RHIC Collider Projections (FY 2016 – FY 2023)

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This note discusses in Part I the running modes for the RHIC Run-16 (FY 2016) operating period including constraints from cryogenic cool-down, machine set-up and beam commissioning. In Part II an outlook is given until 2023. This latest update is based on the experience gained during the Run-15 operation, the shutdown work in 2015, and the physics plans for Run-16 and beyond.

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. Quoted beam polarization numbers are intensity-averaged and time-averaged as measured by the hydrogen jet. The luminosity-weighted polarization functions and figures of merit can be calculated from the center polarization and polarization profile parameters.

Part I – Run-16 Projections

Cryogenic operation – After the shutdown the two RHIC rings will be at room temperature. After bringing the rings to 50 K over approximately 1 month, 0.5 weeks will be required to cool them down from 50 K to 4 K. At the end of the run 0.5 weeks of refrigerator operation is required for the controlled warm-up to room temperature.

Running modes – The modes under consideration for Run-16 are Au+Au at 100 GeV/nucleon, and d+Au at 9.8, 19.5, 31.2 and 100 GeV/nucleon. The run length is assumed to be 20 cryo weeks.

When starting the run we plan for about 1.5 weeks of machine set-up (no dedicated time for experiments) with the goal of establishing collisions, and about 0.5 weeks machine ramp-up (8 h/night for experiments) 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 would be about 1 week 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. Estimates for set-up and ramp-up times are based on past performance and expected commissioning efforts.

Higher weekly luminosities and polarization are achievable 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 1-3 days assuming no unusual machine downtime is encountered. The exact time depends on the availability of a tested lattice. A change of the polarization orientation at any or all of the experiments requires 1-2 shifts.

For example, 20 weeks of RHIC refrigerator operation in FY 2016 could be scheduled in the following way:

Cool-down from 50 K to 4 K	0.5 weeks	
Set-up mode 1 (Au+Au at 100 GeV)	1.2 weeks	(no dedicated time for experiments)
Ramp-up mode 1	0.5 weeks	(8 h/night for experiments)
Data taking mode 1	10 weeks	
Set-up mode 2A (d+Au at 9.8 GeV)	1 day	(no dedicated time for experiments)
Data taking mode 2 with further ramp-up	1.5 weeks	
Set-up mode 2B (d+Au at 19.5 GeV)	3 days	(no dedicated time for experiments)
Data taking mode 3 with further ramp-up	1.5 weeks	
Set-up mode 2C (d+Au at 31.2 GeV)	3 days	(no dedicated time for experiments)
Data taking mode 3 with further ramp-up	1.0 week	
Set-up mode 2D (d+Au at 100 GeV)	2 days	(no dedicated time for experiments)
Data taking mode 3 with further ramp-up	1.0 week	
CeC PoP (Au at 40 GeV)	1.0 week	(no dedicated time for experiments)
Warm-up	0.5 week	

Past performance – Table 1 shows the achieved luminosities for all ion combinations at the highest energy, and for polarized protons at 100 and 255 GeV. The time in store was 68% of the total time for Au+Au (Run-14) and 54% for p↑+p↑ (255 GeV, Run-12). Note that the total time includes all interruptions such as ramping, set-up, maintenance, machine development, accelerator physics experiments, and failures. 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 at close to full energy for heavy ions, and 100 and 255 GeV for polarized protons.

