

# THE LUMINOSITY UPGRADE AT RHIC\*

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## Abstract

Starting with the high energy heavy ion run for Fiscal Year 07 (Run7), the Relativistic Heavy Ion Collider (RHIC) underwent a series of upgrades in all three tiers of its activities: machine hardware, lattice design and operational efficiency. The following presents a review of these upgrades and how their combined contributions to heavy ion operations lead to average store luminosities that exceed the initial RHIC design by a factor of 25.

## INTRODUCTION

RHIC's main objective is to increase its ability to recreate quark-gluon plasma and study the rare processes associated with it. Run7 marked the first efforts towards the implementation of the components aimed at improving the design average store luminosity by a factor of 10. With Run14, all equipments designed for the heavy ion luminosity upgrade have been successfully commissioned with beam and used operationally. Table 1 presents an overview of the main performance parameters of all high energy heavy ion runs from Run7 to Run14, and includes the design, enhanced design and Run4 values as a reference point to the pre-upgrade machine conditions. When looking at the performances of the Au-Au runs alone, the average store luminosities have been improved by a factor of 25 from Run4, reaching a consistent  $L_{avg.}(\text{Run14})=50.0 \times 10^{26} \text{cm}^{-2} \text{s}^{-1}$  while keeping the beams for physics for twice as long. Figure 1 shows the evolution of the integrated luminosity of heavy ion runs at 100 GeV/u from Run1 to Run14 [1], where it can be seen that Run14 outperformed Run4 by over an order of magnitude.

Such a significant improvement can be attributed to the RHIC-II upgrade plans [2]. The next section will highlight the most significant changes and achievements in machine hardware and subsystems. New magnet settings for lattice design that allow for larger dynamic aperture and dynamic  $\beta^*$  squeeze for the STAR and PHENIX experiments are then presented. A review of the changes in machine operations and how the store-to-store turnaround time is pushed to maximize beam time in physics is also included.

## HARDWARE AND SYSTEM UPGRADES

### Injectors

The RHIC-II luminosity upgrade included plans to update the source where heavy ions are generated, from the Tandem Van de Graaf to a new Electron Beam Ion Source (EBIS) followed by an RFQ and a short linac [3]. This new, versatile source allows switching rapidly between various ion species while providing per-bunch intensities similar to the Au ion ones. EBIS was successfully commissioned in 2010 and has

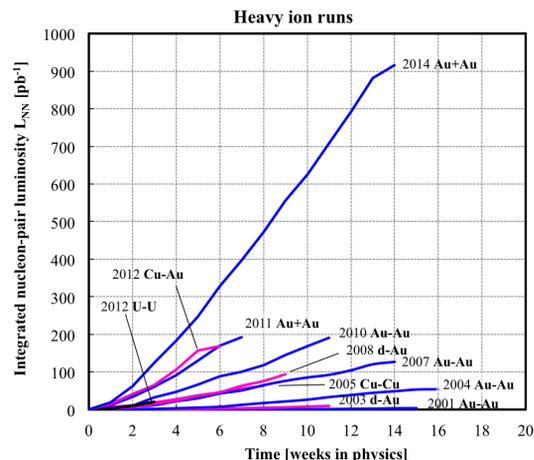


Figure 1: Integrated luminosity of the RHIC heavy ion runs at 100 GeV/nucleon as a function of the number of weeks in physics. The data is presented for the nucleon-pair luminosity  $\mathcal{L}_{N-N}=N_1 N_2 \mathcal{L}$  from Run1 to Run14, where  $\mathcal{L}$  is the luminosity and  $N_1, N_2$  are the number of nucleons for the species in each beam. From [1].

since delivered beams to both RHIC and the NASA facility without slowing down operations for either programs. The ion species other than Au that have been used for RHIC physics are (to date) Cu, U and polarized  $^3\text{He}$ .

Part of the limitations on the intensity of the heavy ion bunches injected into RHIC came from beam instabilities when crossing transition, due to impedance and electron clouds effects [4–6]. However starting with Run10 the intensity threshold was raised thanks to scrubbing runs with high intensity proton beams in 2009 and 2012, as evidenced by the new highs in bunch intensity reported in Table 1.

