RHIC Collider Projections (FY2006 – FY2008)

Thomas Roser, Wolfram Fischer
Angelika Drees, Haixin Huang, Vadim Ptitsyn

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This note discusses in Part I possible operating modes for the RHIC Run-6 (FY2006) operating period including constraints from cryogenic cool-down, machine set-up and beam commissioning. In Part II a 3-year projection is given for gold-gold and polarized proton collisions, assuming that these modes are used in every run. This latest update is based on the experience gained during the Run-5 copper-copper and 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-6 Projections

Cryogenic operation – After the shutdown the two RHIC rings will be at room temperature. They will be first brought to liquid nitrogen temperature, in about 30 days. Then, 1 ½ week will be required to cool 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 – Operation in Run-6 will be with polarized protons only, at a number of energies and polarization orientations. Energies considered for physics are 100 GeV, 31.2 GeV, and 11 GeV. In addition acceleration to 250 GeV is planned for machine development in order to maintain the polarization up to this energy for physics runs in future years. 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. 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. 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, 20 weeks of RHIC refrigerator operation in FY2006 could be scheduled in the following way:

Cool-down from 80K to 4K	1 ½ weeks
Set-up mode 1	1 ½ weeks
Ramp-up mode 1	1 weeks
Data taking mode 1 with further ramp-up	15 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-5). The time in store was 53% and 56% of the total time for Au-Au (Run-4) and p-p (Run-5) respectively. Note that the total time includes all interruptions such as maintenance, machine development, and accelerator physics studies. 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-5). All numbers are given for operation at a beam energy of 100 GeV/n.

Mode	# bunches	Ions/bunch [10^9]	β* [m]	Emittance [μm]	L_{peak} [$cm^{-2}s^{-1}$]	$L_{store\ avg}$ [$cm^{-2}s^{-1}$]	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↑ *	106	90	1	30-35	10×10^{30}	7×10^{30}	1.9 pb^{-1}

* Blue ring average polarization of 49%, Yellow ring average polarization of 44% in RHIC stores at 100GeV.

Luminosity projections – Table 2 lists the expected maximum peak and average luminosities for possible modes in Run-6 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. The weekly integrated luminosity is then obtained using the ratio of the time in store to the total calendar time achieved in Run-4 (53%) and Run-5 (56%). 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.

Note that the quoted ion luminosities are for $\beta^* = 0.9$ m (with the exception of d-Au). This is *only* available at PHENIX and STAR. BRAHMS is limited to $\beta^* \geq 2.5$ m due to the lack of nonlinear IR correctors. Due to the required abort gaps in both beams, the maximum number of collisions can only be provided for two opposing IPs. The other IPs will have a 10% 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	# bunches	Ions/bunch [10^9]	β^* [m]	Emittance [μm]	L_{peak} [$cm^{-2}s^{-1}$]	$L_{store\ avg}$ [$cm^{-2}s^{-1}$]	L_{week}
Au-Au	78	1.1	0.9	15-40	28×10^{26}	7×10^{26}	230 μb^{-1}
Cu-Cu	68	5	0.9	15-30	5×10^{28}	1.5×10^{28}	5 nb^{-1}
Si-Si	68	10	0.9	15-30	20×10^{28}	7×10^{28}	22 nb^{-1}
d-Au	68	140d/1.1Au	1.5	15-35	19×10^{28}	5×10^{28}	15 nb^{-1}
p↑-p↑ *	111	130	1.0	20-30	37×10^{30}	25×10^{30}	9 pb^{-1}

*The Polarized proton mode assumes that the AGS cold snake is operational and 60% polarization can be reached in RHIC stores. 3 experiments can be served with ion collisions, but only 2 with the highest polarized proton luminosities.

Energy scans – 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 more comments on luminosity scaling and restrictions for certain energies, see below.

Following are specific comments on the proton running at the energies considered for Run-6.

