UPGRADE OF BNL ACCELERATOR FACILITY*

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Abstract

A number of upgrades are planned for the Brookhaven accelerator facility that is primarily made of RHIC and its injector, the AGS. The RHIC luminosity and proton polarization are to evolve towards the Enhanced Design parameters by 2008. A new Electron Beam Ion Source is under development, and commissioning is expected in 2009. The aim of the RHIC II upgrade is to increase the heavy ion luminosity by an order of magnitude, through electron cooling in store. With the addition of an electron ring, the high-luminosity electron-ion collider proposal eRHIC can be realized. Ways to increase the luminosity beyond the RHIC II values are under study. The use of superbunches in RHIC requires a different mode of operation. Studies have also been done for a new injector to the AGS replacing the present Booster for an upgrade of the beam average power to 1-4 MW at 28 GeV. The new injector matching the AGS repetition rate can be either a 1.5-GeV SCL or a 1.5-GeV FFAG accelerator. With the upgrade of the injector, neutrino superbeams could be produced.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is in operation since 2000. It has 2 physics programs, one based on colliding ion beams, the other based on polarized protons collisions. The collider has operated with 4 ion combinations (Au-Au, d-Au, Cu-Cu, and polarized p-p) at 7 energies. In polarized proton operation, the average store polarization reached 57%. Luminosity was delivered to 5 experiments (BRAHMS, PHENIX, PHOBOS, STAR, and PP2PP), 2 of which (PHENIX and STAR) are large and designed for high luminosity. Since 2000 the luminosity delivered per run has increased by approximately 2 orders of magnitude (Figure 1). Over the next years upgrades are planned to increase the luminosity and polarization even further, and add the possibility of high-luminosity electron-ion collisions. We look even beyond these upgrades and explore possibilities for the use of superbunches in RHIC.

The RHIC injector complex is made of the ion source, the 200-MeV Linac, the 1.5-GeV AGS Booster and the Alternating Gradient Synchrotron (AGS). A beam power upgrade at 28 GeV in the AGS has also been studied and proposed. The program requires a new injector that matches the AGS circumference for fast beam transfer at higher repetition rate. The new injector is either a SuperConducting Linac (SCL) or a Fixed-Field-Alternating-Gradient (FFAG) accelerator.

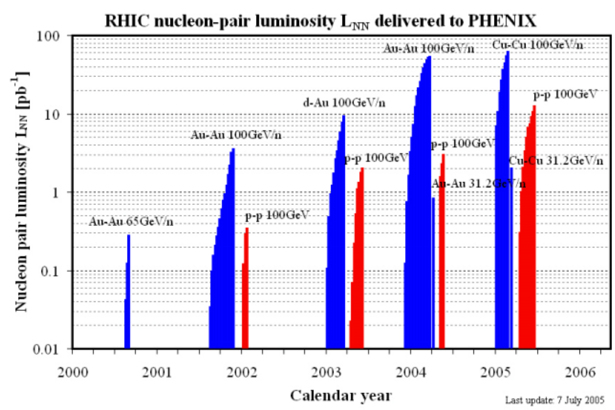

Figure 1. Integrated nucleon-pair luminosity delivered to PHENIX $L_{NN} = A_1 A_2 L$ where A_1 and A_2 are the mass numbers of the colliding ions and L the integrated luminosity.

PLANNED RHIC UPGRADES

By now the RHIC design parameters have been exceeded (see Table 1). Four major upgrades of the RHIC complex are currently planned: the evolution towards the Enhanced Design goals, the new Electron Beam Ion Source (EBIS), RHIC II with electron cooling of colliding beams, and the electron-ion collider eRHIC. The Enhanced Design goals call for a four-fold increase of the heavy ion luminosity over the design value, by reduction of β* and an increase in the number of bunches. While the β* reduction from 2 m to 1 m has been achieved, the doubling of the number of bunches from 56 to 111 has not yet been demonstrated. The number of bunches is limited by dynamic pressure rises caused by electron clouds [1]. An extensive vacuum upgrade program was executed over the last few years. The main elements of this program are the bakeout of all bakeable elements, the large-scale installation of NEG coated beam pipes in the warm regions, and improvements to the cold-bore vacuum system that allow for an average vacuum of 10^{-6} Torr before the cool-down begins. The vacuum upgrade is largely complete, and it is expected that the Enhanced Design parameters for ions can be achieved in the next ion running period. The most fundamental heavy ion luminosity limit is then intrabeam scattering, which leads to luminosity lifetimes of only 2.5 h.