### Stochastic Cooling

It is clear from the data shown in Table 1 that the main limitation to the luminosity lifetime comes from intrabeam scattering (IBS) which induces emittance blow-up during physics stores. The RHIC Stochastic Cooling (SC) system [7–9] was designed to counter this mechanism and reduce the beam emittance: for each of the three planes of motion, it uses a pickup and kicker magnet pair separated by a multiple of  $\pi/2$  phase advance. The longitudinal SC system was installed for Run7, while the transverse one was implemented in stages: vertical plane only for Run10, both planes for Run11.

With a fully operational 3D SC system, the average store luminosity jumped by a factor 2.5 from Run7 to Run11 to  $30.0 \times 10^{26} \text{cm}^{-2} \text{s}^{-1}$  while reducing the transverse emittance in both planes by over 30%. Further upgrades were brought to all pickups and kickers prior to Run14, mainly for reliability purposes [10]. Figure 2 shows the improvement in transverse cooling efficiency from Run7 to Run14.

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Table 1: Overview of performance parameters for the most recent 100 GeV RHIC runs with heavy ions: the U-U collisions during Run12 took place at a top energy of 96.4 GeV/nucleon; the data reported for Run14 is preliminary

	Species	No. of bunches	Intensity [10 <sup>9</sup> ]	$\beta^*$ (IR6/8) [m]	$\epsilon_{rms}$ [ $\mu\text{m}$ ]	$L_{peak}$ [10 <sup>26</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	$L_{avg.}$ [10 <sup>26</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	$L_{week}$ [ $\mu\text{b}^{-1}$ ]	Store length [h]
Design	A-A	55	1.0	2.0	2.5 → 6.7	9	2	50	
Enhanced	A-A	111	1.0	1.0	2.5 → 6.7	30	8	300	
Run4	Au-Au	45	1.1	1.0	2.5 → 6.7	15	5	160	5.0
Run7	Au-Au	103	1.1	0.83/0.77	2.8 → 5.8	30	12	380	5.0
Run10	Au-Au	111	1.1	0.75	2.8 → 3.3	45.3	20.0	670	4.0
Run11	Au-Au	111	1.3	0.75	2.5 → 1.7	52.6	30.0	1000	4.0
Run12	Cu-Au	111	4.0 / 1.3	0.7	4.1 → 1.2	120.0	100.0	3500	14.0
	U-U	111	0.3	0.7	2.2 → 0.4	8.8	5.6	200	7.5
Run14	Au-Au	111	1.6	0.7 → 0.5	2.5 → 0.65	84.0	50.0	2200	10.0

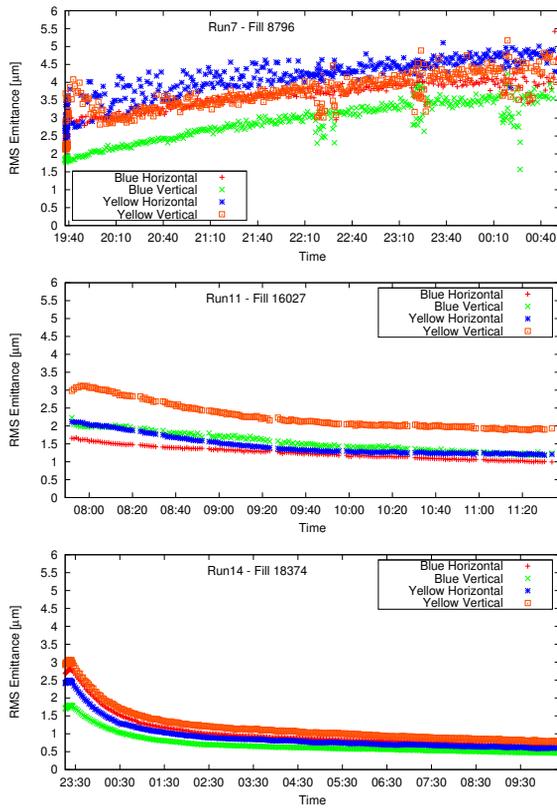


Figure 2: Horizontal and vertical transverse emittances of the Blue and Yellow beams for a typical RHIC 100 GeV Au-Au store with stochastic cooling on during Run7 (top), Run11 (middle) and Run14 (bottom). The improvements brought to the system between those runs can clearly be seen when comparing the slopes of each curve.

