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RHIC Accelerator Commissioning and the Year One Run

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1 Early running periods - strategy

Figure 1 shows the 3 beam running periods scheduled for 1999:

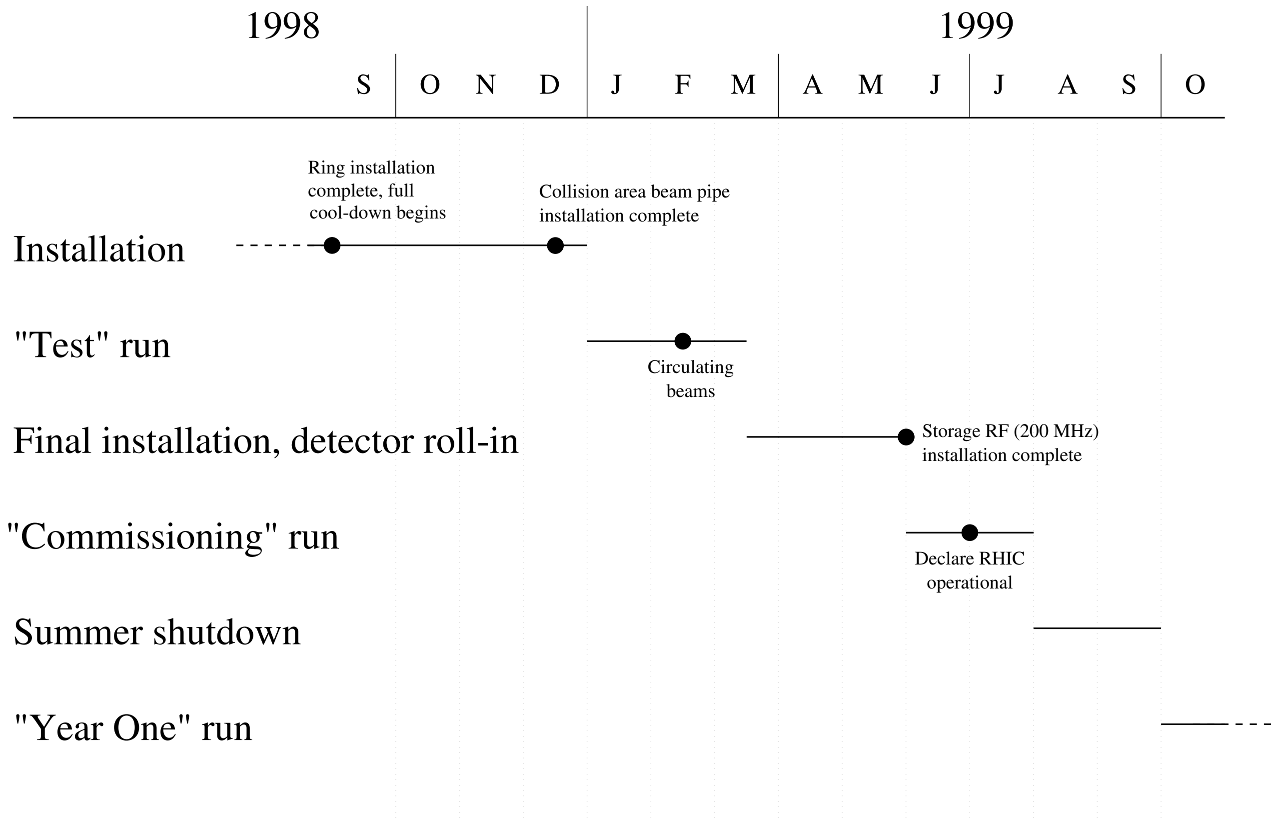
1. The **Test run** of 10 weeks begins as soon as full cool down has been completed, and the final beam pipe has been installed. Operations will be fully dedicated to Machine Studies. First circulating beam in RHIC is nominally estimated to occur 6 weeks into this run.
2. The **Commissioning run** of about 8 weeks begins after final collider installation (eg, RF storage system, final dipole correctors), and after detector roll-in. First collisions (and RHIC project completion) are nominally expected to occur about half way through this run.
3. The **Year One run** begins in September, and lasts 37 weeks, until the next summer shutdown.

