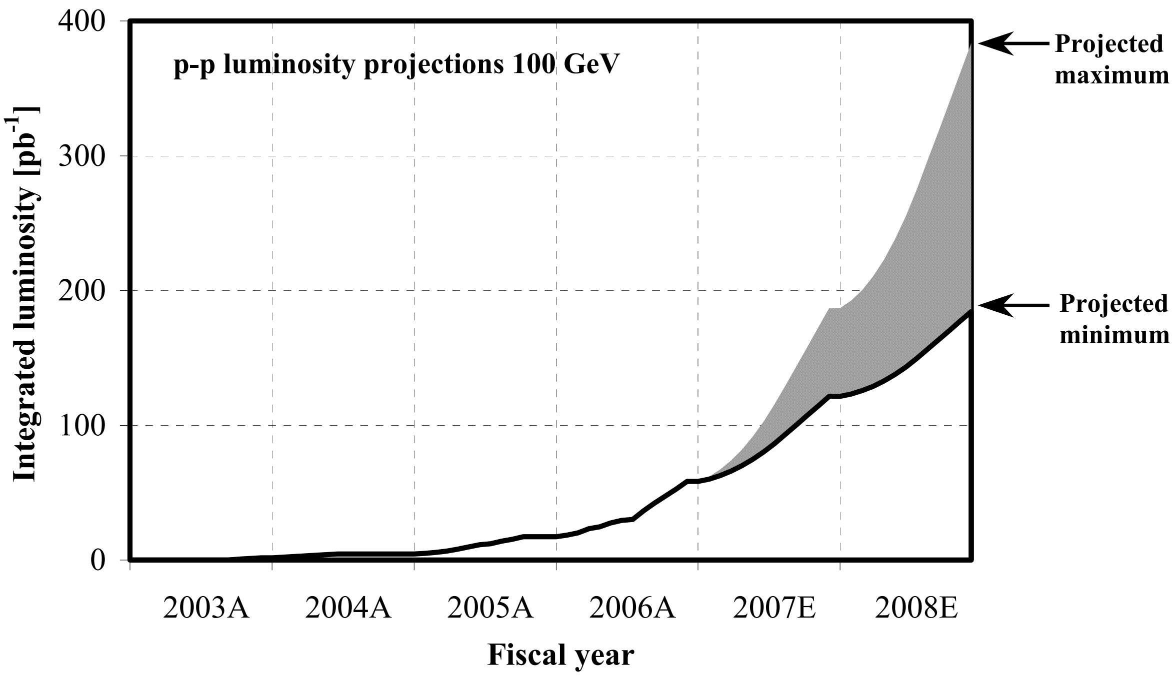

Figure 6: Minimum and maximum projected integrated luminosity for p-p collisions.