**RF Systems**

The RHIC Low-Level RF (LLRF) Upgrade rollout began in December 2009 with the installation of new LLRF “System Controllers” at RHIC. In the ensuing years, the LLRF Upgrade Platform has been deployed across the entire RHIC

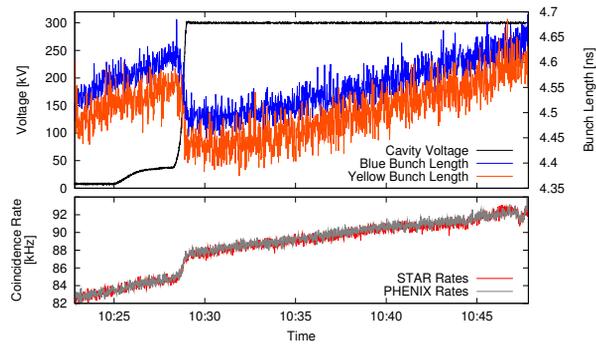


Figure 3: Measurement of the bunch lengths for the Blue and Yellow beam when the 56 MHz SRF cavity is brought to 300 kV during a physics store (top) and the corresponding effect on the STAR and PHENIX coincidence rates during that time (bottom).

accelerator complex in both operational as well as R&D applications. The Platform has proven extremely flexible, powerful and useful and has contributed to RHIC luminosity gains via a broad range of applications: improved flexibility and precision of bunch merging gymnastics in the Booster and AGS; improved stability of synchronization and bunch to bucket transfers between Booster, AGS and RHIC; bunch by bunch longitudinal damping and transient beam loading compensation in RHIC; improved flexibility and precision in the RHIC store rebucket gymnastic; and most recently development of a RHIC bunch by bunch transverse damper.

During Run14, a new 56 MHz Superconducting RF (SRF) cavity was also commissioned and made operational for stronger longitudinal focusing, in addition to what the stochastic cooling system can provide [11]. Figure 3 highlights the effect on both bunch length and luminosity of the 56 MHz cavity when brought to 300 kV.

**Feedback Systems**

One of the main goals for RHIC operations is to deliver high luminosities to experiments with great store-to-store reproducibility. For all operating scenarios (including running

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with different ion species and/or beam energies), this is now made possible using state-of-the-art feedback systems that run simultaneously to control the beams' tunes, coupling and orbits [12].

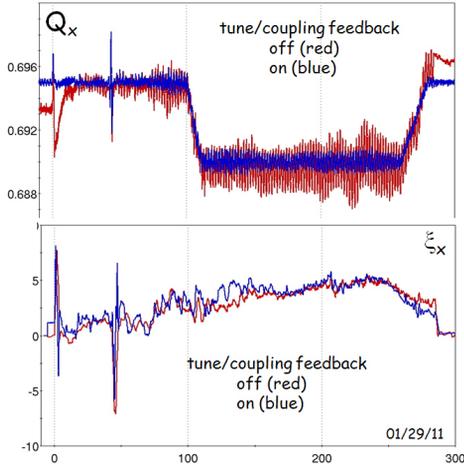


Figure 4: Measured RHIC betatron tunes (top) and chromaticity (bottom) with (blue) and without (red) tune/coupling feedback during the energy ramp and beta-squeeze during Run11. From [12].

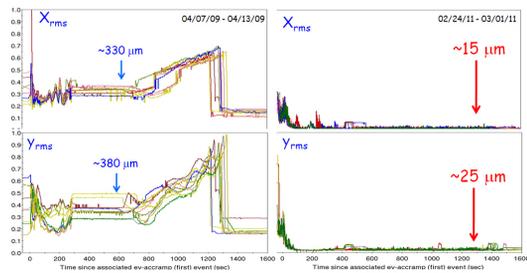


Figure 5: Superposition of measurements from multiple ramps of horizontal (top) and vertical (bottom) orbit rms measured without (left, Run9) and with (right, Run11) orbit feedback. From [12].