Continuous beam testing will, undoubtedly, not be possible in the Test and Commissioning runs. Downtime and ring access will be determined by hardware failure and scheduled breaks in the commissioning. The minimum scheduled beam time will be 2 weeks, since a shorter period would induce an unacceptable level of inefficiency where re-establishing operating conditions would cut into the time available for making progress.

Year One operations will likely begin with a 50% split between collisions and machine studies, interleaving 12 hours of machine studies with 12 hours of quiet time. The fraction of time devoted to machine studies will be reduced as the run progresses, as dictated by diminishing returns. A machine studies duty factor of no more than 25% is expected at the end of the run. Goals for the end of the Year One run include:

1. 50% uptime - the ratio of actual operations to scheduled operations.
2. Store set up time less than 2 hours.
3. 30% of stores terminated voluntarily.
4. Luminosity 10% of the design value, for gold-gold collisions at 100 GeV/u.
5. Collisions with alternative identical ion species available - but discouraged.

Accelerator repair (for example, magnet replacement) with warm up and cool down takes approximately 8 days of down-time. Several such occurrences should be expected during Year One. Again, scheduled beam time of less than 2 weeks duration introduces an unacceptable level of inefficiency.



RHIC Accelerator Commissioning Plan (Oct '96)

2 Accelerator gymnastics

Two beam dynamics effects are expected to be idiosyncratically important to RHIC accelerator operations: transition crossing and Intra-Beam Scattering.

While many other accelerators - such as the AGS - have to cross transition energy during their energy ramp, RHIC will be the first superconducting machine to do so. Since superconducting magnets cannot be ramped quickly, transition crossing will be unusually slow, exacerbating potentially damaging effects such as beam loss and emittance blow up. While these effects get worse with increasing beam intensity, they are still present at low intensities. RHIC is equipped with pulsed quadrupoles to enable a "transition jump" that is expected to remove these problems, at low and high intensities.

Intra-Beam Scattering (IBS) is only expected to be a problem at the highest single bunch intensities, and so should not play a major role during the Year One run. IBS leads to inexorable emittance growth, and luminosity loss. No RHIC compensation scheme will be available for IBS in Year One. The most successful way to combat IBS - with its multi-hour emittance growth rates - may simply be to learn how to re-inject rapidly, and to reduce the storage time. This is discussed further in more detail, in the section "shot profiles", below.

2.1 Test & Commissioning runs

Various gymnastics have to be learned and practiced, before stable and reproducible luminosity runs can be achieved. In the Test and Commissioning runs we expect to learn how to:

1. Circulate beam for ~ 100 turns without RF, and correct the closed orbit.
2. Commission the 28 MHz RF acceleration system, and store beam at injection energy.
3. Accelerate 3 bunches of gold ions to 100 GeV/u, using the 28 MHz RF acceleration system.
4. Pass through transition energy ($\gamma \approx 22.9$) with acceptable beam losses, with first pass tuning of the transition jump system. A moderate amount of emittance blow up will be acceptable.
5. Longitudinally cog 3 Blue and 3 Yellow bunches, for simultaneous crossings at all 6 IPs.
6. Independently tune transverse orbits at IPs, for head-on (or separated) collisions.

7. Tune relevant IR optics so that $\beta^* \ll 10$ meters in a preliminary "low beta squeeze".
8. Commission the 200 MHz RF storage system. The full complement of storage cavities only becomes available in the Commissioning run.

These procedures are listed in the approximate sequence in which they might be commissioned.

2.2 Year One run

Some gymnastics that have been learned in the Test and Commissioning runs will still need a lot of work in the Year One run. Other gymnastics will be performed for the first time. In this period we expect to learn or improve how to:

1. Re-bucket - transfer beam from the 28 MHz RF system to the 200 MHz system.
2. Increase the number of bunches from 3 per beam to as many as 60 - the nominal design value.
3. Jump transition with minimal emittance growth.
4. Achieve collision optics, with $\beta^* \approx 2$ meter.
5. Measure and parameterize IBS effects.
6. Tame the savage beast - learn how to produce high quality beam in a reproducible and efficient fashion.