Polarized protons at 100 GeV – We expect that the initial performance of the AGS with the cold snake is not worse than without it (i.e. bunches of up to 10^{11} protons with 50% polarization can be extracted), and that polarization and bunch intensity can be increased gradually to 65% and 1.5×10^{11} protons respectively. We expect at least 30% average polarization in store after 2 weeks of set-up, and 1 week of ramp-up. This should be improved to the values demonstrated in Run-5 (see Table 1) within a week. Figure 1 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.

Polarized protons at 31.2 GeV – It is planned to operate for a few weeks at this lower energy with 3 experiments. We give luminosity estimates per experiment for this case in Figure 2 below. In all other places in this document luminosity projections for polarized protons are for 2 experiments only. We anticipate operation with β^* = 3.5 m at BRAHMS, PHENIX, and STAR. The luminosity scaling given in Part II is not valid here, since the number of experiment changes. The luminosity is beam-beam limited, and every experiment contributes to the beam-beam induced tune spread equally, independent of beam energy and β^*. We expect that vertical spin polarization can be provided with values comparable to those at 100 GeV. The use of spin rotators at this energy is under investigation. The spin rotators may not be usable because of the large orbit excursions they create at the lower energy.

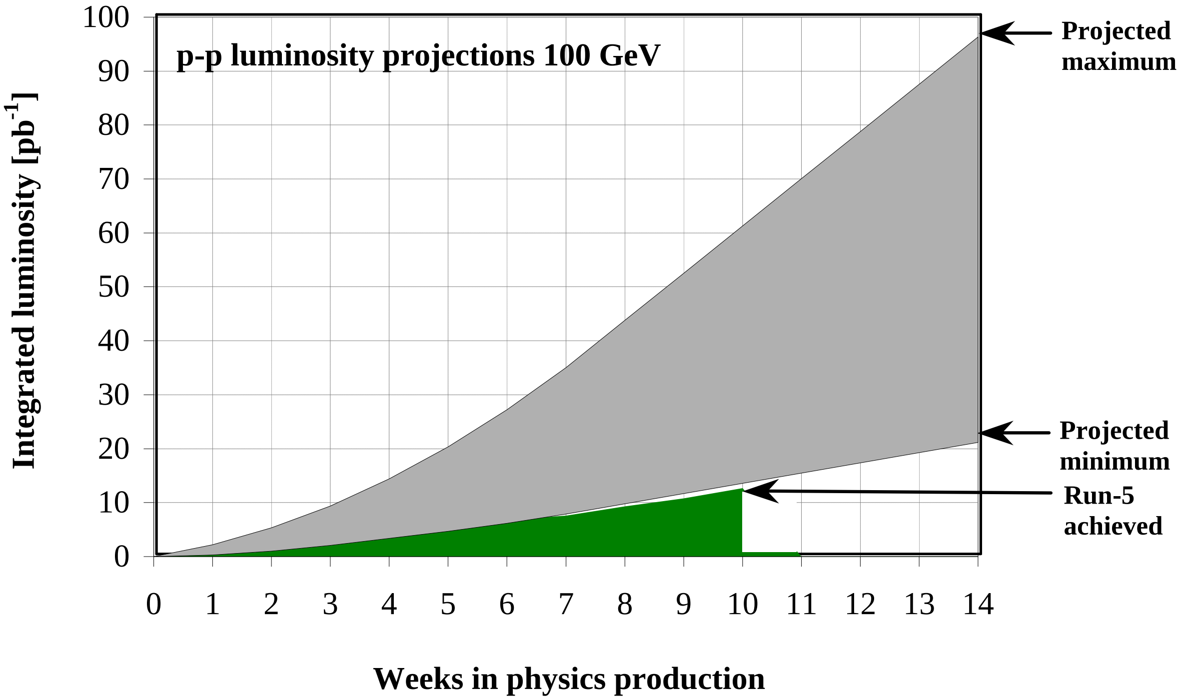

Figure 1: Projected minimum and maximum integrated luminosities for polarized proton collisions at 100 GeV beam energy, assuming linear weekly luminosity ramp-up in 8 weeks. The maximum luminosity assumes improved performance from the AGS cold snake. 60% polarization is then expected in RHIC stores.