mode	beam energy [GeV/nucleon]	no of colliding bunches	ions/bunch $[10^9]$	β^* [m]	rms emittance [μm]	L_{peak} $[cm^{-2}s^{-1}]$	$L_{store\ avg}$ $[cm^{-2}s^{-1}]$	L_{week}
U+U	96.4	111	0.3	0.7	2.2→0.4	8.8×10^{26}	5.6×10^{26}	0.2 nb^{-1}
Au+Au	100	111	1.6	0.7→0.5	2.5→0.65	84×10^{26}	50×10^{26}	2.2 nb^{-1}
Cu+Au	100	111	4.0/1.3	0.7	4.1→1.2	120×10^{26}	100×10^{26}	3.5 nb^{-1}
Cu+Cu	100	37	4.5	0.9	2.5→5.0	2×10^{28}	0.8×10^{28}	2.4 nb^{-1}
h+Au	104/100	111	45/1.3	1.0	2.0→3.0/1.5	17×10^{28}	10×10^{28}	33 nb^{-1}
d+Au	101/100	95	100/1.0	0.85	2.5→3.3	27×10^{28}	13.5×10^{28}	40 nb^{-1}
p↑+Au	103/97	111	225/1.6	0.85/0.7	2.7→3.2/3.0→1.3	88×10^{28}	45×10^{28}	140 nb^{-1}
p↑+Al	103/98	111	240/11	0.85/0.7	2.5→3.8/2.4→1.9	715×10^{28}	400×10^{28}	1.2 pb^{-1}
p↑+p↑*	100	111	225	0.85	2.8→4.0	115×10^{30}	63×10^{30}	25 pb^{-1}
p↑+p↑*	255	111	185	0.65	3.1→3.9	245×10^{30}	160×10^{30}	60 pb^{-1}

*Blue and Yellow ring intensity- and time-averaged polarization of P = 55% in stores at 100 GeV in Run-15 and P = 52% at 255 GeV in Run-13 as measured by the H-jet.

Luminosity projections – Table 2 lists the expected maximum peak and average luminosities for possible running modes in Run-16 and Run-17, and other modes. These maximum luminosities are anticipated after a sufficiently long running period, typically a few weeks, unless unexpected machine limitations are encountered. With experience from past runs we expect luminosities at the end of the initial ramp-up period to be 25 to 50% of the value at the end of the running period. The integrated luminosity is derived from the predicted beam parameters and the calendar time in store. The expected initial rms diamond length for ions is 20 cm with the 197 MHz storage cavities. For protons we expect an initial rms bunch length of 60 cm or less at both 100 GeV and 255 GeV. The bunch length in polarized proton operation is adjusted to maximize the luminosity lifetime. For asymmetric operation the initial rms diamond length is expected to be 50 cm. Due to the required abort gaps in both beams, the maximum number of collisions can only be provided for either STAR or PHENIX while the other experiment will have approximately 9% fewer collisions.

Table 2: Maximum luminosities at full energy that can be reached after a sufficiently long running period.

mode	beam energy [GeV/nucleon]	no of colliding bunches	ions/bunch [10^9]	β^* [m]	rms emittance [μm]	L_{peak} [$cm^{-2}s^{-1}$]	$L_{store\ avg}$ [$cm^{-2}s^{-1}$]	L_{week}
Au+Au	100	111	1.85	0.7	2.5→0.7	111×10^{26}	70×10^{26}	2.8 nb^{-1}
Ru+Ru[§]	100	111	1.7	0.7	2.5→4.0	0.9×10^{28}	0.5×10^{28}	1.9 nb^{-1}
Zr+Zr[§]	100	111	1.9	0.7	2.5→4.0	1.1×10^{28}	0.6×10^{28}	2.3 nb^{-1}
d+Au	101/100	111	110/1.5	0.85	2.5→3.3	56×10^{28}	34×10^{28}	110 nb^{-1}
p↑+p↑[*]	255	111	250	0.60	3.0→4.2	500×10^{30}	300×10^{30}	100 pb^{-1}

[*] We expect that an intensity- and time-averaged store polarization *P* of up to 55%, as measured by the H jet, can be reached at 255 GeV.

[§] Assumes that enriched source material for Ru-96 and Zr-96 can be obtained. For Ru-96 presently no enriched source material is readily available.

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 each run from the luminosity lifetime, the average time between stores, and the detector turn-on times. For polarized proton operation the polarization lifetime is also considered.

Operation at energies other than 100 GeV/nucleon – For Au+Au operation at 100 GeV/nucleon the limiting aperture is in the triplets. For energies less than 100 GeV/nucleon the beam size in the triplets is maintained with a smaller β-function, which results in a larger β^*. The combined effect is that the luminosity scales with the energy E as $L(E) \propto E^2$. Figure 1 shows the observed peak and average luminosities and the scaling according to the formula. Note that operation near the transition energy (γ_{tr} = 23 for ions) is not possible. At the nominal injection energy (9.8 GeV/nucleon) and below refilling is very efficient since no acceleration is required. At the lowest energies significant deviations from the quadratic scaling occur. With the use of the storage RF system the initial bunch length is independent of the energy. The storage RF system cannot be used below an energy of 19.5 GeV/nucleon for Au.