There is also a litany of greater and lesser secondary problems - such as orbit control up the ramp, chromaticity tolerances for the head-tail effect, et cetera - that will have to be faced while we are learning how to live with RHIC. It is not possible to predict in anything like an accurate manner how difficult (or easy) it will be to learn how to routinely handle these chores and constraints.

These learning curve projections constitute a "plan for success" - with a plausible and defensible level of optimism.

2.3 Alternative species & energies - penalties

There may be requests in the Year One run to store beam and take data with ion species other than gold, at energies other than 100 GeV/u. Some non-standard conditions are easier to contemplate than others. In increasing order of difficulty, one might consider colliding:

1. **gold at energies below 100 GeV/u**. This, the most minor deviation from standard conditions, would also shed useful light on how RHIC beam dynamics scale with energy.
2. **protons at full energy, or at intermediate energies**. This would necessitate re-learning much of the injection process, et cetera, (almost) from scratch.
3. **other ion species**. Possible, but discouraged, in the Year One run.
4. **protons on ions**. Although RHIC is capable of operating in this non-standard mode, it would be extremely disruptive in the Year One run.

The main Year One goal of reaching 10% of the design luminosity under standard conditions is already a significant challenge, even with dedicated running. Therefore, plausible luminosities for non-standard conditions are expected to be significantly less than this.

3 Shot profiles

When collisions first occur early in the Year One run, it is quite possible that only

- $N_b = 3$ bunches will be circulating, with
- $N = 2 \times 10^8$ ions per bunch, in optics with
- $\beta^* = 10$ meters

Even at storage energy, this results in only a very modest luminosity. In order to reach the goal luminosity of 10% of the nominal value, an aggressive program of parameter development will be necessary. Even planning for success - in the absence of major difficulties - this will take a lot of hard work and effort in the control room. Good communications and cooperation between Accelerator Physicists and Experimental Physicists will be essential.

3.1 Accelerator luminosity parameters

When two identical Gaussian beams collide, the instantaneous luminosity is given by

$$L = \frac{N_b N^2 f}{4\pi\sigma_h\sigma_v} \tag{1}$$

where $f = 78.196$ kHz is the revolution frequency, and σ_h and σ_v are the root mean square transverse beam sizes. Assuming from here on that the beam is round ($\sigma_H = \sigma_V$), the beam size is given by

$$\sigma = \sqrt{\frac{\epsilon\beta^*}{6\pi\beta\gamma}} \tag{2}$$

where $\epsilon = \epsilon_H = \epsilon_V$ is the "6π" normalized emittance used at RHIC, $\beta^* = \beta^*_h = \beta^*_v$ is the collision beta function, and $\beta\gamma$ is the Lorentz factor. The luminosity is conveniently rewritten as

$$L = \frac{3f}{2} \frac{N_b N^2 \gamma}{\epsilon\beta^*} \tag{3}$$

where the first term on the right hand side of the equation is a constant.

The second term on the right contains the variables of interest in understanding how the luminosity will suffer if the accelerator parameters fall short of the nominal values listed in Table 1. Some experience has already been gained with gold injection parameters, during the 1995 AtR test [1]. The measured emittance was approximately as expected, while the single bunch intensity was about 25% of nominal.

Name	Symbol	Units	Gold AtR	Gold start	Gold end	Proton
Bunch count	N_b			60	60	60
Bunch intensity	N	10^9	.25	1.0	$\sim .6$	100.0
Lorentz gamma	γ		12.1	108.4	108.4	268.2
Emittance	ϵ	$\pi\mu$m	9.9	15.0	40.0	20.0
Beta function	β^*	m		2.0	2.0	2.0
Peak luminosity	L	cm^{-2}s^{-1}		$8\ 10^{26}$	$1\ 10^{26}$	$1.5\ 10^{31}$

Table 1: RHIC parameters: as measured in the AtR test in 1995, as expected at the start and at the end of a 10 hour gold store, and at the beginning of a proton store

3.2 Beam dynamics model

The beam dynamics model of single bunch effects which generates the shot profiles shown below includes emittance blow up due to IBS, and beam losses due to IBS, nuclear interactions, and the dynamic aperture [2]. Note that this model is only semi-quantitative, and needs empirical adjustment driven by practical experience to make it reliably quantitative. Emittance growth and beam loss nominally lead to a factor of 8 loss in instantaneous luminosity during a nominal 10 hour store of gold ions. IBS causes the normalized emittance to grow from $\epsilon = 15\pi\mu$m at the beginning of a 10 hour store, to $\epsilon = 40\pi\mu$m at the end.