Since the successful proof-of-principle during Run6 [13], tune and coupling feedbacks are routinely used in operations (ramp development then ramps for physics store) as of Run10: Figure 4 highlights the precision with which the betatron tune and chromaticity are controlled during an energy ramp for Run11. Figure 5 shows the improved performance of the orbit feedback system that was developed during Run10 and used routinely since Run11, together with a radius feedback loop which adjusts the RF frequency based on an energy deviation measurement from the readings of all horizontal arc beam position monitors. In parallel, a fast orbit feedback loop controlling closed orbit distortions due to vibrations of the final focus triplet quadrupoles was prototyped in Run10, implemented and applied at full energy for all physics stores in Run11 and applied at all times after injection since Run12 [14]. Routine operation of the feedback loops not only guarantees reproducibility of accelerator conditions but also provides significantly higher availability of beams for physics operation.

## LATTICE DESIGN AND BEAM DYNAMICS

For either of the STAR or PHENIX experiment in RHIC, the luminosity is defined in the case of equal Gaussian shaped bunched beams colliding head-on as:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x^* \sigma_y^*}, \quad (1)$$

where  $\sigma_{x,y}^*$  is the transverse beam size in each plane at the interaction point (IP),  $N_{1,2}$  is the number of particles per bunch for each beam,  $f$  the revolution frequency and  $N_b$  the number of colliding bunches. The transverse beam sizes are given by:

$$\sigma_x^* = \sigma_y^* = \sqrt{\beta_{x,y}^* \cdot \epsilon_{x,y}} = \sqrt{\beta_{x,y}^* \cdot \epsilon_{x,y}} = \sqrt{\beta^* \cdot \epsilon}, \quad (2)$$

where  $\beta_{x,y}^*$  is the betatron function in each plane at the IP and  $\epsilon_{x,y}$  the emittance in each plane. Having already maximized  $N_b$  and with emittances being reduced during physics stores by the SC system, the RHIC-II upgrade aims at improving the beam lifetimes, so that  $N_{1,2}$  can be maximized throughout physics stores, and reducing  $\beta_{x,y}^*$  further than 0.7 m.

### Lifetime and Dynamic Aperture

As mentioned previously, the emittance blow-up from IBS is the limiting factor to delivering high luminosity physics stores. Prior to the implementation of stochastic cooling, new "IBS-suppression" lattices were designed, for which a new set of optics functions are calculated to minimize the effect of longitudinal IBS diffusion to the transverse emittances  $\epsilon_{z=\{x,y\}}$ , which is given by [15]:

$$\frac{d\epsilon_z}{ds} = H(s) \frac{d\delta_E^2}{ds}, \quad H(s) = \gamma_z D_z^2 + 2\alpha_z D_z D_z' + \beta_z D_z'^2. \quad (3)$$

A direct path to reducing  $H(s)$  is raising the integer tunes to get lower average dispersion  $D_z$  in the arcs. In RHIC's case, the first tests with beam took place during the Deuteron-Gold run in Run8, with a full implementation for Run10 and Run11. The phase advance per cell was increased from 84° to 95°, leading to integer tunes (31,32), 3 units higher than the design values. During operations for those three runs, the measured transverse emittance growth rate was 30% lower than for previous high energy Au-Au runs, matching the predictions from simulations [15].

With the RHIC 3D SC system fully operational since Run11, new long-term tracking simulations were performed to study the off-momentum dynamic aperture for both standard and IBS-suppression lattices [16]. As shown in Figure 6, the results demonstrated significant differences in favor of the standard lattices: at 4.7 (Blue)/4.3 (Yellow)  $\sigma_z$  for the maximum relative offset  $\delta p/p=1.8 \times 10^{-3}$ , the off-momentum dynamic aperture is more than 2  $\sigma_z$  larger than for the IBS-suppression lattices. The integer tunes were therefore reverted to their design values of (28,29). As a

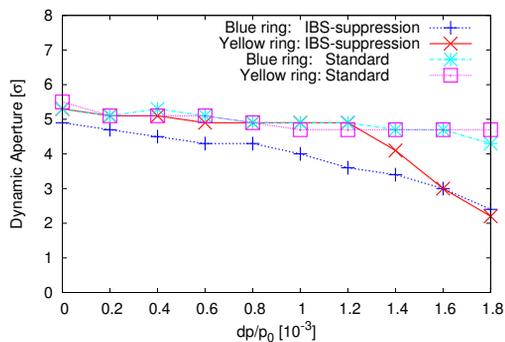


Figure 6: Calculated off-momentum dynamic aperture for the RHIC standard and IBS-suppression lattices. From [16].

result, since Run12 beam losses were highly dominated by the collisions at STAR and PHENIX, a regime called *burn-off* [17].