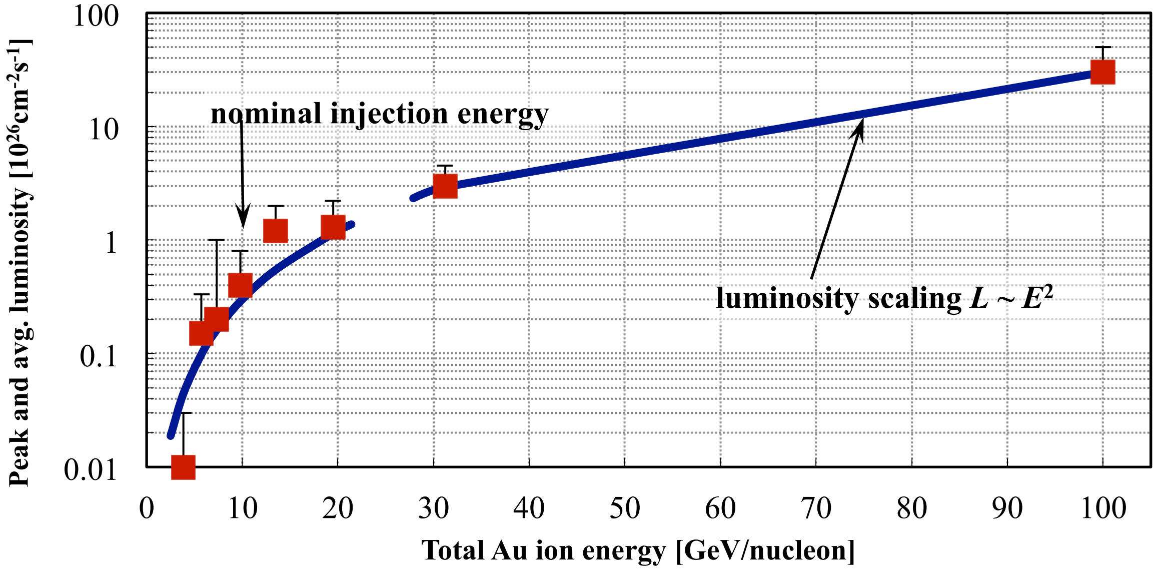

Figure 1: Observed average (red squares) and peak (top bar) Au+Au luminosity for 8 different energies. The blue line shows the luminosity scaling quadratically with the energy. Near the transition energy operation is not possible.

Below energies of 100 GeV/nucleon stochastic cooling is not possible when the beam size in the pick-ups and kickers becomes too large, or the slip factor $\eta = \gamma_{tr}^{-2} - \gamma^{-2}$ becomes too small. In practice, this prevents the use of stochastic cooling below about 30 GeV/nucleon. A few days are required to change filters in the stochastic cooling systems after an energy change and re-commission the system. So far stochastic cooling has not been used below 100 GeV/nucleon.

For polarized protons the luminosity below 100 GeV scales with the square of the energy, where 100% of the luminosity is reached at 100 GeV. For energies between 100 and 255 GeV, the luminosity increases less than quadratically with the energy. This is shown in Figure 2. The polarized proton bunch length is only weakly dependent on the energy (for constant longitudinal emittance and gap voltage), also shown in Figure 2.