Although most of the predicted 10 hour beam loss of 40% is due to IBS, beam losses through Coulomb interactions at beam crossings also play a significant role. Definitive calculations [3] for gold on gold at 100 GeV/u lead to Coulomb cross sections of:

- $\sigma = 117$ barns for electron pair production and capture, and
- $\sigma = 95$ barns for Coulomb nuclear dissociation

The instantaneous current lifetime, defined by

$$\tau_N \equiv \frac{N}{dN/dt} \tag{4}$$

is given by

$$\tau_N = \frac{N_b N}{N_{IP} L \sigma_{tot}} \tag{5}$$

where N_{IP} is the number of high luminosity interaction points, and σ_{tot} = 212 barns is the total nuclear cross section. For example, if $N_{IP} = 2$ experiments (PHENIX and STAR) experience an instantaneous luminosity of $L = 8 \times 10^{26}$ cm^{-2}s^{-1}, with 10^9 gold ions in each of 60 bunches, then the partial current lifetime due to nuclear interactions is approximately 49 hours. The partial luminosity lifetime is half of this value.

It is worth noting in passing that the identical horizontal and vertical beam-beam tune shift parameters are given by

$$\xi = \frac{3Nr}{2\,\epsilon} \tag{6}$$

where the classical radius r is $r_p = 1.5347 \times 10^{-18}$ meters for protons and $r_{Au} = 48.992 \times 10^{-18}$ meters for gold. Note that the tune shift parameter is independent of energy (γ), and independent of β^*. RHIC is not expected to be beam-beam limited under nominal operating conditions [4].

3.3 Optimum storage time

RHIC has a nominally stated storage time of $T_{store} = 10$ hours that is quite likely to hold true in the Year One run. As the machine performance increases, however, it may become natural to refill more often, especially if high average luminosity performance is emphasized, and other goals and constraints are deemphasized or ignored. The highest average luminosity is attained by turning off the detectors and dumping the beams when the instantaneous luminosity is equal to the average luminosity since the last time beam was dumped.

For two reasons, RHIC will "look and feel" more like an electron collider than a hadron collider such as the ISR, the Tevatron, the SPS, or HERA. First, RHIC will have a relatively short luminosity lifetime ($\tau_{lum} \approx 1$ or 2 hours) that is characteristic of electron colliders, and which is a full order of magnitude shorter than conventional hadron colliders ($\tau_{lum} \approx 1$ day). Second, rapid refills will be possible in RHIC ($T_{refill} << 1$ hour), in contrast with previous hadron colliders ($T_{refill} \approx$ a few hours). It is fortunate that luminosity lifetimes are long in rings which store antiprotons, since injection tune up is often a time consuming and laborious affair, necessary to avoid losing many of the scarce particles. In brief, conventional electron and hadron storage rings have very different characteristic timescales, which lead to typical storage times of $T_{store} \approx 1$ or 2 hours in electron rings, and $T_{store} \approx 1$ day in hadron rings (before RHIC).