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RHIC is the only machine that can collide polarized protons [2]. The acceleration and storage of polarized protons requires special care, and years of development. Depolarizing resonances in the AGS injector, and RHIC, are overcome by special magnets, so-called Siberian Snakes. RHIC has collided polarized protons up to a beam energy of 205 GeV [3]. The Enhanced Design luminosity for polarized protons is larger than the current proton luminosity record, held by the Tevatron. The polarized proton luminosity is also limited by electron cloud effects, and in addition by beam-beam effects.

Table 1 Main RHIC parameters for gold ions and polarized protons.

Quantity	Unit	Design 1999	Achieved 2005	Enhanced Design 2008	RHIC II ≥2012
Au^{79+} on Au^{79+}					
Beam energy	GeV/n		— 100 —		
Number of bunches	...	60	45	— 112 —	
Bunch population, initial	10^9	1.0	1.1	— 1.0 —	
β-function at IP	m	2.0	1.0	1.0	0.5
Peak luminosity	$10^{26}cm^{-2}s^{-1}$	12	15	32	90
Average store luminosity	$10^{26}cm^{-2}s^{-1}$	2	5	8	70
polarized p^+ on polarized p^+					
Beam energy	GeV	250	100	— 250 —	
Number of bunches	...	60	106	— 112 —	
Bunch population, initial	10^{11}	1.0	0.9	— 2.0 —	
β-function at IP	m	2.0	1.0	1.0	0.5
Peak luminosity	$10^{30}cm^{-2}s^{-1}$	15	10	220	750
Average store luminosity	$10^{30}cm^{-2}s^{-1}$	10	7	150	500
Average store polarization	%	–	46	70	70

Currently only species for which high intensity negative ion sources exist can be used. These negative ions are accelerated in the electrostatic Tandem accelerator, and then injected into the AGS Booster. It is planned to replace the pair of Tandems with an Electron Beam Ion Source (EBIS) [4] followed by a Radio Frequency Quadrupole (RFQ) and short Linac. With the construction of EBIS a further upgrade of the Tandems can be avoided, needed to maintain their reliability, and new ion species can be prepared for RHIC, including uranium and polarized ^3He. The overall system reliability is expected to be improved at reduced operating costs, with beam intensity and brightness comparable to the existing scheme. It is planned to commission EBIS in 2009.

The luminosity lifetime of heavy ion beams is dominated by intrabeam scattering effects. These lead to particle loss out of the radio frequency buckets, and to an increase in the beam size during stores. The effects of intrabeam scattering can only be overcome through active cooling. To cool heavy ion beams at store, an electron beam of 54 MeV with a charge of 5 nC per bunch is required [5]. A high intensity, high brightness superconducting rf electron gun is being developed, which will injected into a superconducting energy recovery linac (ERL). To advance the technology, a R&D ERL is being constructed, in which the electron beam will reach about half the energy required in the electron cooler. Technically constrained, electron cooling could be commissioned in RHIC in 2012.

With the addition of an electron machine, either a ring or an ERL, an electron-ion collider can be realized. The proposed electron-ion collider eRHIC [6] has a center-of-mass energy range of 30-100 GeV with a luminosity of 10^{32}-10^{34} for e-p and 10^{30}-10^{32} e-Au collisions. An essential design requirement is the availability of longitudinally polarized electron, proton, and possibly light ion beams at the interaction point. The eRHIC design work concentrates on the electron gun, the interaction region optimization, and the mitigation of limiting beam dynamic effects such as the beam-beam interaction, and electron clouds for the hadron beam. Technically constrained, eRHIC construction could start in 2012, and last for approximately 3 years.