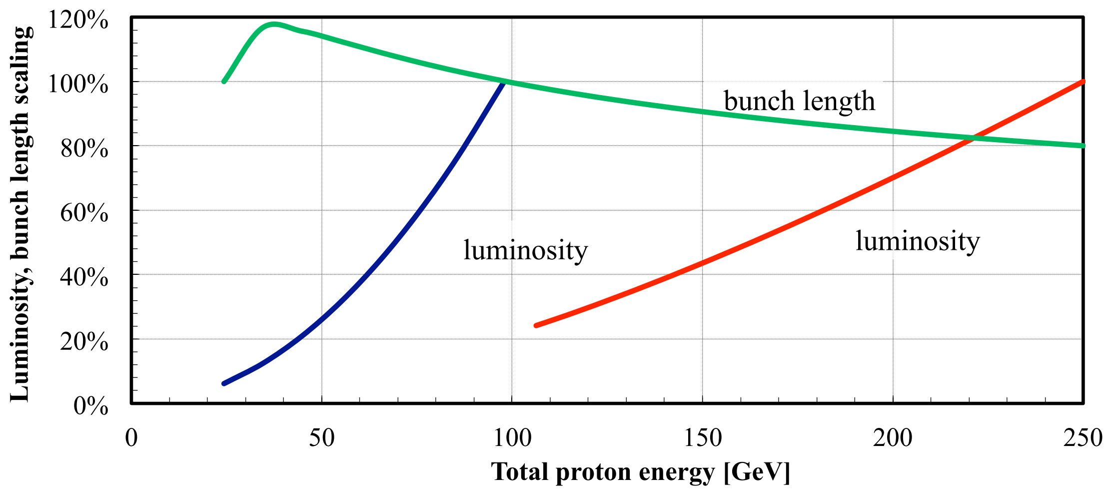

Figure 2: Luminosity scaling for polarized proton operation in the energy range 24 to 255 GeV, and well as bunch length scaling assuming constant longitudinal emittance and gap voltage.

Asymmetric collisions – To date d+Au collisions were provided in Run-3 and Run-8, h+Au collisions in Run-14, Cu+Au collisions in Run-12, and p+Au and p+Al collisions in Run-15. The machine was designed for p+Au collisions, and with stochastic cooling only the initial Au beam sizes needs to be accommodated in the DX magnets. For p+Au operation all DX magnets need to be shifted transversely by 1.75 to 2.5 cm depending on the location. The installation of an undulator in IR2 for the Coherent electron Cooling Proof of Principle (CeC PoP) test in 2015 prevents any asymmetric p+Au or h+Au operation while d+Au operation is still possible.

Following are specific comments on the running modes considered for Run-16.

Au+Au at 100 GeV/nucleon – In Run-14 a major upgrade period of heavy ions ended with the first use of full 3D stochastic cooling for Au+Au. A further increase over the Run-14 performance is possible, primarily due to an increase in the bunch intensity, and possibly the use of the 56 MHz SRF cavity.

The pre-injector complex is continually improved in order to provide more intensity at greater stability. This and an expected increase in the beam stability threshold at transition in RHIC can lead to higher bunch intensities, and therefore initial luminosities, than in Run-14. The increase in the stability threshold at transition is expected due to scrubbing with high-intensity proton beams in Run-15.

Even with longitudinal stochastic cooling ions migrate to neighboring buckets. This effect can be reduced with more longitudinal focusing provided by a 56 MHz superconducting RF system (h = 720). This cavity operated in Run-14, but below the design voltage of 2 MV, limited by quenches in the higher-order mode (HOM) dampers. An HOM damper was redesigned and tested but still quenched at 420 kV cavity voltage. The redesigned HOM damper was removed and operation without the HOM damper is studied. Without the HOM damper the luminosity increase from the 56 MHz SRF will be smaller than the 25-50% previously anticipated.