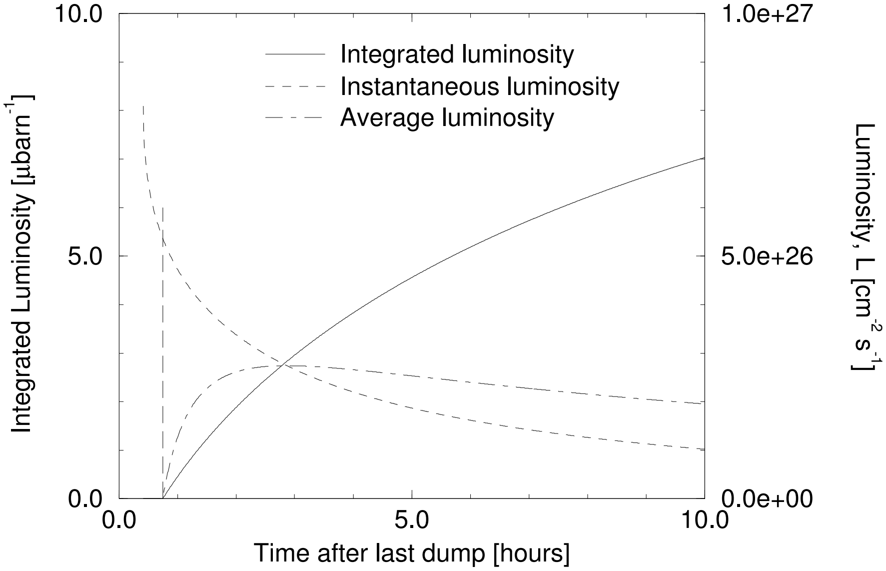


Figure 1: Integrated, instantaneous, and average luminosities during a nominal store of gold ions. $T_{refill} = 25$ mins, $T_{pause} = 45$ mins.

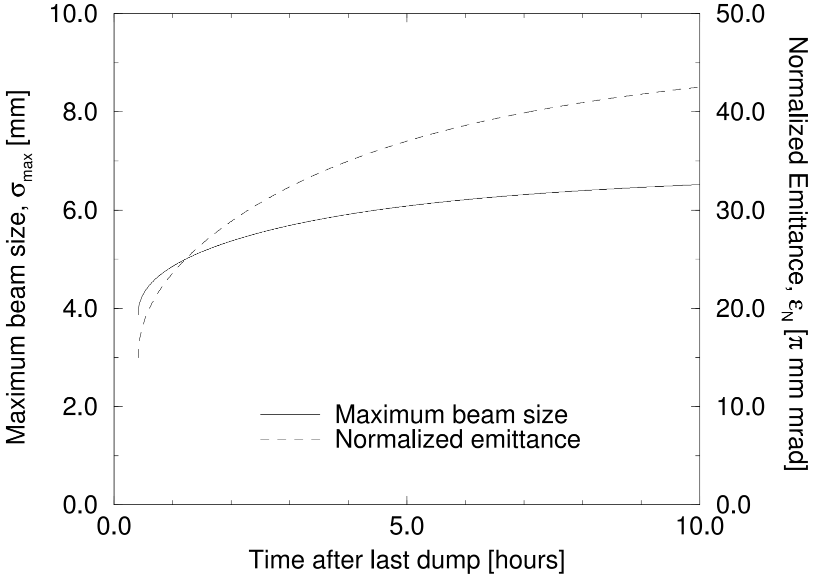


Figure 2: Transverse emittance and maximum beam size (in the triplet) during a nominal store of gold ions. $T_{refill} = 25$ mins, $T_{pause} = 45$ mins.