### Luminosity Leveling with Smaller $\beta^*$

Preliminary studies to squeeze  $\beta^*$  in the RHIC experimental insertions below 0.7 m were performed in the final weeks of Run11, following the first successful stores with stochastic cooling which provide additional transverse aperture in the triplet quadrupoles of STAR and PHENIX [18]. While it demonstrated the feasibility of optics changes in end-of-store conditions, the method used for those tests showed some restrictions in its implementation due to the current limits in the individual shunt power supplies of the quadrupole magnets of the squeezed insertions.

Lattice studies at CERN for the Large Hadron Collider (LHC) upgrade brought a new technique, the Achromatic Telescopic Squeeze (ATS) [19]. The concept of ATS is to use the insertions around the targeted IP to launch and close a  $\beta$ -beat wave to allow reducing the  $\beta^*$  further with little to no change to the chromatic functions. However ATS comes with restrictions in terms of initial (pre-squeeze) lattice design, which the standard A-A RHIC lattices do not meet. The general concept of the  $\beta$ -beat wave can still be applied though if one uses a global rematching algorithm over a section of the machine that includes STAR and PHENIX as well as the insertions immediately downstream and upstream of them. Figure 7 shows a comparison of the main Twiss parameters for the Blue beam between the standard and squeezed lattices; for the latter,  $\beta^*$  (STAR, PHENIX) is lowered to 0.5 m. Once commissioned, the squeezed lattices became part of routine Run14 operations and were applied to the machine once the emittances stabilized to their minimum, typically after 7 hours. Figure 8 shows the impact of the squeezed optics on the instantaneous luminosity at PHENIX: by reducing  $\beta^*$  from 0.7 m to 0.5 m, a 14.54% increase was measured, when theory predicted 14.47% - taking into account the measured linear optics prior to the squeeze [20], a stable bunch length and the change in hourglass factor associated with the new optics.

## OPERATIONAL EFFICIENCY

A major asset of the RHIC facility is its extraordinary versatility: it can routinely produce collisions for multiple physics programs during one calendar year, often for only a few weeks in each running mode which can include both heavy ions and polarized protons - each at multiple collision energies. Generic, highly configurable tools for sequencing accelerator tasks have been developed, along with software for saving and restoring many accelerator configuration parameters that allow fast switching between operating modes and/or species. The generic nature of the tools allows new equipment to be integrated and reconfigured on the fly, as demonstrated by the fast integration of the electron lenses into the operations ramp for Run15 with polarized protons [21]. Figure 9 highlights the noticeable increase in machine availability for physics stores from Run4 and on, one of the most relevant performance indicators.

Since Run4, the rate of operations personnel replacement has been halved. The increased stability in the number of operators is beneficial in that more operators are experienced in accelerator operation. The Operations group was expanded to include accelerator specialists who could be relied upon to train operators and others and solve accelerator performance problems. Accelerator specialists were also charged with managing the “cold restart” of RHIC following each yearly shutdown. In spite of the automation via software described above, operators were encouraged to explore parameter changes at appropriate times in the cycle: the resulting operator tuning of the parameter space paid dividends, for example in the commissioning and operation of Stochastic Cooling during Run10 and Run11.

## CONCLUSION

With the RHIC-II upgrade now completed, there is a significant increase of all performance indicators of the entire accelerator complex: heavy ion bunches are injected at higher intensities with greater reliability, and fast switching between species. Solutions against intrabeam scattering, which limited the delivered luminosity to STAR and PHENIX, have been successfully implemented: the Stochastic Cooling system is reducing the transverse emittances by more than a factor 3, allowing for new mechanisms for luminosity leveling to be commissioned for the first time with beam. A new, superconducting 56 MHz RF cavity was also installed to help focusing the beam longitudinally. Upgrades to the instrumentation and feedback systems introduced state-of-the-art beam control tools, and the operations group is now comprised of highly trained personnel thanks to system experts and lower turnaround.