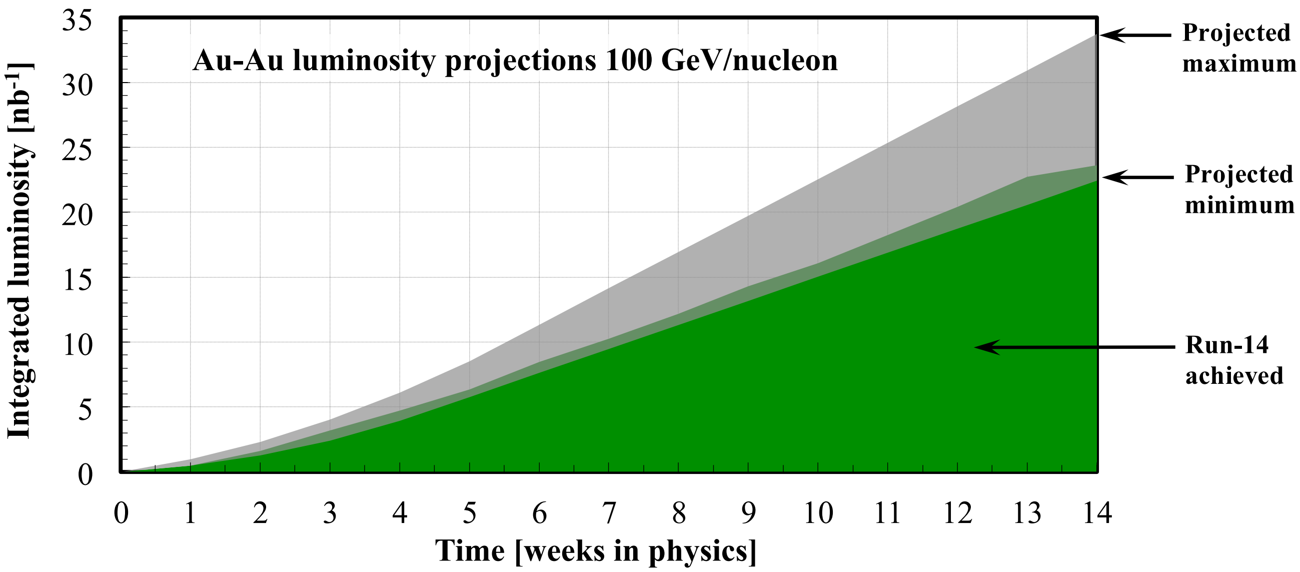

Figure 3: Projected minimum and maximum integrated luminosities for Au+Au collisions at 100 GeV/nucleon beam energy, assuming linear weekly luminosity ramp-up in 6 weeks.

Several tools exist to adjust the instantaneous luminosity during a store, and create a desired time-dependent luminosity profile. These include the selection of the initial β^*, a change of β^* during the store (as implemented in Run-14), a change of vertical separation at the interaction point (also implemented in Run-14), and changes in the cooling rate. All but the last measure can be implemented in one or the other experiment individually.

d+Au at 9.8, 31.2, 19.5 and 100 GeV/nucleon – The projected luminosities are:

beam energy [GeV/nucleon]	d+Au luminosity [nb^{-1}/week]	L in |z|<30 cm [%]	L in |z|<10 cm [%]	comment
100	110	50	20	Run-14 performance for h+Au
31.2	10.6	50	20	197 MHz on, cooling on for Au
19.5	3.8	50	20	197 MHz on, cooling off for Au
9.8	1.5	15	5	197 MHz off, cooling off for Au

Ru+Ru and Zr+Zr at 100 and 9.8 GeV/nucleon – In both cases isotopes with 96 nuclei (i.e. Ru-96 and Zr-96) are requested as possible species combinations in Run-17. In RHIC, bunches with the same number of charges as in Au beams can be accelerated and stored. However, for these two isotopes the intensity limit will be set at the source.
Enriched Zr-96 (about 85% enrichment) is available in metallic form. The luminosity estimate in Table 2 accounts for the less than 100% enrichment. To date no Ru-96 source material could be located, and about 1 g would be needed. GSI has a stock of 400 mg, and all precautions are taken to retrieve any Ru-96 after it has been lent out to an experiment. To obtain Ru-96 it may be necessary to place a special order for enrichment (e.g. with a Calutron). The substantial cost of this order may be shared with other laboratories in the world. Since no Ru-96 source is readily available, and some source development is necessary for Zr-96, it is unlikely that these two isotopes can be used in RHIC operation in Run-17. In Run-16 it is also planned to test acceleration Ru-96 delivered from the Tandem from an source with naturally occurring ruthenium.

RHICf request for Run-17. 255 GeV, beta* = 10, single collision at STAR IP.