Polarized protons at 250 GeV – One week of work is planned to develop the polarization at this energy. During this week the sensitivity of the final polarization with respect to orbit errors, and the effect of the vertical realignment will be evaluated. A limited number of stores at the end of the development period may be available for physics.

Protons at 11 GeV – PHENIX also asked for operation at this energy. This energy is approximately half of the current injection energy. Luminosity estimates for this energy are very difficult since the nonlinear magnetic field errors of the superconducting magnets are not known. These errors are expected to be the main performance limitation. Delivered luminosities are likely in the 10-40 nb^{-1}/week range. At least one day of set-up is required. Running at this energy is also useful to evaluate the collider performance for future heavy ion operation at energies below the current injection energy.

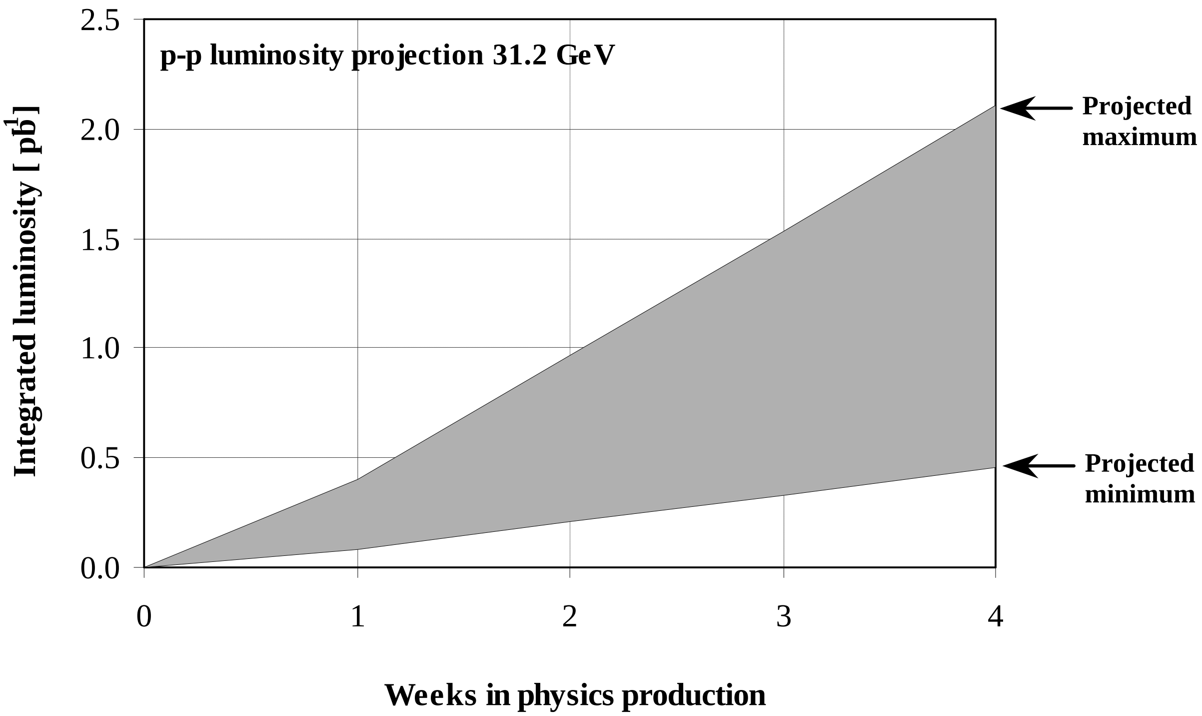

Figure 2: Projected minimum and maximum integrated luminosities for polarized proton collisions at 31.2 GeV.

Part II – 3-Year Projections

In both Au-Au and p-p operation RHIC exceeds the Design Luminosity. The 3-year plan laid out below aims at reaching the RHIC Enhanced Luminosity consisting of

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

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

Below we present 3-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 time of 3 weeks and a luminosity production period of 12 weeks in each fiscal year from 2006 to 2008. Note that running 3+12 weeks of Au-Au and p-p in a single year requires 33 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 with the exception of p-p in 2006. For 2006 we assume 8 weeks to allow for a gradual performance improvement of the AGS cold snake. 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 reliably demonstrated in the past. The yearly evolution of the final maximum weekly luminosity is based on the assumption that all the improvements outlined below are successful and that a minimum of 12 weeks of physics running in the particular mode 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. Should one of the modes not be run in any particular year, the performance development will be delayed.