RHIC UPGRADES WITH SUPERBUNCHES (SuperRHIC)

We explored RHIC luminosity upgrade possibilities with Superbunches [7, 8], beyond the upgrade path laid out in the previous section. Superbunches can potentially increase the luminosity in three ways. First, the ion bunch intensity is limited by instabilities during transition. This can be ameliorated with a reduced peak current in long bunches. Second, with electron cooling for heavy ions, the dominant beam loss is from burn-off. To increase the luminosity further, one can only increase the number of bunches, or use superbunches. Third, in polarized proton operation the dominant luminosity limit is the beam-beam interaction, and a luminosity increase is also possible with superbunches.

Transition Crossing

In RHIC, all ions except protons cross the transition energy. The short bunches at transition can lead to single bunch instabilities and limit the bunch intensity [9]. Up to a certain intensity, the instabilities can be suppressed with chromaticity settings, and octupoles. The shorter bunches also lead to denser electron clouds, which lead to an increase in the electron-impact desorption rate. The pressure rises in some locations when the beam energy approaches the transition energy, and falls again when the transition energy has been crossed. The increase in the electron cloud density can further lower the stability threshold and lead to beam losses, more pronounced near the end of the bunch train [10]. All these effects can be mitigated with a reduced peak current. Focusing-free transition crossing (FFTC) has been proposed for RHIC, using induction acceleration [11]. In this scenario, the rf voltage is ramped down when approaching transition, and the bunches are accelerated through transition with an induction acceleration device, after which the rf voltage is increased again.

Superbunches for Heavy Ion Operation

With electron cooling in RHIC II the dominant beam loss in collision will come from burn-off, the beam loss due to the particle interactions studied by the experiments. Table 2 shows the calculated luminosity lifetimes τ for various RHIC parameters compared to those of LHC. Ion operation in RHIC II (with electron cooled beams in store), and an upgraded LHC (with the same bunch intensity and number of bunches) would operate close to the burn-off limit. With such a low τ a further increase of the transverse beam density at the interaction point, through more cooling or β^* reduction, will not yield more integrated luminosity. With these measures the burn-off rate is increased and the store length becomes even shorter. Most of the collider operation time is then spent with refilling. One can, however, increase the luminosity at the burn-off limit further, by filling more beam of the same density. Two such possibilities exist: (i) An increase of the bunch intensity N_b and the emittance ε_n at the same rate so that the ratio N_b / ε_n is constant. In this case the luminosity increases as $L \sim N_b$, and the beam-beam parameter ξ is held constant. The bunch intensity N_b is likely to be limited by either the injector chain or the beam size in the final focus quadrupoles. (ii) An increase in the number of bunches N, which leads in the extreme case $N \rightarrow \infty$, or conversely to superbunches. The number of bunches is likely limited by electron cloud effects, or the stored energy. However, electron cloud effects for superbunches are less severe.

Table 2 Calculated luminosity lifetimes τ for various RHIC and LHC parameters.

		RHIC I Enhanced 2008		RHIC II (e-cooling) > 2012		LHC design > 2007	LHC 5x design ?
		Au-Au	**p-p**	**Au-Au**	**p-p**	**p-p**	**p-p**
Energy	GeV/n	100	250	100	250	7000	7000
Peak luminosity £/IP	10^{30} cm^{-2}s^{-1}	0.003	220	0.009	710	10000	50000
Number of IPs n_{IP}	…	2	2	2	2	2	2
Lifetime τ	**h**	**15**	**233**	**5**	**73**	**45**	**9**

We consider a scheme for the RHIC heavy ion operation with three long bunches in each ring filling half of the circumference. With these bunches luminosity can be delivered to any experiment, and enough space is provided for the abort gap. Table 3 shows the calculated peak luminosities and luminosity lifetimes for the RHIC II and SuperRHIC conditions. The projected luminosity for ions of gold in SuperRHIC is expected to be a factor 16 above that of RHIC II.