Part II – Projections until 2023

A number of improvements are planned over the next years to increase the RHIC luminosity and polarization further. The upgrades, shown in Table 3, are for performance increases for heavy ions at high and low energies, and for polarized beam operation. It is presently planned to have no RHIC operation in FY 2018 for the installation of the Low-Energy RHIC electron Cooling (LEReC) upgrade, and only low-energy operation for the Beam Energy Scan II in FY 2019 and FY 2020. High-energy operation resumes in FY 2022 for a few years with the new sPHENIX detector before the facility transitions to eRHIC.

Table 3: Main upgrades planned for RHIC A+A and p↑+p↑ operation.

	A+A	p↑+p↑
For FY 2016	56 MHz SRF upgrade Transverse dampers	Linac reliability upgrade Transverse dampers
For FY 2017	--	Electron lenses for full proton energy
For FY 2018	No beam operation planned	No beam operation planned
For FY 2019	New RHIC 9 MHz RF LEReC (low energy cooling)	New RHIC 9 MHz RF
For FY 2023	In-situ beam pipe coating 56 MHz SRF upgrade	In-situ beam pipe coating

Heavy ions – high energy – With the full implementation of 3D stochastic cooling, a major upgrade phase came to an end in 2014, and the average store luminosity reached 25× the design value. A further luminosity increase is possible with an ultimate goal of

$L_{\text{store avg}}$ **= 100×10^{26} cm^{-2}s^{-1} for Au+Au at 100 GeV/nucleon (50× design).**

The achievable luminosity is limited by intrabeam scattering (IBS), and the bunch intensity. IBS leads to debunching and transverse emittance growth, and is counteracted by 3D stochastic cooling. Even with longitudinal stochastic cooling ions migrate to neighboring buckets. This effect can be reduced with more longitudinal focusing provided by a 56 MHz superconducting RF system (h = 720). This cavity operated in Run-14 at 300 kV, below the design voltage of 2 MV, and was limited by quenches in the higher-order mode (HOM) damper. A second-generation HOM damper still quenched at 420 kV and further modifications are necessary.
The beam intensity is limited by the injectors and a fast transverse instability at transition, driven by the machine impedance and electron clouds. The beam intensity can be further increased with upgrades in the pre-injectors, namely he Laser Ion Source (LION) and Electron Beam Ion Source (EBIS).
In Run-14 the STAR experiment asked for luminosity leveling to optimize the use of available time for its physics program. As an operational test dynamic β-squeeze during the stores was implemented during Run-14 when β^* was decreased from 0.7 to 0.5 m at STAR and PHENIX 7 h into store, and the beams were partially separated vertically for some stores.

Table 4: Demonstrated and projected luminosities for 100 GeV/nucleon Au+Au runs.

Parameter	Unit	FY2010	2011	2014	2016E	2022E	2023E
No of bunches	…	111	111	111	111	111	111
Ions/bunch, initial	10^9	1.1	1.3	1.6	1.85	1.9	2.0
Avg. beam current/ring	mA	121	147	176	203	209	216
Stored beam energy	MJ	0.39	0.47	0.56	0.65	0.67	0.69
β^*	m	0.75	0.75	0.70	0.70	0.65	0.60
Hour glass factor	…	0.93	0.70	0.74	0.75	0.70	0.65
Beam-beam param./IP	10^{-3}	1.5	2.1	2.5	2.9	2.9	3.0
Initial luminosity	**10^{26} cm^{-2}s^{-1}**	**40**	**50**	**80**	**111**	**115**	**125**
Events per bunch-bunch crossing	…	0.10	0.13	0.21	0.28	0.30	0.32
Avg./initial luminosity	%	50	60	62	64	80	80
Avg. store luminosity	**10^{26} cm^{-2}s^{-1}**	**20**	**30**	**50**	**71**	**92**	**100**
Time in store	%	53	59	68	65	60	60
Max. luminosity/week	μb^{-1}	650	1000	2200	2790	3350	3630
Min. luminosity/week	μb^{-1}				2200	2200	2200

Heavy ions – low energy – For the Beam Energy Scan II a large increase in the luminosity is needed for the search of a critical point in the nuclear matter phase diagram. To facilitate this luminosity increase bunched beam electron cooling is being implemented for the 2 or 3 lowest of the 5 beam energies. The luminosity is further enhanced with a new 9 MHz RF system that increases the bucket area and provides longer bunches. Significant luminosity improvement with electron cooling could be expected only with time and only after electron cooling is fully commissioned for each energy point.