All of those factors contributed to making the Au-Au run of Run14 the most successful heavy ion physics run to date, with a record average luminosity of  $50.0 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ . Run14 is now the staple for all coming RHIC runs with heavy ions, with the goal of pushing the most recent tools (dynamic  $\beta^*$  squeeze and 56 MHz SRF cavity) to their limit in order to achieve flat, high level luminosity for Run16.

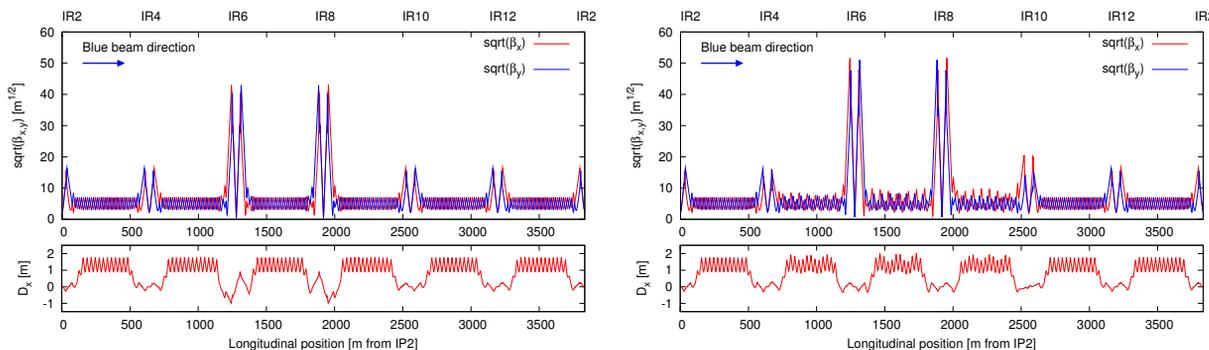


Figure 7: Comparison of the linear  $\beta_{x,y}$  functions (top) and horizontal dispersion  $D_x$  (bottom) of the Blue lattice between the baseline optics with  $\beta^*$  (IR6,IR8)=0.7m (left) and squeezed optics with  $\beta^*$  (IR6,IR8)=0.5m (right) as designed for RHIC Run14 Au-Au 100 GeV collisions. The  $\beta$ -beat wave generated for the squeezed optics can be seen starting from IR4 and collapsing at IR10.

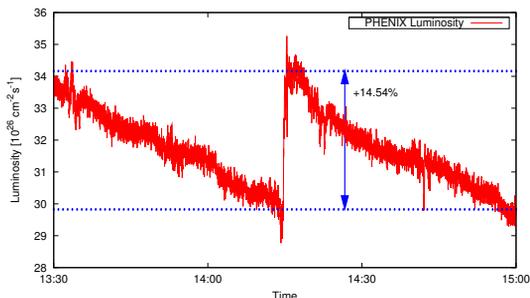


Figure 8: Delivered luminosity for the PHENIX experiment as a function of time during dynamic  $\beta^*$  squeeze. The measured relative luminosity increase matches very well with the predicted ratio  $\Delta(h/\beta^*) / (h/\beta^*) = 14.47\%$  where  $h$  is the hourglass factor and  $\beta^*$  uses the value from linear optic functions measurements.

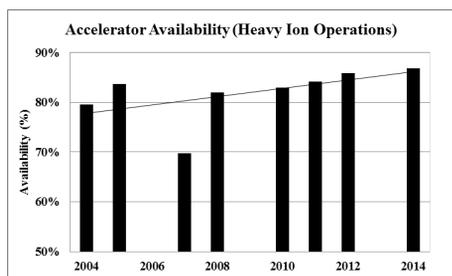


Figure 9: Accelerator availability for heavy ion physics stores as a fraction of the overall duration of each run, from Run4 to Run14. Despite the integration of new or updated systems for the RHIC-II upgrade, the performance kept getting better to peak at over 85%.

## ACKNOWLEDGMENTS

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