Table 3. Parameters for Heavy Ion Superbunch Operation in RHIC.

		RHIC II	**SuperRHIC**	**comment**
Energy	GeV/n	100	100	
Number of bunches N	…	111	3	6-fold symmetry
Bunch intensity N_b	10^9	1.0	800	same peak current (limit at γ_t-crossing)
Bunch length l_b	m	0.3	600	rms (RHIC II), full (SuperRHIC)
Average beam current I_b	A	0.11	2.4	
Full crossing angle α	mrad	0.0	0.5	possible with existing correctors
Peak luminosity £/IP	10^{26} cm^{-2}s^{-1}	80	1200	
Average luminosity £/IP	**10^{26} cm^{-2}s^{-1}**	**70**	**1100**	requires major e-cooling upgrade
Number of IPs n_{IP}	…	2	2	
Lifetime τ	h	5	5	

Superbunches for Polarized Proton Operation

In polarized proton operation, RHIC is primarily limited by the beam-beam effect. Hadron colliders (SppS, Tevatron) have achieved total beam-beam induced tune spreads of $Q_{bb,tot} \sim 0.025$. Compensating beam-beam effects in hadron colliders, both head-on and long-range, is still an unsolved problem, but progress has been made in recent years, giving new hope to a larger total achievable beam-beam tune spread. We will assume a SuperRHIC scenario with $Q_{bb,tot} = 0.025$, and one with $Q_{bb,tot} = 0.05$. The schematic now has four superbunches in each of the RHIC rings. The number of bunches must be a multiple of four to allow for all spin combinations at the single interaction point. Table 4 shows the main parameters for RHIC II with electron cooling, and SuperRHIC with $Q_{bb,tot} = 0.025$ and $Q_{bb,tot} = 0.05$. The luminosity lifetime in all cases is 3 h. In the SuperRHIC case with $Q_{bb,tot} = 0.025$ the luminosity increases by a factor 30. Currently it is not clear if cooling under these conditions can be made sufficiently strong. For the SuperRHIC case with $Q_{bb,tot} = 0.05$ both a cooling system upgrade and beam-beam compensating is required. If this can be accomplished, a more than 2 orders of magnitude increase in the luminosity over the RHIC II parameters can be expected.

Table 4. Parameters for Polarized Proton Superbunch Operation in RHIC

		RHIC II	**SuperRHIC**		**comment**
Energy	GeV/n	250	250	250	
Number of bunches N	…	111	4	4	for all spin combination
Bunch intensity N_b	10^{11}	2.0	1500	3000	limited by $\Delta Q_{bb,tot}$
Bunch length l_b	m	0.15	480	480	rms (RHIC II), full (SuperRHIC)
Average beam current I_b	A	0.28	7.5	15	
Full crossing angle α	mrad	0.0	0.5	0.5	possible with existing correctors
Beam-beam parameter ξ/IP	…	0.012	0.012	0.025	limited by $\Delta Q_{bb,tot}$
Peak luminosity £/IP	10^{34} cm^{-2}s^{-1}	0.07	2.2	8.85	
Average luminosity £/IP	**10^{34} cm^{-2}s^{-1}**	**0.05**	**1.6**	**6.3**	requires major cooling upgrade
Number of IPs n_{IP}	…	2	2	2	
Luminosity lifetime $\tau_£$	h	3	3	3	dominated by beam-beam, IBS