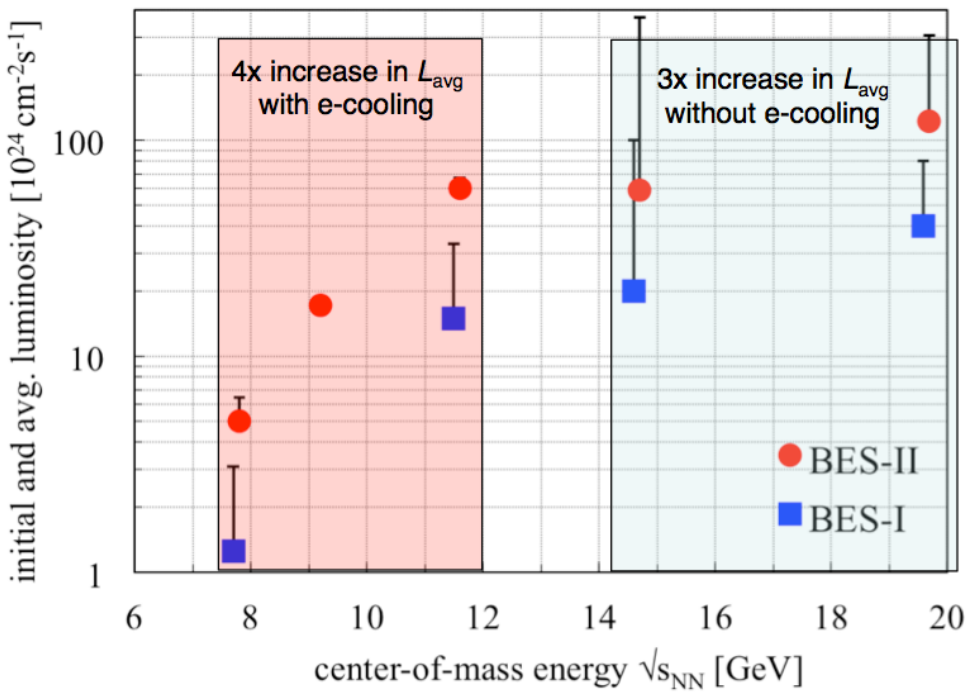

Figure 4: Demonstrated luminosities during BES-I and expected luminosities with electron cooling for the 3 lowest energies in BES-II, and without electron cooling at the 2 highest energies.

Polarized protons – Based on the experience to date and planned further improvements the ultimate luminosity and polarization goals for polarized proton operation are

$$L_{\text{store avg}} = 175\times10^{30}\ \text{cm}^{-2}\text{s}^{-1} \text{ at } 100 \text{ GeV} \qquad \text{with 60\% average polarization}$$
$$L_{\text{store avg}} = 600\times10^{30}\ \text{cm}^{-2}\text{s}^{-1} \text{ at } 255 \text{ GeV (60× design) with 55\% average polarization}$$

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 leads to a tune shift (called beam-beam parameter ξ for small amplitude particles), and a tune spread of the particles in the distribution. Only a limited amount of tune spread can be tolerated. In addition nonlinear elements also create, enhance, or modify resonance driving terms that affect the stability of particle motion.

To increase the tolerable beam-beam parameter ξ, the lattice was modified and two electron lenses were installed. The new lattice minimizes resonance driving terms and the low-energy electron beams that collide head-on with the proton beams reduce the beam-beam induced tune spread. This configuration was used for the first time during Run-15 at 100 GeV and approximately doubled the peak and average luminosity compared to Run-12.