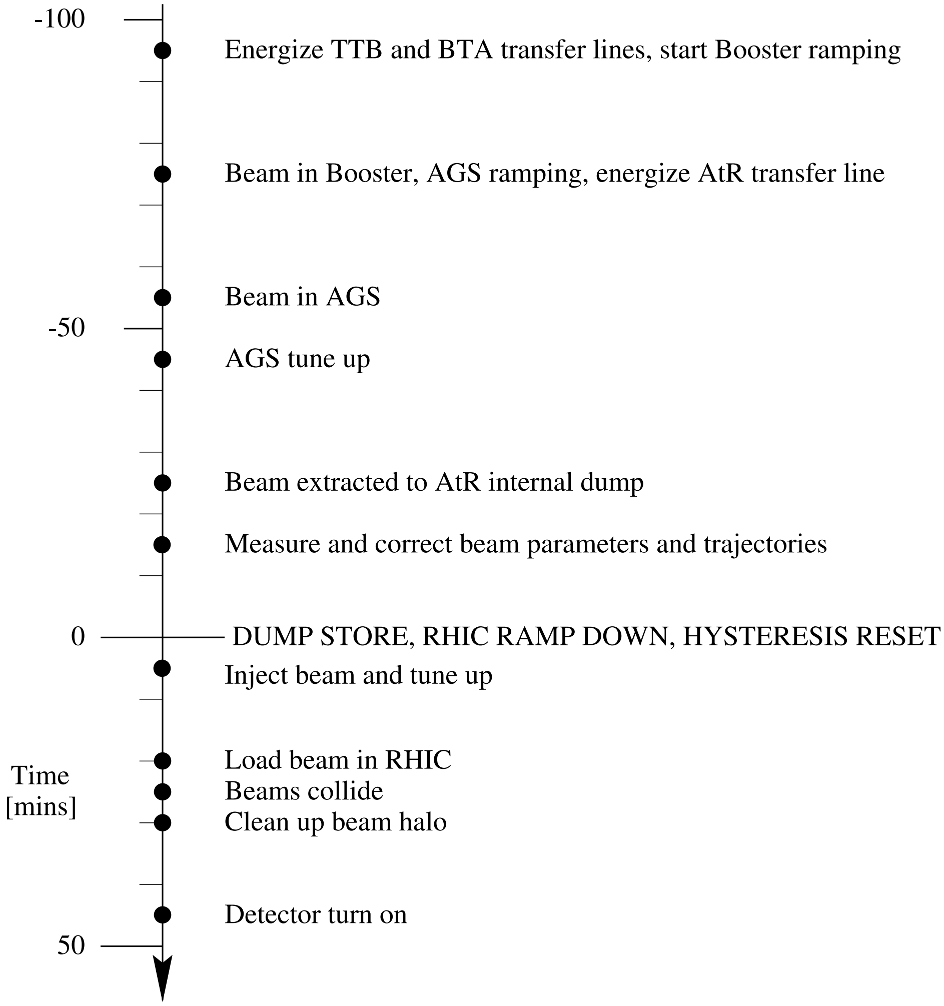


Figure 3: The nominal refill choreography for RHIC operations.

Figures 1 and 2 show the nominal "shot profile" performance for RHIC operations with gold ions, consistent with the beam parameters quoted in Table 1, specifically $N_b = 60$ bunches, $N = 10^9$ ions per bunch, and $\beta^* = 2$ meters. The maximum beam size (in the triplet quadrupoles) grows to a maximum of about 6 mm. Figure 1 suggests that the optimum store length is $T_{store} \approx 3$ hours, since that is when the average luminosity (since the last beam dump) is maximum. The average luminosity is reduced by about 35% if the store length is increased to 10 hours.

3.4 Injection choreography

Most of the other goals and constraints tend to make the optimum storage time longer than the naive maximum average luminosity value. One example is the large power cost associated with running the injector chain, or keeping it on full hot standby. A relatively modest injection system duty factor of only $\approx 20\%$ results when the nominal refill scenario shown in Figure 3 is combined with a 10 hour store [5]. In this dance, the Booster, AGS, and associated transfer are powered down during most of the RHIC store, while the Tandem and the Linac are maintained on hot stand by.

In the nominal refill scenario, first collisions occur $T_{refill} = 25$ minutes after the previous store has been dumped, followed by a $T_{det} = 20$ minute pause while the detectors turn on, for a total period of $T_{pause} = 45$ minutes with no data taking. These parameters are thought to be quite conservative - amenable to significant improvement when RHIC operations are mature and routine. Such improvements will pay off with significantly larger average luminosities. For example, Figure 4 shows the luminosity performance when the time to first collisions is 10 minutes, and the detector turn on time is 10 minutes. As Table 2 shows, this raises the maximum average luminosity by about 30%, from $2.7\ 10^{26}\text{cm}^{-2}\text{s}^{-1}$ to $3.5\ 10^{26}\text{cm}^{-2}\text{s}^{-1}$, simply by clean and efficient living.