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 full stochastic cooling system will be installed during Run-6 in the Yellow ring, and reduction of the debunching rate in that ring may be possible for medium or heavy ions towards the end of the run. Ultimately, electron cooling is required, beyond the 3-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. Furthermore, in proton operation only 2 collisions per turn can be accommodated with high bunch intensities. Instabilities, especially around transition will require a transverse damper in the future. 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.

Operation at energies other than 100 GeV/n – 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 3. For BRAHMS the scaling is slightly modified, since it is favorable to cross the transition energy, corresponding to the relativistic $\gamma = 23$, with $\beta^* = 5$m in all IPs, and not to un-squeeze β^* after transition crossing. 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.
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.

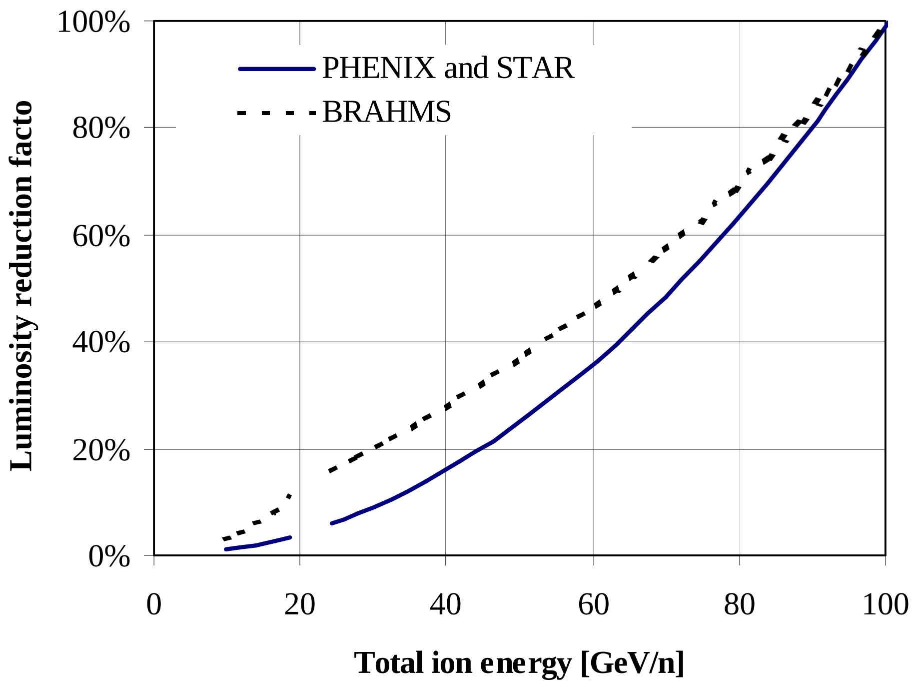

Figure 3: Luminosity scaling for Au-Au operation at energies below 100 GeV/n.

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. This can still be improved in a number of areas (see Table 3). Time can be gained through faster machine set-up, the reduction of magnet quenches, a careful scheduling of machine development time, an increase of automation in operation, improved reliability of some of the power supplies, and the reduction of scheduled maintenance. In p-p operation, time can also be gained through the acceleration of multiple bunches in each AGS cycle. We project that the time in store can be increased to about 100 hours per week, or 60% of calendar time.

3-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 4 shows the total integrated luminosities for the period under consideration.
In Table 5 and Figure 5 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.