Proton beams accelerated to 255 GeV showed only about 85% polarization transmission from injection to the beginning of the physics store, and a polarization loss of 0.5-1.0%/h (absolute) in store. During Run-12 extensive test were made to determine the cause of the polarization losses during the ramp and during store. No single parameter was found that had a large impact on the polarization, which makes it unlikely that further large polarization gains can be made through parameter changes. Since the primary reason for a reduction in the average polarization is the development of polarization profiles, a reduction in beam emittance will increase the polarization. In Run-13 (255 GeV) the event rate reached a fundamental limit for the STAR detector. To provide more useful luminosity to STAR, leveling at the maximum acceptable luminosity is required.

A polarized ^3He source is under development in collaboration with MIT. With EBIS as an ionizer we expect that polarized ^3He can be made available in RHIC in about 3 years. To have high ^3He polarization in RHIC an upgrade of one of the RHIC rings with 4 more Siberian snakes is necessary. Polarimeters for the injectors and RHIC also need to be developed.

Table 5: Demonstrated and projected luminosities and polarization for p↑+p↑ runs at 100 GeV.

Parameter	**Unit**	**FY2009**	**2012**	**2015**	**2022E**	**2023E**
No of colliding bunches	…	109	109	111	111	111
Protons/bunch, initial	10^{11}	1.3	1.6	2.25	2.8	3.0
Avg. beam current/ring	mA	179	214	312	389	411
Stored beam energy	MJ	0.23	0.27	0.40	0.50	0.53
β^*	m	0.70	0.85	0.85	0.85	0.85
Hour glass factor	…	0.72	0.74	0.75	0.95	0.95
Beam-beam param./IP	10^{-3}	6.3	5.8	9.7	12.1	14.5
Initial luminosity	**10^{30} cm^{-2}s^{-1}**	**50**	**46**	**115**	**227**	**288**
Events per bunch-bunch crossing	…	0.3	0.3	0.7	1.3	1.7
Avg./initial luminosity	%	56	71	55	60	60
Avg. store luminosity	**10^{30} cm^{-2}s^{-1}**	**28**	**33**	**63**	**136**	**173**
Time in store	%	53	59	64	60	60
Max. luminosity/week	pb^{-1}	8.3	9.3	25	50	63
Min. luminosity/week	pb^{-1}				25	50
AGS extraction, P_{max}	%	65	72	72	72	72
AGS extraction, P_{min}	%		67	67	67	67
RHIC store avg., P_{max}	**%**	**56**	**59**	**57**	**60**	**60**
RHIC store avg., P_{min}	%				57	57

Table 6: Demonstrated and projected luminosities and polarization for p↑+p↑ runs at 255 GeV.

Parameter	**Unit**	**FY2012**	**2013**	**2017E**	**2022E**	**2023E**
No of colliding bunches	…	109	111	111	111	111
Protons/bunch, initial	10^{11}	1.7	1.85	2.5	2.8	3.0
Avg. beam current/ring	mA	226	257	344	389	412
Stored beam energy	MJ	0.74	0.84	1.12	1.27	1.34
β^*	m	0.65	0.65	0.60	0.55	0.50
Hour glass factor	…	0.80	0.78	0.78	0.76	0.76
Beam-beam param./IP	10^{-3}	5.7	7.3	10.1	12.2	14.5
Initial luminosity	**10^{30} cm^{-2}s^{-1}**	**177**	**248**	**500**	**724**	**1000**
Events per bunch-bunch crossing	…	1.2	1.7	3.5	5.0	6.9
Avg./initial luminosity	%	59	64	60	60	60
Avg. store luminosity	**10^{30} cm^{-2}s^{-1}**	**105**	**160**	**300**	**431**	**600**
Time in store	%	54	56	55	55	55
Max. luminosity/week	pb^{-1}	32	60	100	143	200
Min. luminosity/week	pb^{-1}			60	60	60
AGS extraction, P_{max}	%	70	72	72	72	72
AGS extraction, P_{min}	%	67	67	67	67	67
RHIC store avg., P_{max}	**%**	**52**	**52**	**55**	**55**	**55**
RHIC store avg., P_{min}	%			52	52	52

Asymmetric operation with p↑+Au – In Run-15 the first asymmetric operation with p↑+Au and p↑+Al was demonstrated. Based on the experience and planned further improvements, we expect that the delivered luminosity will reach up to 400 nb^{-1}/week by 2023.