THE AGS UPGRADE PROGRAM

It was recently proposed to upgrade the AGS facility for an average proton beam power of at least 1 MW and possibly up to 4 MW. The main application of the Upgrade is to provide an intense beam of neutrinos to be launched at a distance about 2,500 km away in the Homestake region where a gigantic detector would be placed to detect neutrino oscillation and to determine better the neutrino masses. The present mode of operation of the AGS and the path of the Upgrade are listed in Table 5. The present BNL-AGS accelerator complex is shown schematically in Figure 2. The 1.5-GeV Booster plays a central role for the collection and preparation of all types of particle beams before they are transferred to the AGS. The AGS circumference is four times that of the Booster, so that a complete fill of the AGS requires also four Booster beam pulses. Presently, the repetition rate of the Booster and the AGS are 7.5 Hz and 0.5 Hz, respectively. That requires a filling time of the AGS to be about 0.5 second, followed by about one second for acceleration to the top energy, and another second for resetting the AGS field cycle. At best, the overall cycle period is 2.5 seconds. Moreover, a filling time of 0.5 second is a long period where several effects on the stored beam may occur, with consequent losses and size deterioration. One would expect a great improvement on the beam quality and performance if the filling time can be shortened so that particles do not have to wait too long before they are accelerated.

The AGS Upgrade can be accomplished in two steps: (1) the replacement of the main magnet AGS power supply [12] with one operating at 2.5 Hz and possibly 5 Hz, and (2) a new injector to replace the present Booster for direct transfer of the beam and matching of the circumference of the AGS. Morever the new injector must be capable to operate at the new required operation rate of the AGS. Two scenarios of possible injector were investigated: (1) a 1.2-GeV SuperConducting Linac (SCL) that can eventually be raised to 1.5 GeV [13], and (2) a 1.5-GeV Fixed-Field Alternating-Gradient (FFAG) accelerator [14, 15]. Both injectors allow for direct acceleration of protons and immediate transfer to the AGS. Their mode of operation completely bypasses the Booster, and eliminates the 0.5 s long injection period. To ease the design of the SCL and FFAG proper and their injection into the AGS, it has also been proposed to raise the energy of the Drift Tube Linac (DTL) from 200 to 400 MeV. The combined layouts for the Upgrade with SCL and FFAG is shown in Figure 3. The SCL would start at the end of the DTL and take the beam to injection into the AGS through a new separate tunnel. The FFAG accelerator would be located entirely in the AGS tunnel and accelerate the beam it takes directly from the upgraded 400-MeV DTL. The design of the SCL has been taken closely to that of the SNS SCL [16]. The AGS-FFAG lattice is made of a periodic sequence of 136 FDF triplets and is Non-Scaling [17].

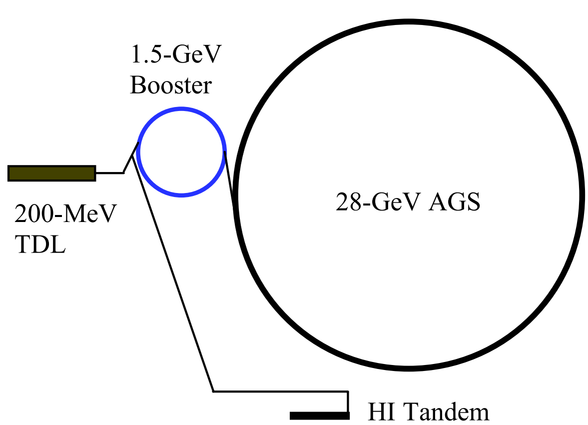

Figure 2 The AGS Accelerator Complex

The AGS upgrade was conceived initially with the SCL injector approach. This resulted in a complex and costly device, demanding a large cryogenic and RF system, not too much different from the SNS SCL. Consequently the concept of the FFAG injector was pursued with the same beam energy and current requirement. The FFAG approach seems to be less costly (by about a factor of two) and requiring only more conventional magnet technology and no superconducting RF. Nevertheless there are some outstanding issues that need, and are indeed at the present, to be evaluated, namely: (i) the space charge intensity at injection (400 MeV now instead of 1.2 GeV); (2) the rapid RF acceleration required that needs RF sweeping from 7 to 9 MHz (matching the AGS RF) in about 7 milliseconds; and (3) because of the use of the Non-Scaling Linear lattice, the concern of multiple resonance crossing during acceleration.