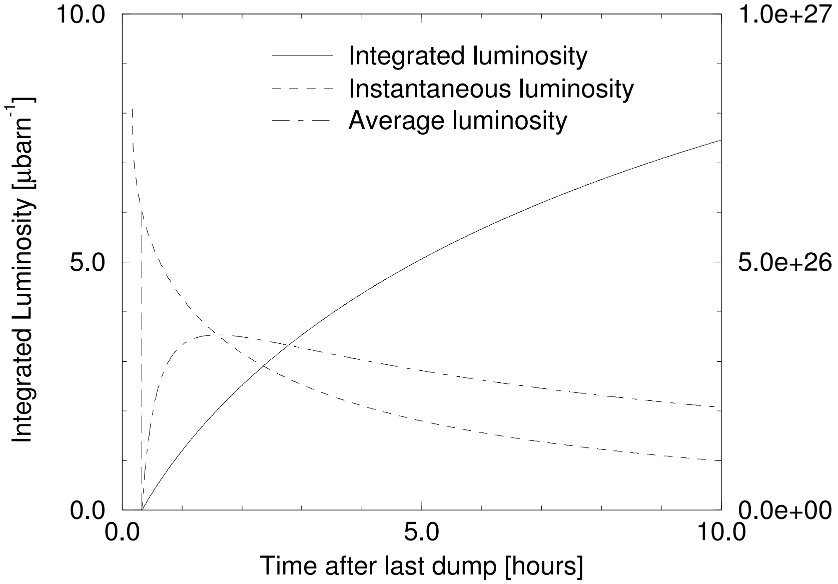


Figure 4: Integrated, instantaneous, and average luminosities during a nominal store of gold ions. $T_{refill} = 10$ mins, $T_{pause} = 20$ mins.

Unecessarily high peak trigger rates, and large trigger rate dynamic ranges, are both undesirable. However, this does not argue very strongly against the desirability of shortening the data taking pause. For example, Table 2 shows that decreasing T_{pause} from 45 minutes to 20 minutes results in only a 10% increase in the peak trigger rate. In fact, the shorter pause scenario has a dynamic range that is 14% less than the longer pause - if the beam is dumped when the average luminosity has reached its maximum. Ultimately, high trigger rates are inevitable if the goal is to get lots of data on tape.

Quantity	Units	short	long
Refill time to first collisions, T_{refill}	min	10	25
Detector turn on time, T_{det}	min	10	20
Data taking pause, T_{pause}	min	20	45
Peak luminosity (detector on)	$10^{26}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	6.0	5.4
Maximum average luminosity	$10^{26}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	3.5	2.7
10 hour average luminosity	$10^{26}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.1	2.0
10 hour instantaneous luminosity	$10^{26}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.0	1.0

Table 2: Instantaneous and average luminosities for "short" and "long" (nominal) data taking pauses.

4 Machine-Experiment interface

Luminosity and background monitoring is essential before and during the Year One run, to gain insight into RHIC tuning for good experimental conditions. Accelerator tuning uses for these diagnostics are both direct (eg, interaction point orbit control), and indirect (eg, allowable range of chromaticities). The measurements to be performed by each experiment are:

1. a beam-beam coincidence rate, proportional to the instantaneous luminosity
2. an "out-of-time" coincidence rate, proportional to relevant background rates from upstream sources
3. a timing difference signal, giving the average collision location along the beam direction

In the End Game Report and in the Second Machine Backgrounds Workshop, each experiment specified a set of counters from which these signals will be provided to the accelerator data acquisition system [6, 7]. To do this, a general purpose set of VME modules will be selected, consisting primarily of coincidence registers, ADCs, and TDCs.

The counters will eventually include zero degree calorimeters approximately 20 meters from the interaction point, between DX and D0 dipoles. The current plan is to use these devices to record mutual correlated Coulomb dissociation (a rate comparable to nuclear inelastic collisions) in order to monitor the luminosity, and also to provide a longitudinal luminosity profile from timing differences. In addition, the instantaneous luminosity will also be calculated from accelerator parameters, such as the beam intensity, local β function, et cetera. These two independent methods for luminosity determination will provide a powerful cross checking mechanism.

4.1 Tunnel background

The effectiveness of Cerenkov detectors in carrying out background measurements was discussed at the Second Machine Backgrounds Workshop [7]. Cerenkov radiators are used instead of scintillators because of intrinsic fast rise-time and radiation hardness. "Upstream halo" particles which enter a Cerenkov radiator from the PMT side yield only 1-10% of the signal amplitude according to test beam measurements [8]. One proposal is to temporarily modify the Cerenkov counters to increase their sensitivity. Another proposal is to provide a parallel set of signals with much lower thresholds for diagnostic purposes. Yet another proposal is to provide an additional set of scintillators near the beam counter locations in the early stages of commissioning. These counters will provide useful beam diagnostics and may also help as an initial cross-check on the Cerenkov counters.