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

For FY2006	For FY2007	For FY2008
	RHIC injectors	
LINAC cooling tower	AGS MMPS transformer	AGS low level rf upgrade
	AGS ion pump controllers	
	RHIC luminosity, polarization and background	
Shielding STAR	Sector 3 triplet 24h movement	Low level rf upgrade
Stochastic cooling test	Stochastic cooling	Transverse damper
NEG pipes (150 m)	NEG pipes (100 m)	
CNI polarimeter vacuum and targets	CNI polarimeter upgrade	
10 Hz IR orbit feedback	Rf storage cavity windows	
Vacuum pumps in arcs	Nonlinear chromaticity correction	
Complete vertical alignment		
	RHIC time in store	
QLI reduction	QLI reduction	
BPM system upgrade	BPM system upgrade	
Orbit correction	Orbit correction	
Injection set-up	Injection set-up	
IR PS reliability	Service building environment	Service building environment
Gradient error correction	Gradient error correction	
Decoupling on ramp	Rf accelerating cavity ferrite tuner	
Beginning-of-store automation		

Table 4: Projected RHIC Au-Au luminosities.

Fiscal year		2002A	2004A	2006E	2007E	2008E
No of bunches	…	55	45	78	90	111
Ions/bunch, initial	10^9	0.6	1.1	1.1	1.1	1.1
Average beam current/ring	mA	33	49	85	98	121
β*	m	1	1	0.9	0.9	0.9
Peak luminosity	10^{26} cm^{-2}s^{-1}	5	15	28	32	40
Average store luminosity	10^{26} cm^{-2}s^{-1}	1.5	4.0	7.0	8.1	9.9
Time in store	%	25	53	56	58	60
Maximum luminosity/week	μb^{-1}	25	160	236	282	360
Minimum luminosity/week	μb^{-1}			160	160	160
Maximum integrated luminosity	μb^{-1}	89	1370	2480	2970	3780
Minimum integrated luminosity	μb^{-1}			1680	1680	1680

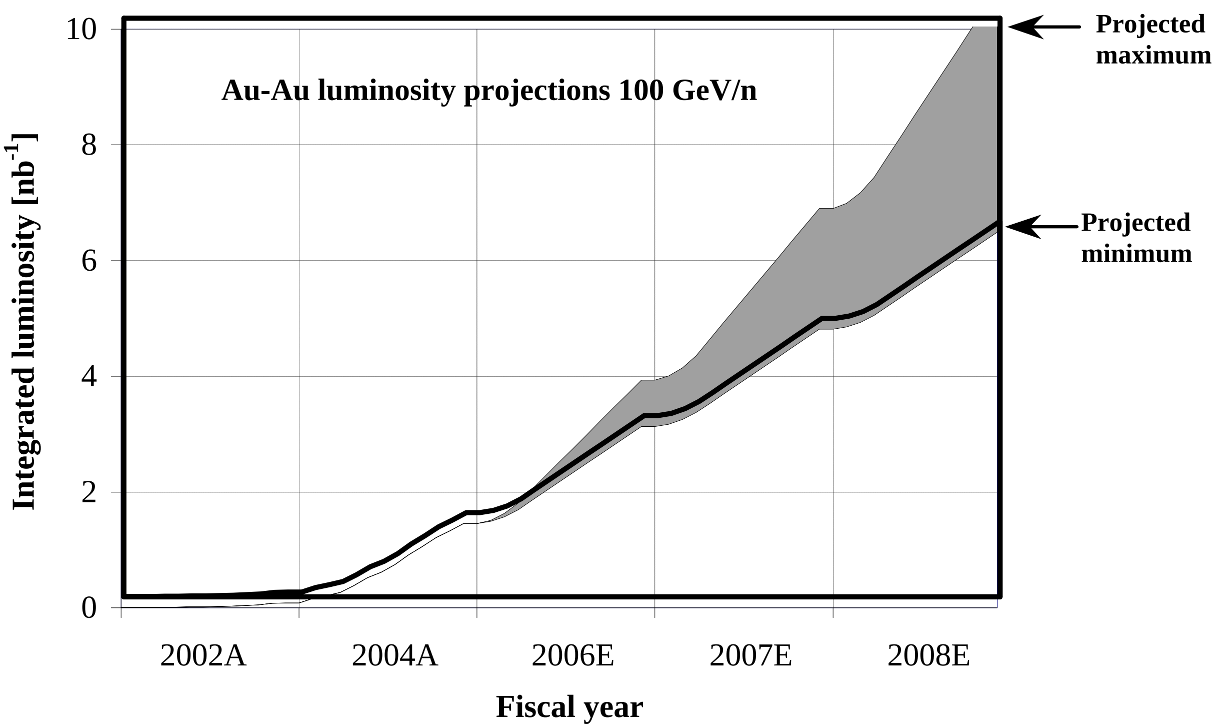

Figure 4: Minimum and maximum projected integrated luminosity for Au-Au collisions.