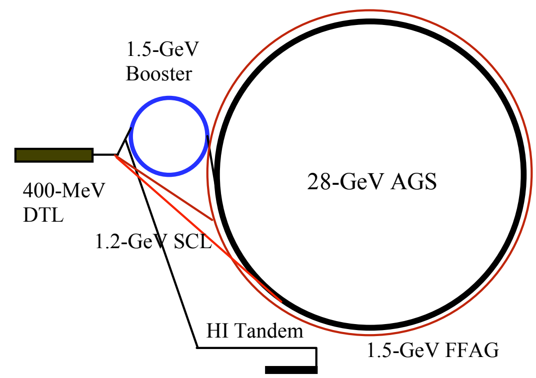

Figure 3. AGS Upgrade with a 1.2-GeV SCL or a 1.5-GeV FFAG in the AGS Tunnel

SUMMARY

Since 2000 RHIC has increased both the heavy ion and the polarized proton luminosity by about 2 orders of magnitude. Planned upgrades of the machine include the evolution towards the Enhanced Design goals, a pre-injector based on an Electron Beam Ion Source (EBIS), RHIC II with electron cooling of colliding beams, and a high-luminosity electron-ion collider. We reviewed further upgrade possibilities with superbunches, which could be beneficial for transition crossing, as well as heavy ion and polarized proton luminosity increases. Such a luminosity upgrade must obviously be accompanied by a detector upgrade, and be agreed upon by the RHIC user community.

At the same time and in parallel, proposals were also made for upgrade of the AGS to a larger beam power in the MWatt range with a new injector. A new injector for the AGS made of a 1.5 GeV FFAG accelerator is the most favourable and promising. Yet few beam dynamics beam issues need still to be resolved with such a scheme. The applications of such much improved AGS performance are multiple, and one of them is for sure the generation of a Superbeam of Neutrinos.

REFERENCES

[1] S.Y. Zhang et al., ``Beam induced pressure rise in RHIC", proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
[2] M. Bai et al., ``Polarized proton collisions at RHIC", proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
[3] M. Bai et al., "Polarized proton collisions at 205 GeV at RHIC", Phys. Rev. Lett. 96, 174801 (2006).
[4] J.G. Alessi et al., ``Progress on Test EBIS and design of an EBIS-based RHIC preinjector", proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
[5] I. Ben-Zvi et al., ``Electron cooling of RHIC", proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
[6] V. Ptitsyn et al., ``eRHIC, a future electron-ion collider at BNL", proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
[7] E. Keil, ``Luminosity optimization for storage rings with low-β sections and small crossing angles", Nucl. Instrum. Methods,**113**, 333 (1973).
[8] K. Takayama et al., "Superbunch hadron colliders", Phys. Rev. Lett., Vol. 88, No. 14, (2002)
[9] M. Blaskiewicz et al., "Transverse instabilities in RHIC", proc. of the 2003 Particle Accelerator Conference, Portland, Oregon.
[10] J. Wei et al., "Observation of electron-ion effects at RHIC transition", proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
[11] K. Takayama et al., "Focusing-free transition crossing in the RHIC using induction acceleration", proc. of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
[12] I. Marneris and A.G. Ruggiero, "Running the AGS MMPS at 5 Hz, 24 GeV". BNL Internal Report C-A/AP/12. Jan. 21, 2000
[13] A.G. Ruggiero, BNL Internal Report, C-A/AP/151, April 2004
[14] A.G. Ruggiero, BNL Internal Report C-A/AP/157, June 20004
[15] A.G. Ruggiero, "1.5-GeV FFAG Proton Accelerator for the AGS Upgrade", proc. of EPAC-04, July 6-11, 2004, Lucerne, Switzerland
[16] SNS http://www.sns.gov/documentation/pubs.htm
[17] A.G. Ruggiero, invited talk on FFAG accelerators in this Workshop.