Modeling of detector backgrounds from upstream sources is underway [7]. These calculations provide some estimates of the most effective shielding design for the purpose of intercepting hadronic showers which start upstream of DX. One characteristic of these showers is a very extensive pattern of low energy hits in the region between DX and D0. The installation of scintillator telescopes in this region has been proposed for the commissioning run [9]. One could then tune on the telescope rates and track their rate dependence on local vacuum pressure - that is, extract the "beam-gas" contribution by introducing temporary pressure bumps. These detectors could rapidly give clear empirical evidence of the need for tunnel shielding between DX and D0, to be installed later. They can also be used to begin comparing numerical simulations with reality. RHIC can set up a variety of controlled scenarios - a single bunch in 1 ring, pressure bumps, beams out of collision, long bunches, et cetera.

With the currently envisaged residual gas levels [10] the "upstream beam-gas" rate is expected to reach about 10 kHz at design currents. This rate is only a 0.1% occupancy, since the bunches cross at approximately 10 MHz. So, the experiments could simply opt to veto the corresponding crossings at the trigger level, without a significant loss in luminosity. The PHENIX group has pointed out that the upstream halo rate could overwhelm their forward muon trigger rate, since hits can be expected in many layers of their muon id system. On the other hand, PHENIX does not currently plan to implement this trigger during the Year One run, and so it is possible to use this period to measure and evaluate shielding and "trigger blanking" schemes.

One primary collimator will be available in each ring during commissioning and the Year One run. It might be possible to demonstrate the need for a secondary (or momentum) collimator, and associated warm-to-cold transitions, at the natural Q9-D9 location. The total cost would be $\sim$ \$500k for both rings.

At the beginning of the Year One run, PHENIX, PHOBOS, and possibly STAR plan to have large numbers of channels of silicon detectors installed close to the beam tube in their experiments. All groups are interested in measuring dose rates in these locations during the commissioning run, prior to detector installation. This will be carried out using sets of pin diodes installed and maintained by each group. Each group is expected to provide a VME board in the local RHIC crate. Instantaneous rates in these detectors will be helpful in tuning against background losses. They should be capable of generating a request to abort beam.

5 Conclusions

A plan with 3 running periods in 1999 integrates accelerator installation and commissioning with detector roll-in and commissioning. The "Test" and "Commissioning" runs will be mostly dedicated to Machine Studies, in preparation for the "Year One" data taking run.

Goals for the Year One run include 50% uptime, and a luminosity of 10% of the design. Accelerator parameters (number of bunches, bunch intensity, β^*) will need aggressive development. Nonetheless, the "plan for success" represents a plausible and defensible level of optimism.

The reliability and efficiency of the injector chain will have a direct effect on the integrated luminosity. Storage times significantly shorter than 10 hours may prove to be desirable. Intra Beam Scattering is expected to be a dominant physical phenomenon limiting the ultimate performance of RHIC.

Good communications between Accelerator and Experimental Physicists will be essential. In particular, cooperation at the machine-experiment interface will be vital in improving the luminosity, and in understanding and reducing the background.

6 Acknowledgments

I am very grateful for discussions with, and contributions from, Sebastian White, Mike Harrison, Satoshi Ozaki, and Tom Ludlam.

References

[1] *Physics of the AGS to RHIC Transfer Line Commissioning*, T. Satogata et al, European Particle Accelerator Conference, 1996. Also available as RHIC/AP/104.

[2] The code "shot" that was used to generate the shot profiles is publicly available, with source code in the RAP directory $HORST/shot, and executable in $HORST/bin.

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[6] *A Commissioning and Initial Operations Scenario for Collider and Detectors*, Final Report of the End Game Task Force, RHIC/DET Note 16, March 1995.

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[10] *1st Workshop Machine Backgrounds at RHIC*, unpublished, 1995.