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	1.3	1.7	2.0
Average beam current/ring	mA	48	48	52	119	180	236	278
$\beta*$	m	3	1	1	1	1	1	1
Peak luminosity	10^{30} cm^{-2}s^{-1}	2	6	6	10	37	64	89
Average store luminosity	10^{30} cm^{-2}s^{-1}	1.5	3	4	6	25	43	60
Time in store	%	30	41	38	56	58	59	60
Maximum luminosity/week	pb^{-1}	0.2	0.6	0.9	1.9	8.8	15.2	21.7
Minimum luminosity/week	pb^{-1}					1.9	1.9	1.9
Maximum integrated luminosity	pb^{-1}	0.5	1.6	3	13	79	126	179
Minimum integrated luminosity	pb^{-1}					17	16	16
AGS polarization at extraction	%	35	45	50	55	65	70	80
RHIC store polarization, average	%	15	35	46	47	60	65	70
Maximum LP^4/week	nb^{-1}	0	9	40	90	1130	2720	5225
Minimum LP^4/week	nb^{-1}					90	90	90

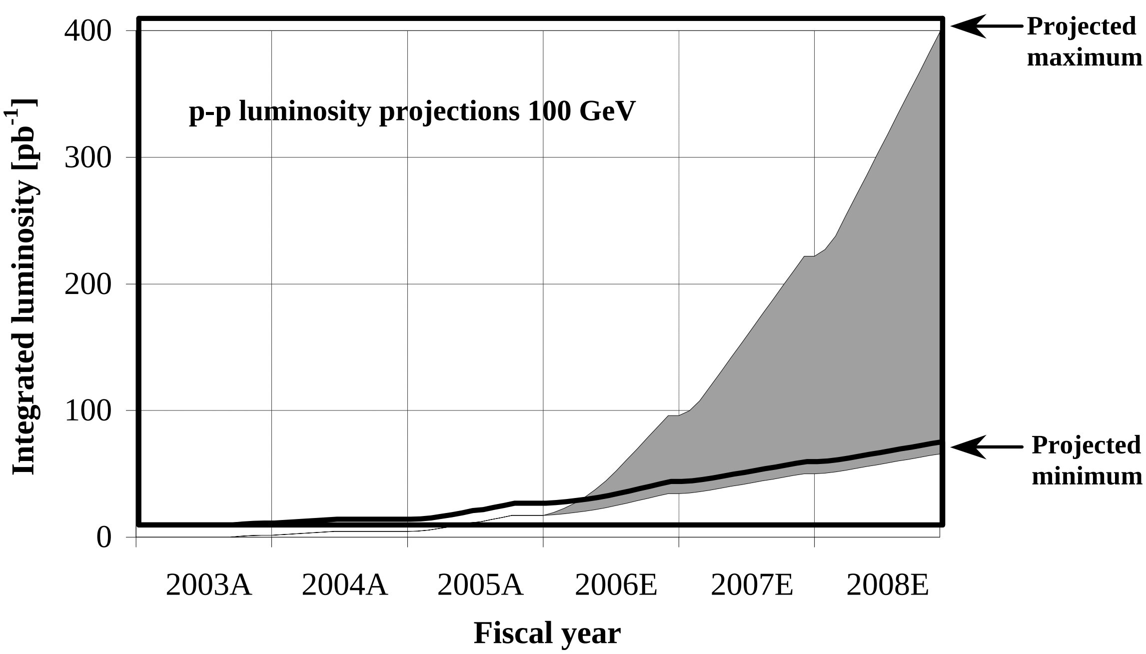

Figure 5: Minimum and maximum projected integrated luminosity for p-p collisions.